UNIVERSIDADE FEDERAL DO RIO DE JANEIRO
INSTITUTO DE ECONOMIA
PROGRAMA DE PÓS-GRADUAÇÃO EM ECONOMIA

MARCIO ALVARENGA JUNIOR

TOWARDS A STRUCTURAL CARBONIZATION OF THE BRAZILIAN ECONOMY: THE IMPLICATIONS OF RECENT STRUCTURAL CHANGES FOR THE COUNTRY'S GREENHOUSE GAS EMISSIONS

RIO DE JANEIRO, NOVEMBER 2024

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Supervisor: Prof. Dr. Kaio Glauber Vital da Costa

Co-supervisor: Prof. Dr. Carlos Eduardo Frickmann Young

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Banca Examinadora:

____

Prof. Dr. Kaio Glauber Vital da Costa
Universidade Federal do Rio de Janeiro

____

Prof. Dr. Carlos Eduardo Frickmann Young
Universidade Federal do Rio de Janeiro

____

Prof. Dr. Fabio Neves Peracio de Freitas
Universidade Federal do Rio de Janeiro

____

Prof. Dra. Carmem Aparecida do Valle Costa Feijó
Universidade Federal Fluminense

____

Dra. Camila Luciana Gramkow
Comissão Econômica para a América Latina e o Caribe

____

Prof. Dr. André Albuquerque Sant'Anna
Banco Nacional de Desenvolvimento Econômico e Social

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ABSTRACT

The debate on structural change resurfaced in Brazil in the mid-2000s, centered on analyzing the causes, intensity, timing, and implications of the processes of deindustrialization and regressive specialization for the country's economic development. However, the environmental repercussions of these changes remained largely unexplored. This thesis seeks to contribute to closing this gap by investigating how the economic structure of production and emissions are interrelated and how structural changes from 2000 to 2019 have impacted Brazil's emission levels. Specifically, this thesis aims to analyze: (i) the Brazilian structural emission profile, meaning which industries and components of final demand are the most carbon-intensive and how their emissions evolve over time, as well as how different industries diverge in their capacity to pull emissions from or propagate emissions to other sectors; (ii) whether changes in the Brazilian productive structure and trade pattern have impaired the country's decarbonization; (iii) the main forces driving emissions growth during the period; and (iv) whether Brazil is increasing its productive and trade specialization in emissions-intensive industries. To meet its general and specific objectives, this thesis puts forward a methodology to build an emissions satellite account and integrates it into a series of estimated input-output matrices for the period 2000-2019. Drawing on these emission vectors, three structural decomposition analyses were conducted: the first focusing on the impact of changes in the sectoral composition of output on emissions; the second on the influence of changes in the structure of final demand and demand leakages on emissions, and the third addressing the main drivers of changes in total emissions embedded in exports. The results reveal that, although the scale effect played a central role in driving emissions upward, changes in the sectoral composition of gross output, final demand, and exports were highly relevant to explaining emission growth, particularly for exports. Putting it into numbers, 71.2% of the emissions associated with export production were, in fact, driven by changes in the export basket rather than by the total value exported. Another significant finding is that highly emissions-intensive industries are gaining ground in both Brazil's productive and trade structures. Industries in the two most emissions-intensive quartiles increased their share of gross output from 47.9% to 54.9%, with the most emissions-intensive quartile gaining 5.1 percentage points over the period. Meanwhile, the share of these industries in exports rose by 23.1 percentage points, with the fourth quartile accounting for 20.1 points. Therefore, this thesis demonstrates that the structural changes that took place in Brazil have created significant obstacles to the country's decarbonization.

KEYWORDS: Structural Change, Deindustrialization, Reprimarization, Regressive Specialization, Environmentally Extended Input-Output Analysis, Structural Decomposition Analysis, Greenhouse gas emissions.

RESUMO

O debate sobre mudanças estruturais ressurgiu no Brasil em meados da década de 2000, centrado na análise das causas, intensidade e implicações dos processos de desindustrialização e especialização regressiva para o desenvolvimento econômico do país. No entanto, as repercussões ambientais dessas mudanças permaneceram em grande parte inexploradas. Esta tese busca contribuir para preencher essa lacuna, investigando como a estrutura econômica e as emissões estão inter-relacionadas, e como as mudanças estruturais no período de 2000 a 2019 impactaram os níveis de emissão do Brasil. Especificamente, esta tese tem como objetivo analisar: (i) o padrão estrutural de emissões brasileiro, ou seja, quais setores e componentes da demanda final são mais intensivos em gases do efeito estufa e como suas emissões evoluem ao longo do tempo, além de como as esses setores divergem em sua capacidade de induzir ou propagar emissões para outros setores; (ii) se as mudanças na estrutura produtiva brasileira e no padrão de comércio prejudicaram a descarbonização do país; (iii) as principais forças que impulsionam o crescimento das emissões durante o período; e se o Brasil está aumentando sua especialização produtiva e de comércio em setores intensivos em emissões. Para cumprir com seus objetivos gerais e específicos, esta tese apresenta uma metodologia para construir uma conta satélite de emissões e integrá-la a uma série de matrizes de insumo-produto estimadas para o período de 2000 a 2019. Com base nestes vetores de emissões, foram realizadas três análises de decomposição estrutural: a primeira centra-se no impacto das mudanças na composição setorial da produção; a segunda foca na influência das mudanças na estrutura da demanda final e do vazamento de demanda sobre as emissões, e a terceira aborda os principais fatores de mudança nas emissões associadas às exportações. Os resultados revelam que, embora o crescimento no nível desses agregados tenha desempenhado um papel central no aumento das emissões, as alterações na composição setorial do valor bruto da produção, da demanda final e das exportações também foram altamente relevantes para explicar o crescimento do total de gases de efeito estufa emitidos, em especial no caso das exportações. Em termos numéricos, 71,2% do aumento das emissões associadas à produção dos bens e serviços exportados resultaram, de fato, de alterações na pauta de exportações e não do crescimento do valor total exportado. Os resultados encontrados também indicam que os setores intensivos em emissões estão ganhando terreno na estrutura produtiva e de comércio do país. Os setores indústrias dos dois quartis mais intensivos em emissões aumentaram sua participação na produção bruta de 47,9% para 54,9%, com o quartil mais intensivo em emissões ganhando 5,1 pontos percentuais no período. Entretanto, o avanço da participação desses dois quartis nas exportações foi amplamente superior, aumentando 23,1 pontos percentuais no período analisado, dos quais o quarto quartil contribuiu com 20,1 pontos. Portanto, esta tese demonstra que as mudanças estruturais que ocorreram no Brasil criaram obstáculos significativos para a descarbonização do país.

Palavras-chave: Mudança Estrutural, Desindustrialização, Reprimarização, Especialização Regressiva, Análise de Insumo-Produto Ambientalmente Estendida, Análise de Decomposição Estrutural, Emissões de Gases de Efeito Estufa

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LIST OF ACRONYMS

AC	Processed agricultural commodities industry group
AGR	Agricultural, fishing and related industry group
APPs	Areas of Permanent Preservation
BL	Backward linkages
CAR	Rural Environmental Registry
EBL	Emission backward linkage
BRL	Brazilian reals
EEIOT	Environmentally extended input-output tables
EKC	Environmental Kuznets Curve
EU	European Union
FL	Forward linkages
EFL	Emission backward linkage
GDP	Gross domestic product
GFCF	Gross fixed capital formation
GHG	Greenhouse gases
GVC	Global Value Chain
GWP	Global warming potential
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
IBGE	Brazilian Institute of Geography and Statistics
IC	Industrial commodities industry group
ICMBio	Chico Mendes Institute for Biodiversity Conservation
ICT	Information communication technology
IM	Innovative manufacturing industry group
IOT	Input-output tables
IPCC	Intergovernmental Panel on Climate Change

LAC	Latin America and the Caribbean
LDMI	Logarithmic Mean Divisia Index
LTS	Long Term Strategy
LUC	Land use change
MRIO	Multiregional Input-Output Tables
NDC	Nationally Determined Contributions
NPISH	Consumption of non-profit institutions serving households
OECD	Organization for Economic Co-operation and Development
$\widetilde{PD}$	Power of dispersion of emissions
PHH	Pollution Haven Hypothesis
PPCDAm	Prevention and Control of Deforestation in the Legal Amazon
RoW	Rest of the world
$\widetilde{SD}$	Sensitivity of dispersion of emission
SDA	Structural decomposition analysis
SEEG	Greenhouse Gas Emissions and Removals Estimation System
SNA	System of National Accounts
SPM	Small particular matter
TM	Traditional manufacturing industry group
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
WIOD	World Input-Output Database

LIST OF VARIABLES

Variable	Dimension	Description
$\boldsymbol{M_p}$	(833 x 91)	Matching matrix
$\boldsymbol{M_s}$	(833 x 42)	Sectoral Emission weight matrix
$\boldsymbol{D'}$	(91 x 42)	Transposed Market Share matrix
$\boldsymbol{SE}$	(833 x 42)	Matrix of sectoral participation
$\boldsymbol{VR}$	(833 x 42)	Sectoral emission share matrix
$\boldsymbol{v}$	(1 x 42)	Summation Vector

$\boldsymbol{v'}$	(42 x 1)	Transposed summation vector
$\boldsymbol{\sigma'}$	(833 x 1)	Transposed summation vector
$\boldsymbol{j}$	(5 x 1)	Summation Vector
$\boldsymbol{e_i}$	(1 x 42)	Vector of total emission by sector
$\widehat{\boldsymbol{GHG}}$	(833 x 833)	Inventoried emissions diagonal matrix
$\boldsymbol{x_i}$	(1 x 42)	Vector of gross output by sector
$\widehat{\boldsymbol{E}}$	(42 x 42)	Sectoral emission intensity diagonal matrix
$\boldsymbol{e}$	(1 x 42)	Total emission vector
$\boldsymbol{A}$	(42 x 42)	Matrix of domestic direct coefficient
$\boldsymbol{A^t}$	(42 x 42)	Matrix of total direct coefficient
$\boldsymbol{\Lambda}$	(42 x 42)	Matrix of domestic content of input supply
$\boldsymbol{L}$	(42 x 42)	Leontief inverse matrix
$\tilde{\boldsymbol{L}}$	(42 x 42)	Leontief environmentally extended inverse matrix
$\boldsymbol{k}$	(42 x 1)	Industry share of total output vector
s	(1 x 1)	Output level
$\widehat{\boldsymbol{G}}$	(42 x 42)	Emission intensity by industry, excluding LUC emissions
$\widehat{\boldsymbol{\beta}}$	(42 x 42)	Matrix of emission augmenting factor from LUC
$\boldsymbol{f}$	(42 x 1)	Final demand vector
$\boldsymbol{F^c}$	(42 x 5)	Final demand by industry and final demand category
$\boldsymbol{F^m}$	(42 x 5)	Matrix of industries` share in the c categories of final demand
$\boldsymbol{f^{cs}}$	(5 x 1)	Vector of total final demand by final demand category
$\boldsymbol{f^{cm}}$	(5 x 1)	Share of each final demand category in the total final demand
f^s	(1x1)	Scalar of total final demand
$\boldsymbol{F^{mt}}$	(42x 5)	Total final demand for domestic and imported production
$\boldsymbol{F^i}$	(42 x 5)	Share of domestic production in total final demand
$\boldsymbol{e_\Phi}$	(42 x 5)	Exports emissions by trading partner
$\boldsymbol{\Phi}$	(42 x 5)	Brazilian exports by industry and trading partner
$\boldsymbol{\mu}$	(42 x 42)	Matrix of domestic content of the total direct coefficient
$\boldsymbol{\varphi}$	(42 x 1)	Vector of total export by industry
$\boldsymbol{\eta}$	(42 x 5)	Share of each trading partner in total exports

ALGEBRAIC SYMBOLS

$\otimes$ Hadamard product

$\oslash$ Hadamard division

^ Diagonal operator

' Transpose operator

Δ Difference

CONTENT

INTRODUCTION

Motivation

The piling evidence that developing countries are shifting their economic structure toward services earlier than ever before is rekindling the debate on the nexus between structural change and economic development. By shortcutting their industrialization phase and moving faster toward services, countries are unable to reap the economic benefits that commonly arise from a more diversified and complex industrial base. (Palma, 2005; Dasgupta and Singh, 2006; Rodrik, 2016; Dosi et al., 2021).

In Brazil, the debate on structural change regained center stage in the mid-2000s, with many studies indicating that, after the trade and financial liberalization reforms of the 1990s, the Brazilian manufacturing sector was left unprotected from external competition in a context of overvalued exchange rates and high interest rates, impairing its performance and driving the country toward a premature deindustrialization process. (IEDI, 2005, 2007; Bresser-Pereira and Marconi, 2008; Comin, 2009; Oreiro and Feijó, 2010; Nassif, Feijó, and Araújo, 2013; Nassif et al., 2020). Other studies highlighted that Brazilian deindustrialization was also accompanied by a regressive specialization pattern in both the productive and trade structures, i.e., a situation in which production and exports steer in the direction of higher specialization in goods with a low value-added and technological degree of sophistication and, and high intensity in natural resources (Coutinho, 1997; Morceiro, 2012; Nassif and Castilho, 2020).

Additional research, such as that conducted by Neves (2013) and Passoni (2019), found divergent results regarding the timing and intensity of the deindustrialization and regressive specialization processes. Both authors indicated that when changes in relative prices are accounted for, the hypothesis of a pronounced deindustrialization and regressive specialization of the productive structure prior to 2008 does not hold, even though there were already concerning signs regarding the specialization pattern of exports. However, from 2008 onward, the evidence supports that the Brazilian economy entered a path of deindustrialization and reprimarization in both its productive structure and exports, but at a much lower intensity than suggested by previous studies. There seems to be, however, a relatively broad acceptance that the regressive specialization was considerably more pronounced for exports than for the productive structure (Torracca, 2017) and that the Brazilian economy was subjected to a process of import penetration, notably in the manufacturing sector (Comin, 2009; Morceiro, 2012, Morceiro and Guilhoto, 2019)

The emergence of China as a key player in international trade in the 2000s influenced both deindustrialization and reprimarization processes. On the one hand, Chinese manufacturing competed with Brazilian production in both domestic and international markets, notably in the Latin American and Caribbean (LAC) region, narrowing opportunities for Brazil's domestic manufacturing sector (Hiratuka and Sarti, 2017; Castilho, Costa, and Torracca, 2017). On the other hand, China's surging demand for commodities has pushed the global economy toward reprimarization (Amaral, Freitas, and Castilho, 2020).

In addition to discussions about the intensity and timing of the deindustrialization and regressive specialization processes, the debate on recent structural changes has largely focused on the policy measures that triggered these transformations as well as their implications for the economic development process. While all these elements are valid and highly relevant to public debate and policymaking, a fundamental issue concerning the recent structural changes in the Brazilian economy has been largely overlooked: their repercussions on the country's environmental performance.

The shift in Brazil's productive and trade structures toward commodity-producing sectors likely carries significant environmental impacts. These goods have a high material base, meaning that value added through their production largely relies on the exploitation of renewable or non-renewable natural resources. For this reason, they tend to be more closely associated with issues such as the depletion of non-renewable natural resources or impacts on ecosystems that sustain the flow of environmental goods and services (IUNC, 2021). In Brazil, for example, agriculture is the primary driver of forest loss and emissions of greenhouse gases (MAPBiomas, 2024; SEEG, 2024), while industrial commodities often require large amounts of energy and, therefore, result in a great quantity of both local and global pollutants in their transformation processes.

Meanwhile, as the world stands at the edge of a climate cliff, countries are urged to decarbonize their economies and reach carbon neutrality no later than 2050 to avoid climate change's most disruptive impacts. (IPCC, 2019). The transition towards a decarbonized world will require profound structural changes, shifting from high to low carbon sectors and technologies (Altenburg and Assmann, 2017; Buttazzoni, Delgado and Alvarenga, 2024).

Brazil ranks 7th among the world's largest emitting countries (WRI, 2021), with most of its emissions stemming from agricultural activities and land-use changes, which are closely tied to the production of raw and processed agricultural commodities. Therefore, it might be the case that recent structural changes in Brazil are posing new obstacles to the country's decarbonization, making it derail from a pathway to emissions neutrality.

Objectives, key research questions, and hypotheses

This thesis aims to investigate how Brazil's productive structure and emissions coevolve and to determine the impacts of recent structural changes on the country's level of greenhouse gas (GHG) emissions. More specifically, this thesis will be guided by four key research questions: (i) what is the Brazilian structural emission profile? (ii) What are the main driving forces of emission growth in the analyzed period? (iii) Are changes in the Brazilian productive structure and trade pattern impairing the country's decarbonization? (iv) How did the share of emission-intensive industries in total output and exports evolve?

Through the first question, we aim to reveal how Brazilian emissions are distributed across industries and components of final demand, highlighting their evolution over time. Their respective emission intensities will also be examined, providing insight into the trajectory of Brazil's emissions in light of the characteristics of the country's economic growth during the analyzed period. Special attention will be given to emissions associated with the production of exported goods and services, as evidence suggests that the process of regressive specialization has been more pronounced for Brazil's exports than for the overall productive structure.

Another important feature of Brazil's structural emission pattern relates to how interindustry relations explain emission flows between sectors. This thesis adapts the Hirschman-Rasmussen backward and forward linkage indicators to identify which industries in Brazil's current productive structure pose the greatest challenges to decarbonization and which could lead the country's transition towards a low-carbon economy.

The second question shifts focus from understanding how emissions evolve to why they evolve – that is, identifying the main factors driving changes in emissions from one period to another. The third question builds on this but focuses specifically on the contribution of changes in the sectoral composition of aggregates, such as gross output and exports, to total emissions. Finally, the fourth and last research question seeks to determine whether Brazil's productive and trade structures increase its productive and trade specialization in emissions-intensive industries.

The hypothesis put forward in this thesis is that the process of structural change during the 2000-2019 period hindered the country's decarbonization efforts by increasing its specialization in emissions-intensive sectors.

Structure of the thesis

This thesis is structured into four chapters. The first chapter provides a comprehensive literature review on the nexus between structural change, economic development, and sustainability, first discussing the importance of structural change for economic development and then exploring how these elements connect with sustainability issues. The final sections of this chapter focus on the Brazilian case by presenting the main characteristics of recent structural changes in the country, as highlighted in the literature. Given the limited number of studies addressing the environmental repercussions of Brazil's recent structural changes, the chapter offers an initial look at the potential environmental implications of these transformations by introducing indicators of natural resource use, GHG emissions, and energy efficiency.

In the second chapter, we build the emission satellite accounts that will be integrated into a series of estimated input-output tables developed by Passoni and Freitas (2022). The key research questions specified above will be addressed with the support of an environmentally-extended input-output analysis. Specifically, we will conduct three structural decomposition analyses (SDA), and the methodological steps will also be presented in this chapter. The first SDA is centered on investigating the impact of shifts in the output structure on emissions, while the second and third decompositions follow a similar strategy but applied to the impacts of changes in the structure of final demand and exports on total emissions. The way these decompositions are structured will also allow for a better understanding of other key elements, such as how demand leakages, technology changes, and deforestation rates affect emissions in this period.

The third chapter presents what we call the "Brazilian structural emission profile", i.e., how final demand forces interact with Brazil's interindustry structure and industries' emission intensities to generate emissions. The results are presented both with and without emissions from land use changes. This chapter also identifies key sectors for Brazil's transition based on their emission backward and forward linkages, as well as the emissions associated with Brazilian exports by trading partners. This latter aspect is undoubtedly one of the novelties of this work.

Finally, the fourth chapter presents the results of the SDA analysis, along with some indicators to shed light on whether Brazil has increased its productive and trade specialization in emission-intensive industries.

CHAPTER 1. STRUCTURAL CHANGE, ECONOMIC DEVELOPMENT, AND SUSTAINABILITY: SEARCHING FOR AN ANALYTICAL INTERSECTION

I. INTRODUCTION

Structural change and economic development are intertwined phenomena. On the one hand, structural change must move in a specific direction and at a particular pace for economic development to take off. On the other, as economic development advances, a set of structural transformations takes place. For this reason, structural change is a central analytical object of development economics, a field of economic science dedicated to identifying and understanding statistical regularities (i.e., stylized facts) between structural transformations and sustained economic growth.

Structural change is often narrowly referred to as a shift in output composition. However, the concept has a much broader meaning, embracing changes in technology, inter-industry linkages, international trade patterns, the level and composition of final demand, accumulation rates, income distribution, and so on (Syrquin, 1988). All the forms taken by these transformations may lead to important variations in the use of energy and natural resources, as well as in levels of pollution and waste disposal (Savona and Ciarli, 2019). Therefore, connecting the dots between structural change, economic development, and sustainability is becoming increasingly relevant in the context of global environmental crises.

Two structural change-related topics have been gaining increasing attention recently. The first relates to the ongoing deindustrialization of most developing countries, which seems to have started much earlier than expected, considering the past experiences of developed countries. For the former group, their share of manufacturing has peaked at significantly lower levels of GDP and employment, and these peaks have occurred at much inferior per capita income levels than historically observed. The second topic concerns how to make structural changes that contribute simultaneously to economic development and environmental sustainability; for the economic development of just a few industrialized nations has brought about a planetary climate crisis, even as many other countries are still waiting in the development queue.

In the mid-2000s, the debate on structural change resurfaced in Brazil, fueled by discussion of the deindustrialization and reprimarization of the country's export basket. Much attention has been paid to analyzing the causes, intensity, and time profile of these events and their implications for productivity and long-term economic growth, competitiveness, economic complexity, and the trajectory of Brazilian economic development as a whole. (Palma, 2005; Bresser-Pereira and Marconi, 2008; Oreiro and Feijó, 2010; Nassif *et al*., 2013; Neves, 2013; Passoni and Freitas, 2018; Passoni, 2019; Amaral, Castilho and Freitas, 2021). However, the environmental repercussions of these changes are still largely underexplored.

This chapter organizes an extensive literature review on the nexus between structural change, economic development, and sustainability and is divided into two parts. The first part consists of two sections: (i) a discussion of the relationship between structural change and economic development and (ii) an extension of that discussion to integrate sustainability issues, presenting the main lines of debate on the relationship between structural change, economic development, and the environment. The second part is structurally very similar to the first but delves into the analysis of the Brazilian case. Its first section presents the debate on structural change in Brazil, specifically focusing on deindustrialization and the regressive specialization of both production and export basket, and the second extends the analysis to incorporate the environmental dimension. Given the limited number of studies addressing the environmental repercussions of recent structural change in Brazil, this chapter introduces some environmental indicators of natural resource use, GHG emissions, and energy efficiency.

II. STRUCTURAL CHANGE AND ECONOMIC DEVELOPMENT

Kuznets (1973) coined the term "*modern economic growth*" to describe the economic development of nations following the Industrial Revolution. In this case, "modern" refers to some distinctive elements that characterized economic growth during this period. According to the author, some nations began to experience economic growth accompanied by high structural transformation rates and systematic productivity increases driven by science-based innovations. These combined elements allowed output rates to increase faster than demographic growth, leading to a persistent expansion of per capita income.

During the economic development process, resources are progressively shifted towards sectors with greater capacity to drive productivity growth. Lewis (1954) presented one of the most influential contributions to development literature. The author put forward a dualistic model to explain the process of economic development, in which excess labor is displaced from a traditional, low-productivity sector to a modern, high-productivity one. In the initial stages, this labor transfer would exceed demand for it at the prevailing wage in the modern sector, preventing labor costs increases. As a result, as the modern sector grows, output surplus over wages would increase, freeing up resources for investment. The Lewis model led the way in addressing two fundamental aspects of economic development: (i) sector composition and (ii) accumulation rates. Later, Chenery (1960) revisited these two elements and defined economic development as a process of capital accumulation and structural transformation that would support economic growth through a fuller and better utilization of economic resources.

In the absence of an endogenous mechanism constantly and continuously balancing out productivity differentials across sectors, structural change becomes a relevant source of long-term economic growth. As Syrquin (2008: p.49) pointed out, structural change *"can retard growth if its pace is too slow or its direction inefficient, but it can contribute to growth if it improves the allocation of resources by, for example, reducing the disparity in factor returns across sectors or facilitating the exploitation of economies of scale.*" This gain in production and productivity resulting from the transfer of resources from traditional to modern sectors is often referred to as a structural bonus, and it tends to be considerably higher for low-income countries, where sizeable productivity differences still remain across the economic sectors (Timmer and Szirmai, 2000).

Understanding the link between structural change and sustained economic growth, and identifying statistical regularities (i.e., stylized facts) is paramount for policymaking, as economic development is the primary channel through which it is possible to improve socioeconomic conditions. As economic development advances, an improvement in various socioeconomic indicators comes along: for example, in per capita income and overall productivity, the creation of better-paid and more skilled jobs, poverty alleviation, and the reduction of external structural constraints (Syrquin, 1988, 2010; Rodriguez, 2009). In many cases, economic development is accompanied by an expansion in the provision of public services, with an increase in access to energy, water, sanitation, health, and education, further improving socioeconomic conditions (Oliveira, 2015; Bastos and Oliveira, 2021). More controversial, though, is the debate on whether economic development can endogenously improve environmental conditions.[1]

Development economics is a field of economic science dedicated to answering these queries and supporting the formulation of long-term policies conducive to growth, especially in developing nations, where many socioeconomic problems still persist, and the need for rapid economic development is pronounced. As Syrquin (1988: p.205) put it, development

[1] This discussion will be presented in Section II.

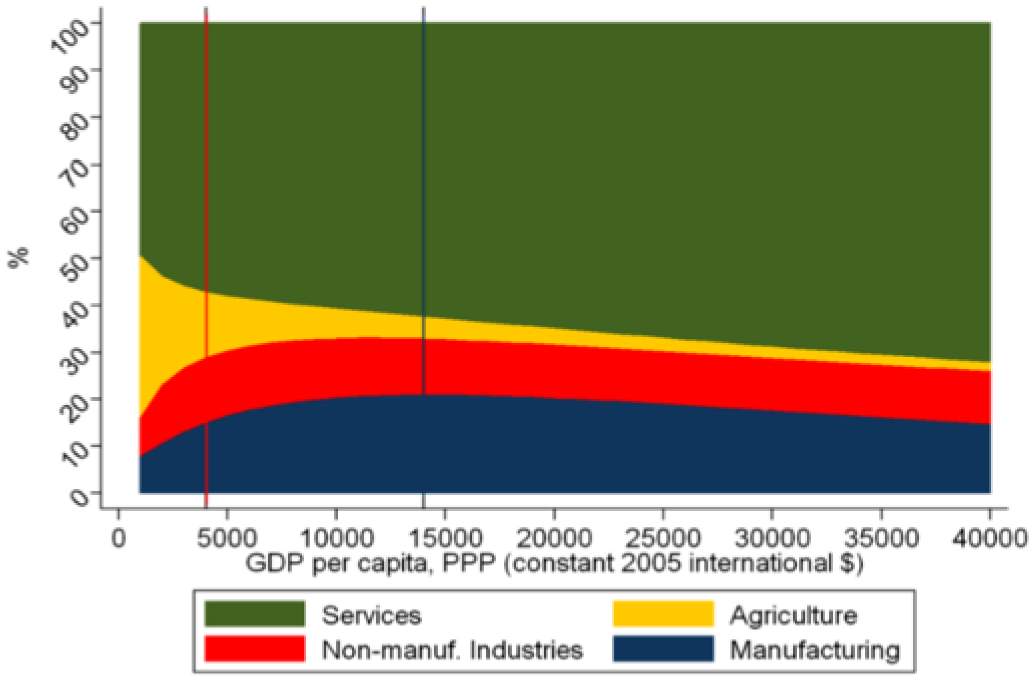
economics is dedicated to "*dealing with issues of structure and growth in less developed countries*."

Structural change is a central analytical object of this field of study, working both as a triggering element and a foundation of economic development, but also being transformed by it.[2] This term is often used as a synonym for a shift in output composition. However, this definition of structural change fails to incorporate many other important transformations that come with the economic development process, such as in accumulation rates (Lewis, 1954; Rostow, 1960), in the sectoral composition of employment, in technical requirements for inputs (Chenery and Taylor, 1968), and in inter-industry linkages and density (Rasmussen, 1956; Hirschman, 1958), as well as changes in the composition of demand in import and export coefficients. (Syrquin, 1988).

Although there are features specific to each national development process, there are also converging elements, commonly referred to as "stylized facts." As already mentioned, one of the most important examples of the latter is the reallocation of resources towards high-productivity sectors (Lewis, 1954). Historically, this transfer of resources occurs first from agriculture to manufacturing, with the latter increasing its weight in terms of both total employment and gross domestic product (GDP). Later, a similar movement occurs, but this time from manufacturing towards services (CLARK, 1940), as exemplified in Figure 1.

[2] As put by Abramovitz (1983: p.85), "*sectoral redistribution of output and employment is both a necessary condition and a concomitant of productivity growth*".

Figure 1 - GDP composition by income level and sector



Source: UNIDO (2017)

II.1. Industrialization phase

The evidence suggests that industrialization has been the main path taken by high-income countries in seeking to achieve higher levels of development. As Chang (2016: p.31) noted: *"very few countries have developed their economies without developing a strong manufacturing base – so much so that the term 'industrialized country' and 'developed country' are often used interchangeably."*

The importance of manufacturing for economic development has been widely and well documented in the literature of economic science. Kaldor (1966, 1967) drew attention to the fact that manufacturing exhibits important static and dynamic returns to scale, so its output expansion tends to be accompanied by productivity increases within the sector. Manufacturing expansion also contributes to increasing the economy's overall productivity by draining excess labor in activities with diminishing returns (Kaldor, 1966, 1967). As a result, the more a country`s manufacturing industry grows compared to its non-manufacturing sector, the faster that country's average productivity increases, as does its GDP. Hirschman also saw manufacturing as a key sector for economic development due to strong inter-industry connections. Compared to the primary and service sectors, manufacturing exhibits stronger backward and forward linkages - i.e., it exhibits a great capacity to pull production from other sectors as its demand increases, and it also plays an essential role in providing inputs to other industries downstream (Hirschman, 1958). The stronger linkages for the manufacturing sector also result in more numerous opportunities to diffuse technological progress. According to Cornwall (1977), this sector is the one most responsible for creating state-of-the-art technologies and propagating technological progress embodied in fixed capital goods across the economy through its linkages. Prebisch's (1950) and Singer's (1950) contributions dealt with the difference between the income elasticity of demand for manufactured goods and that for primary goods. The authors highlighted that the greater elasticity of the former leads to a tendency for the terms of trade for primary goods to deteriorate,[3] creating structural external constraints on the economic growth of primary exporters. (Thirlwall, 1979).

Many important structural transformations emerge during industrialization. Rostow (1960) emphasized the steep increase in investment rates in this phase.[4] A key aspect of this increase concerns its potential to impact both aggregate demand and supply, according to Kaldor (1956). On the demand side, it creates effective demand, preventing unplanned idle capacity. On the supply side, the fixed capital formation resulting from investment decisions creates new productive capacity. Additionally, investment is a crucial channel through which technical progress and technological change are incorporated into production. (Syrquin, 1988).

The composition of final demand also undergoes significant changes, with a larger share going to manufactured goods. Due to rising investment rates, demand increasingly shifts towards manufacturing, as many capital goods are typically produced in this sector. This trend is reinforced by changes in the income elasticity of demand. As per capita income rises, the demand for food tends to grow but at a progressively slower rate. Beyond a certain threshold, the income elasticity of demand for food is surpassed by the income elasticity of demand for manufactured goods. Consequently, the share of food in private consumption sharply declines, further pushing final demand away from agriculture towards manufacturing. As pointed out by

[3] The dominant idea that a decline in the relative prices of primary goods would lead to a compensating increase in demand was strongly challenged by the work of Prebisch and Singer. These authors argued that a higher income elasticity of demand for manufactured goods would translate into a much steeper expansion of imports for countries exporting primary goods than for industrialized countries as their income increased.

[4] Lewis (1954) in his dualistic model combined the accumulation issue with changes in output composition. The author argued that the transfer of resources from traditional to modern sectors allowed for an increase in profit share, therefore shifting income distribution in favor of the saving class. According to the author: "*the central problem in the theory of economic development is to understand the process by which a community which was previously saving and investing 4 or 5 per cent of its national income or less, converts itself into an economy where voluntary savings is running at about 12 to 15 per cent of national income or more*." (*Ibid.*, p.155)

Syrquin (1988), in the early stages of industrialization, household consumption and food expenditure account for about 75% and 40% of GDP, respectively, and as this process advances, both shares can fall by as much as 20 percentage points of GDP (Syrquin, 1988). This statistical regularity, known in the literature as Engel's Law, is a fundamental driving force behind changes in output composition, as highlighted in the work of Clark.

As mentioned above, the manufacturing sector exhibits stronger backward and forward linkages. So, when industrialization takes off, a process of densification of productive relations comes along, with vertical artisanal forms of production being progressively replaced by a factory-based production system with greater levels of complexity and chaining. As a result, the ratio of intermediate demand to gross output increases, together with a change in its composition towards a higher participation of manufactured inputs. (Syrquin, 2008).

This phenomenon also occurs within the primary sector. According to Deutsch and Syrquin (1989), a rise in labor costs due to industrialization compels the agricultural sector to adopt more intensive methods, involving machinery, equipment, fuels, chemical pesticides, and fertilizers. Consequently, the intermediate consumption of the primary sector relative to its gross output increases, and this intermediate consumption is increasingly reliant on manufactured goods. Chenery and Syrquin (1986) estimated that during this process of agricultural modernization, the ratio of agriculture’s value added to its gross output declined by 25 percentage points, from about 80% to 55%.

When it comes to trade patterns, the accumulation of physical and human capital and the increase in the capital-to-labor ratio tend to shift comparative advantages towards manufacturing (Balassa, 1979).[5] In the early stages of industrialization, the export basket progressively shifts from primary goods to products from light industries. As the industrialization process continues and countries acquire more complex productive capabilities, the share of skill-intensive and capital-intensive industries in their exports tends to increase (*Ibid.*).

[5] Substantial changes in the Brazilian trade pattern were observed to be affecting the Brazilian economy in the early 1980s, as a result of the II National Development Plan (II PND). In addition to a surge in import substitution, the country's export agenda changed significantly after the maturation of the investments made by the Plan. Between 1974 and 1984, the value of exports (in US$) of manufactured goods grew by 568.8%, while the weight of manufactured goods exported jumped from 28.4% to more than 56% (BACEN, undated). For more on the impact of the II PND on the Brazilian productive and trade structure, see Castro and Souza (1985).

Stylized facts aside, countries' specificities also influence their development trajectory. Natural resource endowment and internal market size can affect the pace and intensity of industrialization and also trade specialization patterns. Small countries poorly endowed in natural resources often rush into industrialization to build a base for manufacturing exportation. On the other hand, natural-resource-rich countries can live with a weak industrial base for a longer time, as they can, to some extent, export primary products to obtain international reserves and pay for their import needs. As for large countries, the size of their domestic markets allows for the adoption of inward development strategies, and their industrialization usually begins as an import substitution process (Chenery, 1979). Despite the influence of these elements, both the starting point and the rhythm of these changes respond strongly to the adoption of consistent development-conducive policies (Medeiros, 2014).

It is important to mention that the reorganization of production in global value chains has relevant implications for the analysis of manufacturing production, international trade, and economic development. Indeed, the fractionalization of production into multiple stages and their geographic dispersion have allowed for a higher degree of vertical specialization. Countries can now specialize in only one or a few stages of production within a global value chain instead of creating a whole industry. Therefore, manufacturing production now requires less resource mobilization in financial, managerial, technical, and technological terms. On the one hand, this can ease developing countries' entry into manufacturing production and exportation. On the other, depending on which stage of GVC countries are specializing in, increasing their manufacturing production may not lead to stronger interindustry linkages, and exhibits few learning and limited spillover opportunities. (Baldwin, 2012; Hiratuka and Sarti, 2017).

II.2. Deindustrialization phase

As stated earlier, the industrialization process does not continue indefinitely. When a certain level of per capita income is reached, a country's manufacturing enters a path of sustained decline, giving way to an increasing share of services in the economy. Rowthorn and Wells (1987) defined deindustrialization as a continuous retraction of the manufacturing share of total employment. Tregenna (2009) conducted a decomposition analysis of changes in manufacturing employment shares and levels for 48 countries. Her work concluded that, in the majority of cases, a decline in manufacturing employment resulted mostly from a reduction in labor intensity in the manufacturing sector. Therefore, the author advocated a dual indicator approach based on both the share of manufacturing in total employment and GDP.

So far, much attention has been paid to analyzing deindustrialization, trying to frame this process according to its causes, starting point, and implications for countries' economic development trajectories. Based on this framework, the process of deindustrialization has garnered different qualifications, frequently being associated with adjectives such as "natural", "premature", "positive", or "negative".

Clark's work emphasized the role played by changes in the demand structure resulting from shifts in consumption patterns in pushing an increasing share of a country's labor force towards services. As the development process progresses and per capita income grows, income elasticity of demand tends to grow faster for services than for manufactured goods until, finally, the elasticity of the former overcomes that of the latter. Once this happens, the growth in demand for services outpaces that for manufactured goods, so labor is continuously displaced from the secondary to the tertiary sector (Clark, 1940). In this sense, in Clark's approach, deindustrialization emerges as a natural and positive implication of economic development, as its effect on the composition of final demand is endogenously produced by a country's increasing per capita income.

Other works, like those of Rowthorn and Wells (1987) and Rowthorn and Ramaswamy (1999), endorse the idea of deindustrialization as a positive and natural consequence of economic development. These authors attribute the process of deindustrialization to differential productivity growth. They argue that, in advanced economies, labor productivity expands much faster in manufacturing than in services, while output growth is roughly the same for both sectors. The result of combining this imbalance in productivity growth with similar output expansion is a progressive reduction in manufacturing's share of employment. Once again, deindustrialization is seen not as "*a negative phenomenon, but a natural consequence of further growth in advanced economies*" Rowthorn and Ramaswamy (1997: p.11).

Even though these authors adopt the same typology of positive and natural deindustrialization as Clark (1940), there are some divergences regarding the trigger element of these processes. Rowthorn and Ramaswamy (1999) argued that Clark's approach to deindustrialization fails by not considering the effect that the difference in productivity growth between manufacturing and services has on relative prices and on the structure of demand itself. More specifically, as productivity grows faster in the manufacturing sector than in services, the relative prices for manufactured goods decline, stimulating demand for these goods. Nevertheless, the empirical evidence presented by the authors suggests that the labor-reducing effect of a different rate of productivity growth outweighs the demand stimulus that arises from the decline in relative prices of manufactured goods. Hence, the net impact of the imbalanced productivity growth rates is a decrease in the share of manufacturing in total employment.

International trade can also exercise influence on deindustrialization (Rowthorn and Ramaswamy, 1999). Trade specialization in services or non-manufactured goods would imply a smaller relative size of manufacturing in the economic structure. In addition, in the last decades, industrialized countries have been increasingly specializing in labor-skilled manufacturing segments and resorting to international trade to access labor-intensive manufactured goods from low-wage countries. Such an international division of labor may result in the reduction of manufacturing employment in industrialized countries, either because their specialization moves them away from lower-skilled, labor-intensive manufacturing or because competition from cheap imported manufactured goods forces firms in advanced economies to employ labor more efficiently (*Ibid.*).

An intense debate has also emerged about the point at which deindustrialization kicks in, fueled by increasing evidence that many countries have been shortcutting their transition towards services. Indeed, in the past few decades, deindustrialization has been taking place at much lower levels of per capita income, and manufacturing's share of total value added, and employment is peaking at a much earlier point than would be expected based on the experience of the first industrialized economies (Dasgupta and Singh, 2006). This early shift to services is usually referred to as "premature deindustrialization". As Dasgupta and Singh (2006) noted, this process may or may not be a result of a pathological phenomenon. A best-case scenario suggests that this process is the outcome of natural changes in demand, sectoral productivity, and technology as economic development continues. In this scenario, the labor displaced from manufacturing tends to be absorbed by a highly dynamic service sector, particularly in its technologically sophisticated segments. However, this process can also result from economic policies that are detrimental to the maintenance of the industrialization process. In such cases, poor performance in the manufacturing sector is seldom compensated by the absorption of labor into technologically sophisticated services. Thus, the displaced labor force ends up in low-productivity segments of the service sector, if not unemployed (Dasgupta and Singh, 2006). Therefore, in its pathological form, premature deindustrialization halts resource reallocation from low-productivity sectors to high-productivity ones, aborting the process of overall productivity expansion and compromising long-term economic growth.

Palma (2005) was the pioneer in identifying Dutch disease as a cause of early deindustrialization. According to this author, intense and precipitous trade and financial liberalization in the early 1990s resulted in a sharp and sudden change in relative prices that left the policy-induced manufacturing sector unprotected, pushing some Latin American countries towards a specialization in sectors with Ricardian advantages in natural resources (Palma, 2013; 2014). In this sense, the deindustrialization process described by Palma is neither natural nor positive, as it results from economic policies inconsistent with industrial development.

According to Rodrik (2016), deindustrialization is a global phenomenon that is happening earlier today than ever before and which has spared only a few Asian countries with comparative advantages in manufacturing production. Nevertheless, the pattern of deindustrialization differs across different groups of countries. In developed nations, the deindustrialization process is felt through a decline in the share of manufacturing in total employment but not in GDP. This pattern of deindustrialization is explained by relatively higher rates of productivity growth in the manufacturing sector, associated with the adoption of labor-saving technologies for less skilled work. These factors have resulted in a reduction in manufacturing employment in this group of countries, particularly within their low-skilled manufacturing branches. However, in developing economies, the deindustrialization process exhibits a different pattern, featuring a declining share of manufacturing in both total employment and GDP. The author attributed this pattern of deindustrialization to trade and globalization, which arguably pushed developing countries with a weak comparative advantage in manufacturing to become net importers of manufactured goods.

Dosi *et al*. (2020) rejected the idea of a natural deindustrialization. These authors based their analysis on the taxonomy of industrial groups proposed by Pavitt (1984) and found a very uneven pattern of deindustrialization within the manufacturing sector. Instead of cutting across all manufacturing sectors, deindustrialization between 1970 and 2010 was concentrated in scale-intensive and supplier-dominated branches of industry. For these industrial clusters, deindustrialization began quite early in the development process. Meanwhile, specialized suppliers and science-based manufacturing presented a very different pattern. The former managed to retain their employment share up until a very late stage of economic development, while the latter did not exhibit the traditional inverted U shape at all; rather, they enjoyed an ever-increasing share of employment and value-added. These findings support the idea that the composition of their manufacturing sector influences the timing, pace, and intensity of countries` deindustrialization.

The underlying idea is that not all manufacturing activities present the same opportunities for learning, accumulating capabilities, technological diffusion, and increasing returns on investment. In order not to stray from a virtuous development path, countries must accumulate productive capabilities by capitalizing on specialization opportunities that arise at each stage of industrialization while moving from less to more technologically sophisticated industries. The authors found that the more diversified the manufacturing sector, the more resilient a country tends to be in the face of deindustrialization. However, the authors also found that globalization caused a decline in opportunities for technological upgrading, increasing the likelihood of developing countries becoming entrenched in those manufacturing sectors that are most vulnerable to deindustrialization.

Andreoni and Treggena (2020) argued that some countries had failed to sustain their industrialization process or had even been unable to avoid premature deindustrialization due to the adoption of inconsistent policies that drove them towards a middle-income technology trap.[6] According to these authors, countries must confront three major challenges to escape this situation. The first is to break into a globally concentrated manufacturing sector and compete with low-wage or large-scale industrialized countries. The second consists of moving towards more technologically sophisticated and capital- and skilled-labor-intensive production stages of global value chains (GVC). In order to harness opportunities for creating new capabilities and increasing productivity, countries must simultaneously succeed in linking up to GVCs and linking back with domestic producers. Finally, the third challenge relates to countries' ability to keep the pace of technological change and innovation.

[6] Andreoni and Treggena (2020, p.324) defined a middle-income technology trap as "*a specific structural and institutional configuration of the economy that is not conducive to increasing domestic value addition and to sustained industrial and technological upgrading*."

III. STRUCTURAL CHANGE, ECONOMIC DEVELOPMENT AND THE ENVIRONMENT

III.1. The Environmental Kuznets Curve Hypothesis

As already discussed, structural change and economic development are interrelated processes that trigger and accompany sustained economic growth (Kuznets, 1971; Chenery, 1979), meaning that economic development occurs through structural changes at the same time as it induces them.[7] This interaction accelerates economic growth through an unbalanced pattern of expansion of productivity and output that runs across economic sectors.

The way these elements interact with one another is also of great interest from an environmental sustainability standpoint. As already mentioned, the degree to which they are endowed with natural resources can influence the temporality of countries' industrialization processes and their pattern of productive and trade specialization (Chenery, 1979). As Syrquin (1988: p228) pointed out: "c*hanges in the sectoral composition of production are the most prominent feature of structural transformation. Associated with income growth are shifts in demand, trade, and factor use. These interact with the pattern of productivity growth, the availability of natural resources, and government policies to determine the pace and nature of industrialization."* Most importantly, structural change in all its domains, whether in the form of changes in the sectoral composition of output, final and intermediate demand, in trade patterns and rates of capital accumulation, in inter-industry density, or as unbalanced productivity growth, results in alterations in the rates of depletion of natural resources, the use of energy, and the total and average emission levels of an economy.

The most widespread attempt to establish a nexus between economic development and environmental sustainability was formulated in the early 1990s and came to be known as the Environmental Kuznets Curve (EKC) hypothesis. Its proponents, Grossman and Krueger (1991; 1993), found an inverted-U relationship between per capita income and environmental degradation. Although Grossman and Krueger were the first to draw attention to this

[7] The interrelation between economic development and structural change is very well put by Matthews, Feinstein and Odling-Smee (1982, p.250) when they say that: "*neither structural change nor growth in GDP is an exogenous variable; both result from a complex of interesting causes on the supply side and the demand side*." In a similar way, Abramovitz (1983: p.85) argued that: "*sectoral redistribution of output and employment is both a necessary condition and a concomitant of productivity growth*".

relationship, Panayotou (1991) was the one to coin the term after noticing the resemblance of this relationship to the one described in the original Kuznets Curve.[8]

During the early 1990s, much effort was dedicated to testing the validity of the EKC for different groups of countries and pollutants. Several academic works were published suggesting the EKC as a possible stylized fact (statistical regularity) of economic development, such as those by Grossman and Krueger (1991, 1993, 1995), Bernstam (1991), IBRD (1992), Shafik and Bandyopadhyay (1992), Beckerman (1992), Panayotou (1993, 1997) and Cropper and Griffiths (1994).[9] In subsequent years, the EKC continued to receive considerable attention, facilitated by an increase in the availability of data on local and global pollutants.

The EKC posits that environmental degradation can be expected to rise quickly in the early stages of economic development. Usually, during this time, economic agents prioritize jobs and income over environmental protection and conservation, while industrialization pushes the environmental burden of economic growth upward, especially when countries are going through the heavy industrialization phase. However, the increase in environmental degradation is not a trend that continues indefinitely. As per capita income increases, important changes would take place in the direction of a reduction in environmental degradation.

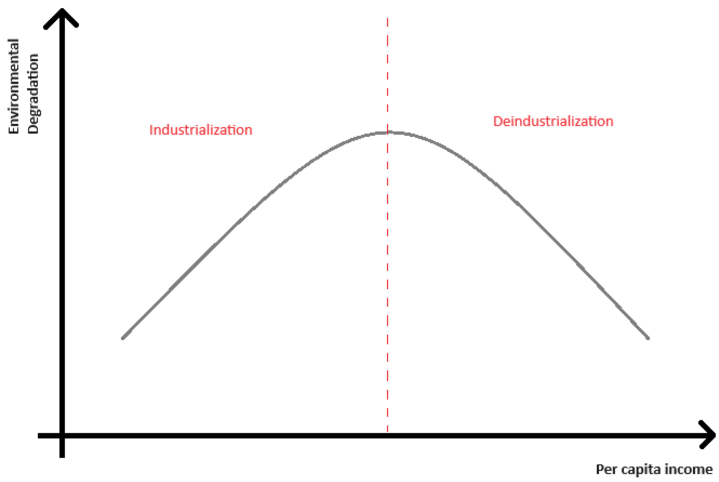
At the microeconomic level, once all basic needs have been satisfied, preferences start shifting towards environmental protection. This is the result of an increasing income elasticity of demand for environmental goods, which for higher levels of per capita income tends to be greater than one (Panayotou, 1993). Under such conditions, the willingness to pay for environmental protection increases faster than income itself (Roca, 2003). This argument is also typically presented at the aggregate level. As nations become wealthier, more human and financial resources would be made available for environmental protection. Simultaneously, there would be a process of increasing awareness of environmental problems as people gain access to better formal education, or simply due to the more evident impacts of environmental degradation (Panayotou, 1993). All in all, not only can wealthier nations spend more on environmental protection and surveillance, but their individuals are better informed about the

[8] The original Environmental Kuznets Curve presents a statistical relationship between per capita income and inequality. The curve has an inverted U shape, with a per capita income on the x-axis and an inequality indicator on the y-axis. Thus, according to Kuznets' formulation, in the early stages of a country's development, inequality has a positive relationship with the increase in per capita income, but only up to a certain level of per capita income. After this level is reached, the relationship between these two variables inverts, with inequality decreasing as per capita income grows. For more, see Kuznets (1955).
[9] For more recent works on the EKC hypothesis, see Ansari (2020) and Wang et al. (2024).

impacts of environmental degradation and have a revealed preference for sustainability over growth, since they can more easily bear the opportunity costs of environmental protection.

Allegedly, another source of environmental alleviation would result from changes in the composition of output. As previously seen, industrialization has a tipping point at a certain level of per capita income. Even before that point is reached, some alleviation in environmental conditions would take place as countries move past energy-intensive heavy industrialization and approaches more technology-intensive manufacturing. This trend would be reinforced by deindustrialization, given the lower material base required for services (Figure 2). In the meantime, the technical progress that accompanies economic development would also contribute to improving efficiency in the use of natural resources and mitigating pollution (*Ibid.*)

Figure 2 - Environmental Kuznets Curve



Source: adapted from Panayotou (1993)

Implicit in the formulation of the EKC is the idea that economic development itself will unlock processes through which environmental degradation can be solved. To put it another way, environmental degradation is a problem resulting from, but also capable of being solved by, economic development itself. Therefore, the EKC is not a simple correlation (first positive and then negative) between per capita income and environmental degradation. Rather, it is a theory about the inflection point: i.e., a theory about how development solve its own environmental problems, as countries get richer. As argued: "*the view that greater economic activity inevitably hurts the environment is based on static assumptions about technology, tastes, and environmental investments. As incomes rise, the demand for improvements in environmental quality will increase, as will the resources available for investment"* (IBRD, 1992, p.38-39).

The policy implication of this theory is that countries can always grow first and clean up later (Dasgupta et al., 2002).

III.1.1. The Environmental Kuznets Curve Hypothesis: a critical assessment

In the 1990s, the EKC took center stage in discussion on the environmental impacts of economic development. Since the pioneering study by Grossman and Krueger (1991), and with the increasing availability of environmental data, a series of papers was published dedicated to testing whether it is possible to grow out of environmental problems.

Grossman and Krueger (1991) tested this hypothesis for sulfur dioxide (SO_2) and fine smoke and found a turning point at around USD 4,000 to USD 5,000. Shafik and Bandyopadhyay (1992) employed three functional forms to estimate an EKC using ten different environmental indicators. Their results showed that urban sanitation and access to clean water improved as incomes rose. That is to say, for these indicators, the relationship showed a monotonically decrescent pattern. On the other hand, these authors found that local pollutants seem to behave more according to the EKC hypothesis, increasing at low levels of per capita income and then shifting downwards when per capita income reaches around USD 3,000 to USD 4,000. Conversely, these findings revealed an ever-increasing trajectory for other indicators, such as per capita carbon emissions and municipal waste. Panayotou (1991) estimated the turning points for deforestation and SO_2 NOx and small particulate matter (SPM) emissions. This author found that deforestation starts to fall from USD 800 to USD 1,200, while pollutant emissions turn downwards at around USD 3,800 to USD 5,500.

Other studies have shown that the evidence supporting the existence of an EKC is, at best, controversial (Stern, Common, and Barbier, 1996; Stern, 2004). The shape of the curve tends to be very much impacted by the environmental indicator used. Studies using local pollutants (SO_2, NO_x, CO, and suspended particulate matters) are more likely to find an inverted-U trajectory type[10] than those using global pollutants (Stern, 2003), as the internalization of environmental externalities for the latter groups needs to rely on transborder coordination, regulation, and cross-country non-regulatory incentives. Dinda (2004) drew attention to the fact that even some local air pollutants unrelated to, or with little impact on, human health did not follow the pattern described by the EKC. For water quality indicators, the evidence is even

[10] See Grossman and Krueger (1991, 1993, 1995), Shukla and Parikh (1992), Selden and Song (1994), Jaeger et al. (1995), Tucker (1995), Jha (1996), Horvath (1997), Ansuategi et al. (1998) Matyas et al. (1998), Brandoford et al. (2000), and Roca (2003).

more inconclusive, with some studies finding an N-shaped curve (Shafik and Bandyopadhyay, 1992; Shafik, 1994)

Even though some countries may, as per capita income rises, exhibit decrescent environmental degradation, framing this as a stylized fact of economic development may be misleading. Stern et al. (1996), Stern and Common (2001), Harbaugh et al. (2002) Coondoo and Dinda (2002), and Perman and Stern (2003) all pointed out that many of the studies that confirmed the existence of an EKC suffered from econometric problems that compromised the robustness of the models used. These problems ranged from simultaneity and omitted variable bias to heteroskedasticity and cointegration issues.

Besides being susceptible to econometric problems, the conceptualization of the EKC relies on some quite restrictive assumptions. Stern, Common and Barbier (1996) emphasized that such conceptualizations tend to assume that income is normally distributed, so lower environmental degradation can be expected for higher levels of per capita income. However, according to these authors, income distribution is highly skewed, with the largest contingent of people lying below the mean of per capita income. Therefore, the authors stressed that the median rather than the mean of per capita income should be considered in EKC analyses. Since the former is much lower than the latter, environmental degradation may persist much longer than initially predicted. Stern (2003) questioned the models' assumptions that predicted an inverted U-shaped curve, such as ever-living agents, exogenous technology changes, and pollution, whether generated by production or consumption.

Dasgupta et al. (2002) argued that the validity of the EKC also depends on the constant or decreasing marginal utility of consumption, with pollution exhibiting increasing marginal damage and disutility, as well as rising marginal abatement costs. Moreover, "*most theoretical models implicitly assume the existence of public agencies that regulate pollution with full information about the benefits and costs of pollution control.*" López (1994) showed that the EKC validity relies on homothetic preferences – i.e., the share of what is consumed does not change as income rises. If preferences are non-homothetic instead, then the pollution level will depend on the elasticity of substitution of the production function between intermediary goods and pollution, as well as on the relative risk aversion of consumers.

One relevant limitation is the fact that the EKC is generally expressed in terms of pollutant discharge (local or global) and not in terms of environmental impact. Expressing environmental degradation in this way makes the analysis much more straightforward by not requiring a deep understanding of how the depletion of natural capital impacts the flow of environmental goods and services and, ultimately, human well-being. Even if an inflection point is admitted, there is no guarantee that it will occur below the level at which disruptive environmental impacts on human health and ecosystems equilibria begin to be observed. In other words, there is no guarantee that the EKC's turning points will happen before the ecosystems' tipping point.

Moreover, environmental impacts can be very hard to measure accurately, given our limited knowledge of the rules of the natural system and how they interact with the socioeconomic system. It is not fully known how species interact with one another and with their physical environment to generate ecosystem services. More importantly, most of the time, it is also unknown how much distress the natural system can take before it is irreversibly changed. In such a context, determining where the tipping points are and the implications of going beyond them can be difficult (Holt, Pressman and Spash, 2008). Among the many possible implications is a reduction in long-term growth. Regarding this point, Arrow *et al.* (1995) criticize the EKC assumption of a complete absence of feedback effects from environmental degradation and economic growth – i.e., that environmental damage cannot harm economic growth in the future.

It also seems relevant that the environmental improvement advocated by EKC can encounter important rigidities. Even when returning to previous environmental conditions is possible, this can take quite a long time. Many pollutants decay very slowly, so their impacts tend to last for long periods. One example is the emission of greenhouse gases, where many of them stay in the atmosphere for decades or even centuries. Therefore, *"if we stopped emitting greenhouse gases today, the rise in global temperatures would begin to flatten within a few years. Temperatures would then plateau but remain well-elevated for many, many centuries. There is a time lag between what we do and when we feel it"* (*NASA, s/d*). It is dauntingly concerning that GHG emissions are still rising, and according to the Intergovernmental Panel on Climate Change (IPCC) the emission reduction pledges made as part of the Paris Agreement fall largely short of limiting the increase in global average temperature to a 1.5C to 2.0C interval (UNEP, 2023). As will be seen in the next section, studies using GHG emissions as an indicator have found no inverted U-shaped curve between per capita income and environmental degradation.

Finally, another limitation of analyses that rely on the EKC relates to the choice of a "pollutant basket". The works testing the EKC hypothesis usually pick a set of pollutants to check how their emission trajectories vary as per capita income rises. Nevertheless, this set of pollutants is not representative of total environmental degradation. Thus, even if countries adopt more stringent regulations of certain types of pollutants and new production techniques to comply with them, the very same regulations and techniques may push production towards the emission of other pollutants, for which the regulations remain laxer, or their impacts are still unknown (Dasgupta et al., 2002; Stern, 2003).

III.1.2. Dematerialization through services: an overview of the empirical evidence

As already mentioned, according to the EKC hypothesis, an environmental amelioration is expected to take place as a result of deindustrialization. The hypothesis suggests that changes in the output from manufacturing to services, combined with the use of better techniques, can compensate for the pressures arising from the scale effect imposed by economic growth. (Dinda, 2003). This hypothesis is very convenient, as the transition to services is one stylized fact of economic development (Clark, 1940). Recently, the large number of countries experiencing ongoing deindustrialization processes is fueling efforts to ascertain whether a transition to services can alleviate the environmental burden of economic growth.

Kander (2005) analyzed the impact of a sectoral transition to services on Swedish CO_2 levels from the 1970s on and found that changes in the composition of output played a negligible role in explaining a decline in the level of carbon dioxide. Most of the reduction observed resulted from changes in the energy mix towards renewable and cleaner energy sources and a stabilization of energy consumption due to the country's very modest rates of economic growth. Henriques and Kander (2010) employed a similar analysis to a group of ten developed countries and three developing economies using the Logarithmic Mean Divisia Index (LDMI). The authors broke energy intensity changes into structure and intensity effects, and once again, they found that structural change towards services made only a very modest contribution to explaining the reduction in energy intensity between 1971 and 2005. In fact, in seven of the developed countries, changes in output composition accounted for a 2% to 9% decrease in total energy intensity. As for Spain, Italy, and Sweden, the transition to services resulted in a 3% to 4% increase in energy intensity instead. Meanwhile, the intensity effect made a much higher contribution (11% to 37%) to energy intensity reduction in eight developed countries. In countries such as Spain and Portugal, the intensity effect was positive, though.

The list of developing countries studied by Henriques and Kander includes Brazil, Mexico, and India. The results for this group of countries revealed a very different trend. For all of them, changes in the composition of output resulted in a higher energy intensity, which was to some degree compensated for by the intensity effect. Particularly for Brazil and Mexico, the intensity effect was insufficient to fully compensate for the structure effect, which explains the increase in energy intensity for these countries.

More recently, these authors disaggregated their results by sector. The results showed a heterogeneous performance across industry sectors. Except for Sweden, the structure effect within the manufacturing sector was mostly negative, i.e., it led to a decrease in countries` energy intensity. The results pointed in the opposite direction in the service sector, as none of the countries had transitioned towards less energy-intensive service activities. As for the intensity effect, the results show that manufacturing consistently outperformed services in all ten developed countries. Among the developing countries, the intensity effect was negative for the manufacturing sector in India and Mexico, while in Brazil, it increased energy intensity by 7%, meaning that manufacturing production in this last country had not benefited from energy efficiency gains. Not only that, but the increase in the intensity effect for the Brazilian manufacturing sector was even greater than that for the service sector.

Cian et al. (2013) also applied the LDMI to decompose the energy intensity changes of 40 countries into structure and technology effects. These authors' analysis covers the period 1995-2007, using data from the World Input-Output Database (WIOD). The results show that energy intensity reductions observed in this period were mainly driven by technology changes, with structural changes contributing to just a small portion of them. In fact, structural changes contributed to a drop in energy intensity only up to 2003. After that, the results point to a process of output change towards sectors with higher energy intensity. The technology effect, on the other hand, consistently dropped throughout the period analyzed. Jimenez and Mercado (2014) decomposed energy intensity changes into efficiency, intensity, and activity mix effects for an even larger set of countries (75), covering the period 1970-2010. The results revealed an overall reduction in energy intensity but with great performance disparity among countries. While energy intensity dropped 54% in high-income countries and 40% in low-income countries, this reduction was only 20% in Latin America. Moreover, while sectoral change accounted for 10% of energy intensity reduction in high-income countries, it contributed to an 8% increase in Latin American countries. The authors attributed this poor performance of Latin American countries to increasing specialization in extractive and natural-resource-based industries.

Schymura and Voigt (2014) used the LMDI to decompose the CO_2 emissions of 40 major economies between 1995 and 2009 into activity, composition, technology, fuel mix, and emission content of energy mix effects. In this period, CO_2 emissions increased by just over 31%, mostly due to an increase in the economic activity level. Indeed, the activity effect rose by 52% but was partially offset, mainly by the intensity and composition effects, which fell by 9% and 8%, respectively. Despite the contribution of the composition and intensity effects, which suggests that economic structure moved towards sectors with lower emission intensities and approached more environmentally efficient technologies, these elements fell short in compensating for the activity effect. Besides, the falling trajectory for both effects was limited to the period 1995-2002, while the period 2003-2009 exhibited barely any improvement in either composition or intensity effects.

Of the 40 countries, only a small group of high-income ones managed to reconcile economic growth with an absolute reduction in CO_2: Germany, Belgium, and the Netherlands. In none of these countries was the change in output composition a primary culprit of the decoupling process. For all three countries, the main source of CO_2 reduction was the intensity effect. In the case of Germany, in fact, the structural effect was positive, contributing to an increase in emissions. The only countries that showed an absolute decoupling, due to the prominent role played by shifts in their output composition, were the former Soviet republics.

The available evidence raises questions about the extent to which dematerialization through services can occur, casting doubt on the optimistic claims made by proponents of the EKC. The real potential for a sizable decoupling in the passage to a more service-based economy appears to have been overstated by EKC proponents. The transition to a service economy is, in part, driven by outsourcing certain activities from the manufacturing sector (Fix, 2019). For instance, furniture companies increasingly rely on external sources to dispatch, transport, and assemble their products. Similarly, companies in the household appliances, electronics, and automotive sectors often engage specific firms for maintenance and repair services. This means that many services are intricately linked to manufacturing production, with the result that, rather than one sector supplanting the other, in many cases, they complement one another and thrive together (Jespersen, 1999; Lawn, 2001; Djellal and Gallouj, 2016).

Moreover, it is crucial to underscore the substantial heterogeneity within the service sector concerning its material base, energy, and emission intensity. Certain services are quite intensive in energy consumption and/or carbon emissions, as in the case of dispatch and transportation, but this is also the case with some public utility services (such as energy production and distribution and water and sewage treatment). Even some technologically sophisticated activities in the service sector that are now claimed to be part of the backbone of the technological revolution have high energy consumption and result in significant greenhouse gas emissions. The most iconic example is information communication technology (ICT) which already accounts for between 2.1% and 3.9% of global GHG emissions (Freitag et al., 2021)

No less important is the fact that some studies also point to the possibility of the presence of a 'Baumol emissions disease' (Savona and Ciarli, 2019). This term describes a situation in which a sluggish productivity gain and slow technological progress in some segments of the service sector diminish the potential environmental benefits of transitioning away from manufacturing. Mulder et al (2014). analyzed energy intensity changes in 23 service sectors for 18 OECD countries between 1980 and 2005. Their findings revealed that even though a higher participation of services in an economy contributed to alleviating energy use, this reduction was significantly impaired by the poor performance of the service sectors with regard to energy intensity, especially after 1995. Had the energy intensity of services dropped at a similar pace to that of manufacturing, the transition towards a service economy would have resulted in a much greater reduction in energy use. The results of Mulder et al. (2014) are in line with those of Henrique and Kander (2010) presented above.

III.1.3. The possibility of carbon leakage

International trade allows a geographic separation of the environmental impacts of producing goods and services from those of their consumption. On one side of this transaction, a country reaps the economic benefit of producing goods or services for export, increasing its level of income and employment, but at the cost of bearing higher environmental impacts from producing exports. On the other side, the importing country loses the economic benefit of producing these goods and services domestically but avoids the environmental cost of producing them (Arto *et al*., 2014). This geographic separation of consumption from the environmental impact of production allows for carbon and other environmental leakages, raising further concerns about the validity of the EKC hypothesis and, more specifically, about the already modest contribution of deindustrialization to dematerialization, as presented in the previous sections.

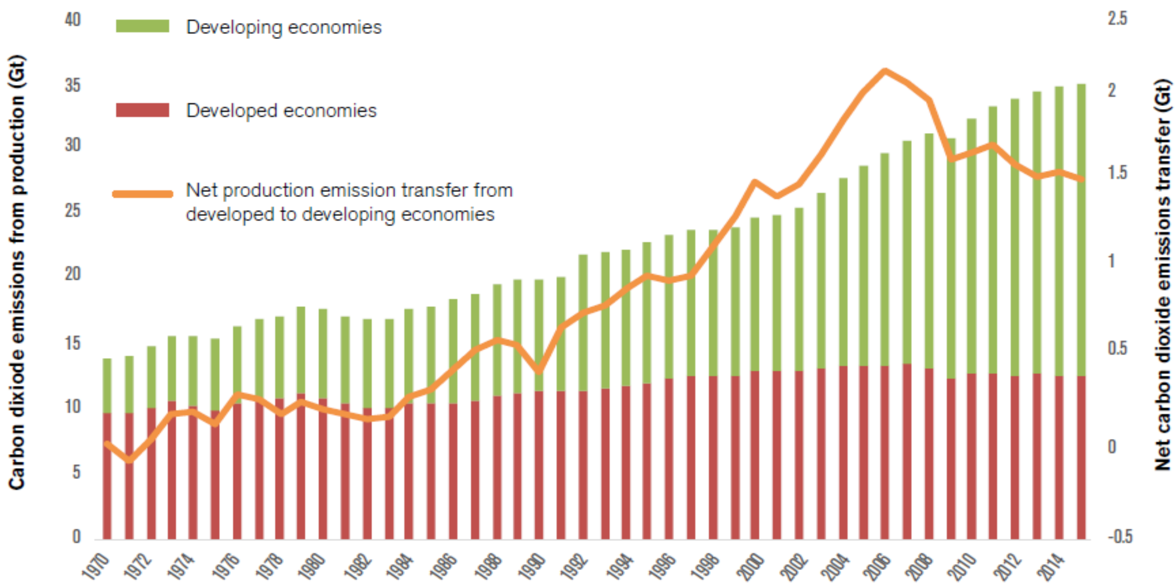
The expansion of trade over the last decades, especially after trade liberalization, has fueled efforts to investigate the existence of imbalanced environmental implications of international trade, characterized by an environmental decoupling in developed countries and an increasing specialization in polluting activities by developing economies. The Pollution Haven Hypothesis (PHH) has garnered the most attention in this debate. According to the PHH, strengthening environmental legislation and its enforcement in developed countries may result in the displacement of polluting activities to developing nations, where environmental regulation remains less rigorous, and supervision is laxer (Savona and Ciarli, 2019). In other words, differences in the stringency levels of environmental regulation, and institutional capacity to enforce them would result in a comparative advantage for developing countries in polluting activities (Cole, 2004).

Therefore, many analyses of the environmental impact of production are being adjusted for trade using two environmental accounting approaches: the production-based approach and the consumption-based approach. Taking the example of GHG emissions, the production-based approach estimates the emissions related to the domestic supply, i.e., the emissions generated within a country`s border in producing goods and services destined for internal markets and exports. Alternatively, the consumption-based approach estimates the emissions related to a country`s demand, namely emissions embedded in the goods and services destined for the domestic market, whether those domestically produced or imported.[11]

Figure 3 reveals an interesting pattern for CO_2e emissions. Since the early 1970s, developed economies have managed to keep their emissions roughly constant. Conversely, developing economies have experienced a sharp increase in their emissions. This sharp increase is partially due to transferring emissions from developed countries (orange line), namely, the emissions that would be produced within the developed countries' borders if they were to produce domestically the goods they import. From the early 1970s to the mid-2010s, this kind of emission transfer rose from approximately 0 to 1.5 $GtCO_2$, after peaking at 2.3 $GtCO_2$ in 2006.

[11] These approaches are commonly applied to analyze the impact of international trade on other environmental issues, such as water, energy, natural resources use, local pollutant emissions, and so on.

Figure 3 - Production-based CO_2 emissions and CO_2 emission transfers from developed to developing countries



Source: Wood *et al*. (2020).

This pattern is consistent with findings from other studies that point to developing countries being net exporters of emissions. Davis and Caldeira (2010) estimated global consumption-based CO2 emissions for 2004 using Multiregional Input-Output Tables (MRIO). These authors found that around 24% of global CO2 emissions were due to international trade from China and other emerging economies. Meanwhile, in countries such as Austria, France, Switzerland, Sweden, and the United Kingdom, emissions embedded in imported goods and services accounted for more than 30% of their consumption-based emissions. The percentage for the United States was lower, at 10.8%. In general, the authors' findings revealed that 22.5% of China's production-based emissions were actually exported.

Peters et al. (2011) analyzed the CO_2 emissions from 113 countries between 1990 and 2008. The authors found that during this period emissions from international trade had increased from 4.3 $GtCO_2$, approximately 20% of global emissions, to 7.8 $GtCO_2$, around 26% of global emissions. In many developed countries, consumption-based emissions overtook production-based ones. As a result, the transfer of emissions to developing countries increased by 1.2 $GtCO_2$ in the period. Yamano and Guilhoto (2021) found that between 2005 and 2015, OECD countries transferred 1.6 $GtCO_2$ to non-OECD countries. Aichele and Felbermayr (2015) found that the countries that made a binding commitment to the Kyoto Protocol increased the emissions embedded in their trade with non-committed countries by 8% and the emission intensity of their import basket by 3%.

Arto *et al*. (2013) extended the analysis to other greenhouse gases. Their results revealed that, in 2008, trade accounted for 24% of global GHG emissions and 20% of total employment. Goods and services imported by the European Union and the United States were responsible for 25% and 18.4% of the total emissions embodied in trade. Meanwhile, China was responsible for 30% of the emissions exported and 37.5% of the jobs created by international trade. Wiedmann *et al.* (2013) carried out a material footprint analysis and found that high-income countries managed to reduce their material extraction by increasing their importation of goods with high material content.

Similar patterns were observed in energy consumption. Babiker (2005) based his research on a multi-regional computable general equilibrium model and found that many energy-intensive industries had shifted from Annex B countries, which had binding commitments to reduce GHG emissions under the Kyoto Protocol, to non-Annex B countries. Gasim (2013) carried out a spatial index decomposition analysis of the energy embodied in the net exports of 41 countries and found that developed countries had managed to reduce their energy consumption by offshoring energy-intensive activities to developing countries. Moreau and Vuille (2018) specifically analyzed the impact of structural change between 2000 and 2011 on energy use in Switzerland, and their results revealed that although there was a modest contribution by deindustrialization to reducing energy use, the energy embodied in the country's imports increased by 80%.

With the emergence of GVCs, it became possible to relocate only part of the production process rather than the entire industry. The vertical disintegration and dispersion of these stages across different countries make it possible for the PHH to occur at a within-industry level. In other words, it allows a country to ship out the most polluting stages when facing increasingly stringent environmental policies and standards. Duan, Ji and Yu (2021) used data from World Input-Output Database (WIOD) for 35 industries and 40 countries covering the period 1995-2011 to investigate the validity of PHH for a trade in value-added units. These authors found that the pollution intensity of value-added trade is higher, the larger the per capita income gap between exporting and importing economies. These findings are consistent with the hypothesis that high-income countries are displacing dirty subsets of production to low-income economies. Similar results were found by Meng et al. (2018), but in this case, the authors also confirmed the validity of PHH among developing economies between 1995 and 2009, with China transferring sizable amounts of emissions to other developing countries.

Other studies focus their analysis at the firm level, seeking to determine whether GVCs have facilitated international companies in offshoring their most polluting stages to countries where environmental policy and enforcement are laxer as a means to reduce domestic pollution and environmental compliance costs. This process is usually referred to as the Pollution Offshoring Hypothesis (Cherniwchan et al., 2017). Saussay and Zagravo-Soilita (2023) found that environmental taxes and standards exert a statistically significant impact on firms' decisions to produce upstream products abroad, especially for companies relying on emission-intensive inputs.

The possibility of offshoring environmentally harmful activities and stages of the production process raises concerns about whether the decoupling process is real or whether it simply consists of a relocation of pollution from one country to another. More than that, from a developing country perspective, concerns also relate to the possibility of increasing trade specialization in environmentally harmful new growth opportunities, in what Savona and Ciarli (2019) called "*trading jobs for emission*".

IV. THE DEBATE ON RECENT STRUCTURAL CHANGE IN BRAZIL

IV.1. The debate on Brazilian deindustrialization

A debate on structural change resurfaced in Brazil in the mid-2000s, sparked by discussions on whether the Brazilian economy was experiencing premature deindustrialization. A secondary discussion followed, focusing on further qualifying this process in terms of its intensity, timing, causes, and potential implications for Brazilian economic development.

IEDI (2005) produced one of the first studies to highlight an intense process of premature deindustrialization taking place in the Brazilian economy. According to this study, the manufacturing sector began to lose momentum as early as the 1980s due to an inflationary crisis and the demand control policies adopted to address it. However, this process continued into the 1990s, even after inflation was brought under control, this time as a result of trade and financial liberalization and the deliberate overvaluation of exchange rates to anchor inflation.

According to the study, despite a decline in manufacturing's share of total GDP, Brazil's industrial structure remained significantly diversified. Moreover, even though manufacturing lost important production links in this period, high-tech sectors were pretty much preserved. The study characterizes structural change in Brazil as a relative deindustrialization process for three reasons: (i) its limited nature, which did not extend to high-tech manufacturing activities, i.e., the drivers of manufacturing productivity and export capacity, (ii) low rates of expansion in manufacturing as compared to other emerging economies, and (iii) the fact that low industrial dynamism was not compensated by dynamism in other sectors, resulting in a trajectory of low economic growth. Another essential characteristic highlighted by the study was an increased specialization of the manufacturing industry in natural resource-intensive activities, which rose from 35.9% to 45.7% between 1991 and 2003.

IEDI (2007) expanded the analysis to cover the period 1996-2004. This study indicates that signs of deindustrialization not only persisted but became even more evident. According to the study, a combination of high interest rates and an overvalued exchange rate created significant obstacles to manufacturing performance in this period. The high-interest rate policy resulted in a more modest economic growth trajectory, either by discouraging private investment or increasing the financial cost of public debt, pushing the government to a more stringent control on primary spending. Finally, and more fundamentally, high interest rates led to an overvaluation of the exchange rate, thereby reducing the competitiveness of the national manufacturing sector and replacing domestic industrial production with imports.

Both IEDI studies emphasized the role played by the liberalization reforms of the early 1990s and the adoption of macroeconomic policies inconsistent with industrial development in pushing Brazil's economic structure towards premature deindustrialization. Nevertheless, the second work introduced a new driving force for deindustrialization: rising international commodity prices, which caused further appreciation in the exchange rate. This new driving force pushed the economy down a Dutch disease path and created a very particular situation in Brazilian economic history in which the deindustrialization process took off despite improvements in terms of trade.

IEDI (2007) was the first of many works to explicitly draw on Palma`s thesis of deindustrialization induced by Dutch disease. This thesis influenced the Brazilian debate on deindustrialization, setting the ground for later contributions on the topic. Bresser-Pereira and Marconi (2008) endorsed Palma`s thesis. According to these authors, natural-resource-rich economies incur very low costs in commodity-producing and other natural-resource-intensive sectors, and when they are left exposed to market mechanisms, Ricardian comparative advantages tend to prevail. Such economies, without market-defying policies, tend to specialize in natural resource-intensive sectors. The authors argued that the Brazilian deindustrialization process is precisely the result of the dismantling of policies that, between 1930 and 1980, were responsible for promoting industrialization and productive diversification and for protecting the country against the emergency Dutch disease.

The exchange rate is a key element in the analysis proposed in this study. In the analysis put forward by Bresser-Pereira and Marconi, whenever the market exchange rate falls below the equilibrium exchange rate for manufacturing, Dutch disease emerges. The intensity of the forces pushing the economy towards deindustrialization correlates with the difference between these two rates. The authors argued that, with the dismantling of policies that protected against Dutch disease, the resulting sharp increase in the trade balance for commodities caused the market exchange rate to fall below the point at which manufacturing production would remain competitive. The data provided in this study show that while the trade balance for commodities jumped from USD 11 billion to USD 46.8 billion between 1992 and 2007, the balance for manufacturing dropped from USD 4 billion to USD -9.8 billion. Within the manufacturing sector, the trade performance for medium-high and high-tech manufactured goods was even worse, falling from USD -0.7 billion to USD -20.2 billion. The authors contended that the decline of 8.3 percentage points in manufacturing's share of the total value-added of tradables provided unequivocal evidence of intense deindustrialization during this period.

Oreiro and Feijó (2010) highlighted the fact that the manufacturing sector systematically expanded below the growth rate for the whole economy, which resulted in its relative shrinkage between 1996-2008. This process took place hand-in-hand with increasing surpluses in the trade balance for commodities that more than compensated for the rising trade deficits for the high and medium-high technology manufacturing branches. Gala and Libanio (2011) addressed the phenomenon of Dutch disease from a novel perspective. These authors emphasized the negative impact of overvalued exchange rates on the markup of sectors involved in the production of tradables, such as manufacturing. According to the proposed analysis, the overvalued exchange rates disincentivized investment in these sectors compared to investment in sectors engaged in non-tradable production, thereby shifting resources to the latter and compromising the overall productivity growth of the economy. Lara (2011) partially endorsed the diagnosis of premature deindustrialization by Duch disease. Even though this author agreed with the argument that trade surpluses for commodities may harm the manufacturing sector performance through a tendency to overvalue the exchange rate, he pinpointed the conduction of monetary policy as the main culprit for deindustrialization by keeping interest rates excessively high.

Nassif, Feijó, and Araújo (2013) added a new dimension to the analysis of deindustrialization, focusing on the productivity gap between Brazil and the countries in the technological frontier. These authors suggested that although Brazil managed to maintain a relatively diversified industrial structure up to 2008 and even to increase the share of science, engineering, and knowledge-based manufacturing in its total manufacturing value added, the country failed to keep pace with the productivity growth observed at the technological frontier. They found a widening productivity gap between Brazil and the US economy across all industrial segments analyzed (science, engineering, knowledge-based, labor-intensive manufacturing, and natural resource-based activity) during the 1980s and from 1997 on. The authors contended that this widening gap, along with an overvalued exchange rate, forced the Brazilian economy towards specialization in goods in which the country had a Ricardian comparative advantage. Based on these combined elements, the authors conclude that not only was Brazil technologically falling behind, but it was also going through a premature deindustrialization.

In a later work, Nassif et al. (2020) decomposed labor productivity growth from 1950 on into within and structural effects. The authors found that the within effect for manufacturing was the main driver of labor productivity between 1950 and 1979. This effect turned largely negative in the period 1980-1994 and became mildly positive from 1995 to 2011. Meanwhile, the structural effect was positive for manufacturing in the first two periods. However, in the third period, it turned negative, indicating that labor had been squeezed out of this sector. Overall, from the 1980s on, productivity growth in Brazil was primarily driven by industries that had low technological sophistication. Additionally, an econometric analysis in the paper revealed that interest and exchange rates and the share of primary goods in Brazil's export basket had a statistically significant negative effect on overall labor productivity growth during the period 1995-2011.

Deindustrialization can also manifest itself as a decrease in industrial density resulting from the loss of production linkages when domestic input production gives way to imports.[12] Comin (2009) used the ratio of the value of industrial transformation to the gross output of industrial production to investigate the possible occurrence of a productive de-densification process between 1996 and 2006. The results supported the thesis of ongoing deindustrialization, but

[12] This process is commonly referred to as productive de-densification, and its implications for economic development are manifold. They range from weakening inter-industrial linkages to diminishing capacity to generate technological spillovers, induce complementary investments, or propagate cost reductions (Morceiro and Guilhoto, 2019).

for specific production chains, with most of the lost links happening in sectors with higher technological intensity. Similar results were found by Morceiro and Guilhoto (2019). They analyzed 258 industrial classes using the import coefficient of tradable inputs and components to measure productive densification and found that medium-high and high-tech classes were at that time at an advanced stage of the de-densification and deindustrialization process.

Other studies found mixed evidence of deindustrialization in Brazil, either regarding its occurrence prior to the late 2000s or its intensity. According to Nassif (2008), manufacturing managed to hold on to a more or less unchanged share in the Brazilian GDP throughout the 1990s. Moreover, when disaggregated by type of technology, the results revealed relative stability in the total value added of scale-intensive and science-based manufacturing between 1996 and 2004. Regarding export composition, the former group of sectors experienced a decline of 5.2 percentage points, while the latter's share slightly increased by 1.06 percentage points. Based on this evidence, the author rejects the hypotheses of deindustrialization and Dutch disease, as there was no relevant transfer of resources from scale-intensive, differentiated, and science-based manufacturing sectors to sectors where Brazil exhibited Ricardian comparative advantages, such as natural resource and labor-intensive manufacturing.

Interestingly, according to the data presented by the author, there was a significant expansion of natural resource-intensive industries. This expansion was reflected in a 7.4 percentage point increase in the industry's value-added and a corresponding 7.25 percentage point increase in its share of the export composition. Half of this growth was accommodated by a decrease in the share of scale-intensive, differentiated, and science-based manufacturing sectors in the total value added by manufacturing and in the export basket.

Medeiros, Freitas, and Passoni (2018) highlighted the fact that the use of traditional indicators based on the share of manufacturing in total value added and employment had important limitations. According to these authors, an analysis of deindustrialization based only on such indicators could be misleading, as the investment-output ratio is pro-cyclical, as an increase in this ratio brings about a relatively faster expansion of manufactured goods, such as machinery and equipment. Therefore, the relative importance of manufacturing, as measured by these indicators, tends to increase during periods of economic growth and decrease during economic downturns. Additionally, the authors steered the emphasis of the analysis to innovative manufacturing, because of its importance in generating technological spillovers and explaining a virtuous pattern of structural change.

The authors analyzed deindustrialization between 2000 and 2014 using three alternative indicators: (i) the share of innovative industry in total value-added (employment), (ii) the market share of Brazilian exports in total world exports by industry, and the import share in total supply by industry; and (iii) inter-industry density using the Hirschman-Rasmussen linkages.

The authors' findings revealed that the innovative industry managed to maintain its share of total gross output, value-added, and employment up to the late 2000s. Meanwhile, the import-to-supply ratio of all industrial groups decreased from 2000 to 2005 and then bounced back. For instance, the import share of the innovative industry decreased from 23.8% to 18.9%, then surged back to 25.3% in 2014. When the composition of the Brazilian export basket was examined, the contents showed a marked trend in which industrial and process agricultural commodities squeezed out the shares of traditional and innovative industries. The two former groups also increased their market share in total global markets throughout the whole period, while the traditional and innovative industries exhibited a declining market share after 2008. Finally, regarding inter-industry density, the results showed that the Rasmussen forward and backward linkages remained roughly unchanged in the period under review. However, by breaking down this period, the authors found two distinct movements: an increase in inter-industry linkages up to 2008, followed by a declining trend from 2010 on.

In summary, the evidence provided by the authors contradicted the thesis of deindustrialization prior to 2008. However, after that year, Brazilian manufacturing started to exhibit concerning signs in this regard, as the share of innovative industry in total employment, value-added, and output began to decline. Clear signs of loss of competitiveness for this industry group could also be observed after 2008, both in external and domestic markets, together with a marked process of reprimarization of the Brazilian export basket.[13]

Relative prices also seem to play an important role in this controversy about the time profile and intensity of deindustrialization. After the 1990s, the deflator for manufactured goods systematically grew at lower rates than the average deflator for the economy (UNIDO, 2017), resulting in notable changes in relative prices. To some extent, these changes can be traced to the integration of China into global value chains, which led to that country accounting for a significantly increasing share of global manufacturing production and exports, as well as the foreign content of its exports (CARNEIRO, 2015). On the one hand, this integration resulted

[13] For more on the debate on the reprimarization of the Brazilian economy, see the next subsection.

in a growing demand for natural resources, leading to a strong rise in commodity prices. On the other, China rose as a global supplier of cheap manufactured goods because of its low labor costs (HARATUKA and SARTI, 2017).

As noted by Pires (2013), a change in relative prices can impact traditional indicators used for measuring deindustrialization, such as manufacturing share in total value-added or output and the value of industrial transformation to gross output of manufacturing, among others. Indeed, after carrying out a relative price deflation of input-output tables, Neves (2013) found no trace of deindustrialization before 2008. However, this author drew attention to a vivid process of penetration of imported inputs, which may have weakened inter-industry linkages. This process was more intense in medium-low and medium-high technology industries. Passoni (2019) extended the analysis for the period 2000-2014 and found similar results. This author decomposed the total output of industry groups into relative price effect and volume effect. After the relative price effect was separated out, the results did not support the hypothesis of a continuous and intense process of deindustrialization from the early 2000s. However, from 2008 onwards, some evidence points otherwise. In this subperiod, the Brazilian innovative industry saw its share of total gross output in volume units reduced and faced a density loss in its inter-industry relations.

IV.2. The debate on regressive specialization and reprimarization of the Brazilian export basket

As seen in the previous subsubsection, significant attention was given to the trade and financial liberalization of the 1990s to explain changes in the Brazilian productive structure. The main argument put forward in several studies[14] was that the reduction in tariff and non-tariff protection and the persistent tendency towards an over-evaluation of the exchange rate eroded the manufacturing sector’s competitiveness. Domestically, national manufacturing began to suffer greater competition from imports, having its production progressively replaced by imported intermediate and final goods (Bresser-Pereira and Marconi, 2008). Externally, these developments promoted a trade pattern marked by greater specialization in products in which Brazil already had Ricardian comparative advantages, moving the country's export basket away from manufactured products, especially those with higher technological content.

[14] For more, see IEDI (2005, 2007); Oreiro and Feijó (2010), Comin (2009), Gala and Libanio (2011), Lara (2011), Nassif, Feijó, and Araújo (2013), and Nassif et al. (2020).

Coutinho (1997) called this process "*regressive specialization*". According to this author, although the Brazilian economy was relatively diversified in the 1980s, various sectors of industry continued to experience a state of competitiveness and structural fragility. Thus, the sudden increase in external competition that resulted from the trade liberalization process ended up driving the country to a pattern of productive and trade specialization marked by "*the preservation of competitiveness only in large-scale commodities-producing sectors with low added value, and intensive in natural resources, agricultural inputs, and energy*" (Ibid., p.105).

Several studies highlighted a significant shift in the composition of the Brazilian export basket toward greater participation of primary goods and industrial commodities, particularly from the late 1990s onwards. Data presented by Bresser-Pereira and Marconi (2008) reveal that, between 1999 and 2007, the share of commodities in the country's total exports increased from 53.1% to 58.9%, reducing the share of manufactured goods. Neves (2013), using a series of estimated input-output tables, analyzed the performance of Brazilian exports by technological intensity. The results show that the manufacturing industry's share of the export basket decreased by nine percentage points between 2000 and 2008. This sharp decline was primarily concentrated in the high and medium-high technology sectors, with their participation in total Brazilian exports dropping by 4.53 and 2.4 percentage points, respectively.

Nassif and Castilho (2020) used Pavitt's taxonomy[15] to investigate the occurrence of regressive specialization in the Brazilian trade pattern. Their findings revealed a slight decrease in the average weight of manufacturing in total exports from the period 1990-1995 to the period 1996-2000, along with a modest increase in the participation of primary goods. However, instead of declining, science-based manufacturing increased its share in the Brazilian export basket by 3.2 percentage points during the 1990s, outperforming all other manufacturing classes in this decade.[16] This upward trend continued during the period 2001-2005, with science-based manufacturing averaging 8.8% of Brazilian exports, 4.4 percentage points higher than the average for the period 1990-1995. During this period too, despite the strong performance of science-based manufacturing, primary goods began to show signs of rapid acceleration in the export basket, jumping to 26.2% of Brazilian exports, compared to an average of 22.4% between 1996 and 2000. And the share of primary goods kept increasing at a faster pace,

[15] For more, see Pavitt (1984).

[16] The average share of resource-based, labor-intensive, and scale-intensive industries in the Brazilian export basket decreased by 1.2, 2.0, and 1.9 percentage points, respectively, from the period 1990-1995 to the period 1996-2000. Meanwhile, the share of specialized supplier industries increased by 0.1 percentage points, and primary goods increased by 1.3 percentage points.

averaging 36.8% in the period 2006-2010, and 45.1% between 2011 and 2016. In the last two periods, however, all manufacturing classes reduced their share of Brazilian exports.

China`s integration into global trade in the late 1990s exerted an influence on Brazil's export basket. This integration led to a substantial increase in global demand for commodities. Evidence suggests that the Chinese economy's big appetite for these products drove a global process of export reprimarization.[17] China quickly became Brazil`s main trading partner, importing mostly soy, mineral ores, and oil. In 2001, the share of Brazilian exports that went to China was under 3%. By 2010, this share had risen to 15.34%, securing China`s position as the main destination for Brazilian exports.[18] During this period, Brazil expanded its exports at a faster pace than the global average by deepening specialization in goods that were highly in demand in the international market and for which the country already had comparative advantages, such as agricultural and industrial commodities (Amaral, Castilho and Freitas, 2020).

Despite these developments, Brazil kept its share of global exports of manufactured goods roughly stable at around 1% up to 2008; and the country even managed to increase its weight in global exports of science-based manufacturing. However, from 2008, the position of Brazil in international trade started to deteriorate due to (i) increasing competition from Chinese manufacturing exports, (ii) the shifting of global demand away from the goods Brazil had a comparative advantage in producing (Amaral, Freitas and Castilho, 2020).

Hiratuka and Sarti (2017) argued that competition with Chinese manufacturing exports increased throughout the entire period but was partially offset by the strong performance of the global economy in the early 2000s. After the outbreak of the international economic crisis in 2008, competition intensified. With the economic slowdown in the US and EU, Latin American markets became increasingly important destinations for Chinese exports (CUNHA *et al*., 2012). Castilho *et al*. (2017) showed that China's manufactured exports penetrated most of the markets where Brazil exported its manufactured goods, accounting for 62% of Brazil's market losses in the Latin American region.

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[17] Data provided by Amaral, Castilho, and Freitas (2020) showed that between 1995 and 2014, primary product and resourced-based manufacturing outgrew low, medium, and high-technology manufacturing exports both globally and in Brazil.

[18] Data from World Bank: https://wits.worldbank.org/CountryProfile/en/Country/BRA/Year/2010/SummaryText

Amaral, Castilho, and Freitas (2020) highlighted two concerning trends in Brazil's integration into global trade, especially from the early 2010s. First, global demand shifted towards products with a higher degree of technological sophistication, for which the country did not have a comparative advantage. Second, Brazil's export basket continued its specialization in commodities despite the slowdown of global demand for these goods. Data provided by Nassif and Castilho (2020) shows that between 2011 and 2016, the average participation of primary goods in Brazilian exports reached 45.1%, well above the 26.4% averaged during the period 2001-2005. During the period 2000-2016, Brazil's market share of total primary exports soared from around 1.8% to 6.3%. Meanwhile, the share of manufactured goods in Brazilian exports dropped from 71.8% to 53%, and Brazil's share in global manufacturing exports fell back to the same level observed in 2000, after a continuous decline from 2008 on.

Passoni (2019) deflated an IOT series to analyze the impact of relative prices on the trajectory of Brazilian exports by industry group between 2000 and 2015. The author found that while relative prices tended to exacerbate the country's regressive specialization trajectory, due to a faster increase in commodity prices during this period, exports measured in volume units confirmed that this process was indeed occurring. The share of unprocessed agricultural goods in total exports, measured in volume units, increased from 6% to 13.3%. An upward trend was also observed for mining and quarrying after 2008, with this industry group's share rising from around 32% to 36%. Conversely, there was a significant decline in the shares of innovative and traditional manufacturing groups. The former group's share dropped from 19.4% to 11.8%, while the latter's declined from around 11.5% to 4.9%.

Torracca (2017) analyzed the co-evolution of productive and trade structures between 2000 and 2008 and found that the process of regressive specialization was much more intensive for the latter. The author argues that, in large economies with a modest degree of trade openness, such as Brazil, domestic absorption tends to play a relatively significant role in shaping the productive structure, while exports have a smaller influence. As Medeiros (2013) points out, industrial development in Brazil is much more reliant on development strategies than on the dynamics of exports. Despite the difference in intensities, Torracca`s findings reveal a concerning convergence of productive structure towards the export pattern in this period.

V. STRUCTURAL CHANGE AND THE ENVIRONMENT: A RELATIVELY FORGOTTEN DEBATE

A convergent element in the interpretations reported above is that recent structural changes in Brazil feature an increasing specialization in natural resources. Some argue that a strong regressive specialization is valid both for the productive structure and for the export basket, such as Bresser-Pereira (2007), Gala and Libanio (2011), and Bresser-Pereira and Marconi (2011). Others, like Neves (2013), Torracca (2017), Medeiros, Freitas and Passoni (2018), and Passoni (2019) maintain that there is a mismatch between the evolution of the productive structure and that of the trade pattern, and that this specialization is much more apparent for Brazilian exports. Either way, the use of natural resources is the elephant in the room, as the debate about structural change that emerged from the mid-2000s largely overlooked the implications of transformations on Brazil's recent environmental performance.

It is striking that, until today, only a handful of studies have attempted to explicitly bridge the gap between Brazil's structural changes and its environmental performance and that the majority of these studies actually predate discussions of premature deindustrialization and reprimarization in Brazil. Despite the relevant contributions of these studies, they are outdated, failing to cover the crucial period post-2008 - precisely the period for which the literature seems to converge toward a high acceptance of deindustrialization and reprimarization processes of the Brazilian economy.

The literature indicates that a respecialization in environmentally harmful activities began as early as the 1980s. Carvalho and Ferreira (1992) disaggregated the growth performance of Brazilian industry according to its polluting potential during the 1980s and showed that, from 1982 to 1992, industries with high and moderate polluting potential consistently outgrew those with low and negligible potential. Young (1996) attributes this increased specialization to structural adjustment policies that promoted export-oriented activities with high polluting potential as a way to alleviate severe external imbalances during that decade. Using input-output analysis, the author examined the trajectory of six water and air pollutants (BOD, heavy metals, particulate matter, SO2, NOx, HC, and CO). The results show that an increasing pollution intensity in industrial output between 1980 and 1985 was primarily driven by a rising share of exports in total final demand. This occurred because exports not only exhibited the highest intensities of four of these pollutants (BOD, SO2, NOx, HC) among all final demand components, but they also worsened pollution intensity in all six pollutants.

Other studies also found a deeper specialization in environmentally harmful activities for exports than for the productive structure as a whole. Ferraz and Young (1999) extended the analysis to eight water and air pollutants, covering the period 1985-1995. Once again, exports exhibited the highest pollution intensity among all final demand components. The results also reveal that, after 1990, exports increased their share of total emissions, along with their pollution intensity, for all the pollutants analyzed. According to the authors, these results substantiate the argument that Brazil deepened its export specialization in highly polluting activities, especially after adopting the trade liberalization reforms of the early 1990s.

Machado, Shaeffer, and Worrell (2001) estimated the energy and carbon emissions embodied in Brazilian trade for 1995. The results showed that Brazilian exports contained approximately 40% more energy and 56% more carbon emissions per dollar traded than Brazilian imports. Gramkow (2011) showed that this result still held when using GHG emissions as an indicator. The author used an environmentally extended input-output model to analyze the trajectory of GHG emissions from 1990 to 2005. The findings demonstrated that, after 2000, exports became the most emission-intensive component of final demand. Additionally, the results indicated a significant increase in the export share of total emissions in this period, rising from 12% to 23% when land-use emissions were considered, and from 11% to 21% otherwise.

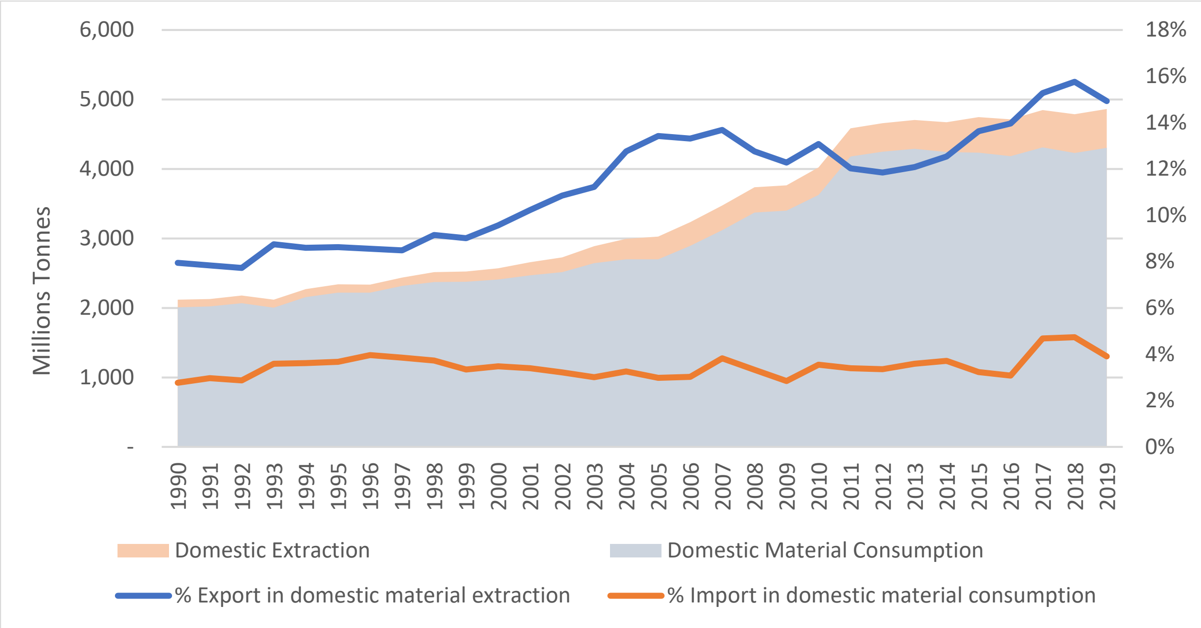
V.1. A glance at environmental indicators

V.1.1. A material flow analysis for Brazil

This section examines the evolution of some key environmental indicators to shed light on Brazil's environmental performance over the past three decades – a period for which the related literature investigates the occurrence of an intense and continuous process of regressive specialization. With numerous studies underscoring a shift towards natural resource-intensive activities, this section analyzes the trajectory of natural resource use in domestic production and the volume of natural resources embedded in trade.

Graph 1 represents the trajectory of domestic resource extraction and domestic material consumption over the period 1990-2019. The former indicator relates to the total amount of natural resources extracted to produce goods and services within the country, whether these are destined for domestic markets or exports. By contrast, the latter corresponds to the natural resources consumed within the country’s borders, including those embodied in domestically produced and imported goods and services.

Graph 1 - Domestic extraction, domestic material consumption, and the relevance of international trade in material use



Source: author's elaboration based on data from WU-Vienna (2024)

Over the entire period, domestic extraction exhibited an ever-increasing trajectory with an accumulated growth of 129.4% (Table 1). However, in the 1990s, domestic extraction followed a relatively modest growth trend (21.3%), despite a sizable increase of 74.6% in exports during this decade. Two factors explain why domestic extraction did not surge during the 1990s. First, the external sector was relatively small compared to the domestic market, so material extraction depended largely on domestic demand. As shown in Table 1, exports accounted for 15.2% and 19.1% of the increase in domestic extraction in the periods 1990-1995 and 1995-2000, respectively. Thus, it is probably the sluggish economic growth in this decade that explains the relatively restrained increase in domestic extraction during the 1990s. The second reason relates to the declining natural resource intensity of exports. While exports increased by 74.6%, the natural resources extracted to produce exported goods and services increased by only 45.9%.

In the 2000s, domestic extraction accelerated. A sharp expansion of 62.1% in exports played a role in explaining the increase in material consumption in the first half of the decade. In fact, exports grew at much faster rates than domestic absorption. As a result, the contribution of exports to an increase in domestic extraction escalated to 35.1%, the second-highest value during the entire period. In the period 2005-2010, economic growth accelerated, so the contribution of household consumption, investment, and government expenditure to domestic natural resource extraction rose to 80.9%. Finally, during the 2010s, the Brazilian economy slowed down, along with international trade, leading domestic extraction to plateau. It is interesting to note that, with virtually no GDP growth between 2015 and 2019, exports became the primary driver of an increase in domestic extraction during this period.

Domestic material consumption followed a very similar trend, highlighting once again the relevance of domestic absorption in driving material use in Brazil. In other words, domestic material consumption increased rapidly during periods of strong economic growth and slowed down when the Brazilian economy decelerated.

Table 1 - Macroeconomic and material use indicators for Brazil

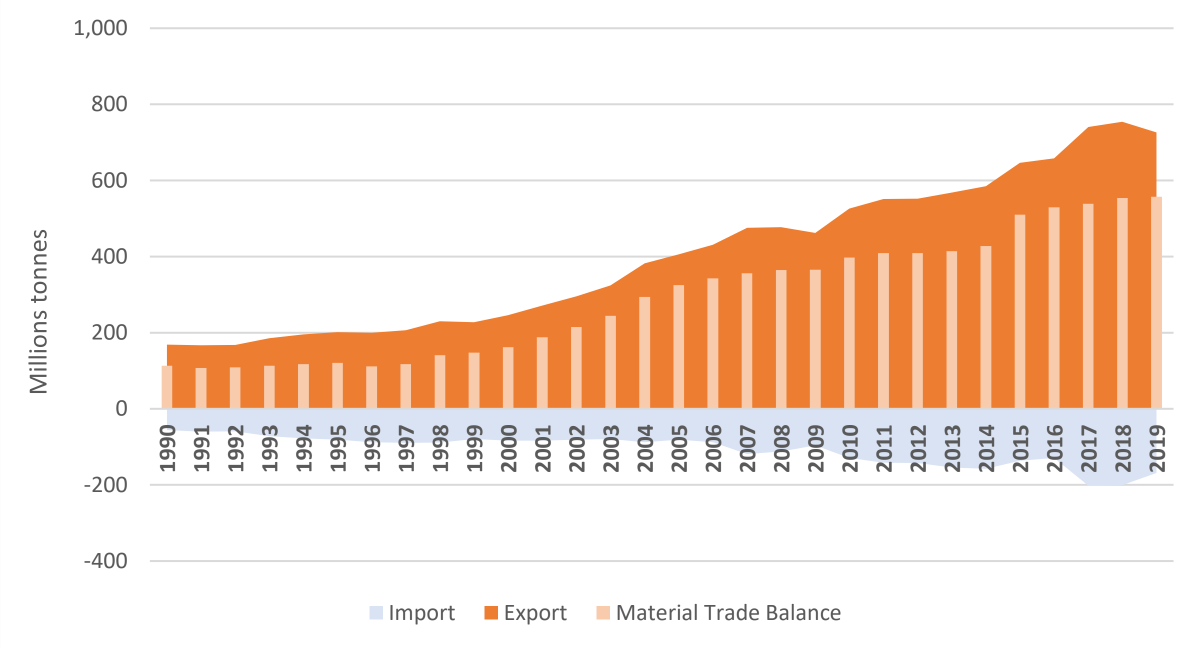
Macroeconomic indicators (accumulated growth rates)				
Period	**GDP**	**Domestic absorption**	**Exports**	**Imports**
1990-1995	16.3%	20.3%	26.2%	131.5%
1995-2000	11.2%	9.6%	38.4%	13.8%
2000-2005	15.3%	10.6%	62.1%	5.7%
2005-2010	24.5%	31.9%	13.3%	103.5%
2010-2015	5.6%	4.0%	13.0%	-1.0%
2015-2019	0.6%	0.3%	7.3%	4.5%
2000-2019	97.2%	100.4%	288.9%	485.8%
Natural resource use indicators (accumulated growth rates)				
Period	**Domestic extraction**	**Domestic material consumption**	**Domestic extraction due to exports**	**Domestic material consumption due to imports**
1990-1995	10.4%	10.6%	19.8%	46.4%
1995-2000	9.9%	8.5%	21.8%	3.2%
2000-2005	17.7%	12.1%	65.2%	-3.9%
2005-2010	133.0%	134.3%	129.5%	159.6%
2010-2015	17.9%	16.7%	22.9%	6.0%
2015-2019	2.5%	1.7%	12.3%	23.3%
2000-2019	129.4%	114.5%	330.8%	203.1%
Contribution to domestic extraction and material cnsumption growth				
Period	**Domestic extraction**		**Domestic material consumption**	
	Export	**C + I + G**	**Imports**	**C + I + G**
1990-1995	15.2%	84.8%	12.2%	87.8%
1995-2000	19.1%	80.9%	1.4%	98.6%
2000-2005	35.1%	64.9%	-1.1%	101.1%
2005-2010	12.0%	88.0%	5.2%	94.8%
2010-2015	16.7%	83.3%	1.3%	98.7%
2015-2019	66.9%	33.1%	44.8%	55.2%
2000-2019	20.3%	79.7%	4.9%	95.1%

Source: author’s elaboration based on data from WU-Vienna (2024)

Although domestic extraction and domestic material consumption follow a very similar trajectory, some aspects should be highlighted. Firstly, as shown in Graph 1, the share of exports in total domestic extraction is significantly greater than the share of imports in domestic material consumption. This indicates that the rest of the world relies more heavily on Brazil's natural resources to produce goods and services than Brazil relies on external resources. Additionally, the share of exports in total domestic extraction surged from 7.8% to 14.9%, with most of this increase occurring during the 2000-2008 period and then again after 2012. Meanwhile, imports maintained a relatively stable share of domestic material consumption at around 3% until 2016, after which they slightly increased to 3.9% in 2019.

The second relevant piece of information is that, for the entire period, domestic extraction exceeds domestic material consumption, and the gap between them increases over time. Such a situation can only occur in countries where natural resource exports are greater than imports. Graph 2 highlights this trend more clearly. During the analyzed period, Brazil's natural resource exports increase much faster than its imports, especially after 2000. As a result, Brazil accumulates growing material trade surpluses throughout the 2000s and 2010s. This increasing surplus indicates that (i) the country has reaffirmed its position as a net exporter of natural resources and (ii) the rest of the world has deepened its dependence on Brazil's natural resource extraction to sustain its economic growth to a larger extent than Brazil has become reliant on external natural resources.

Graph 2 - Material trade balance

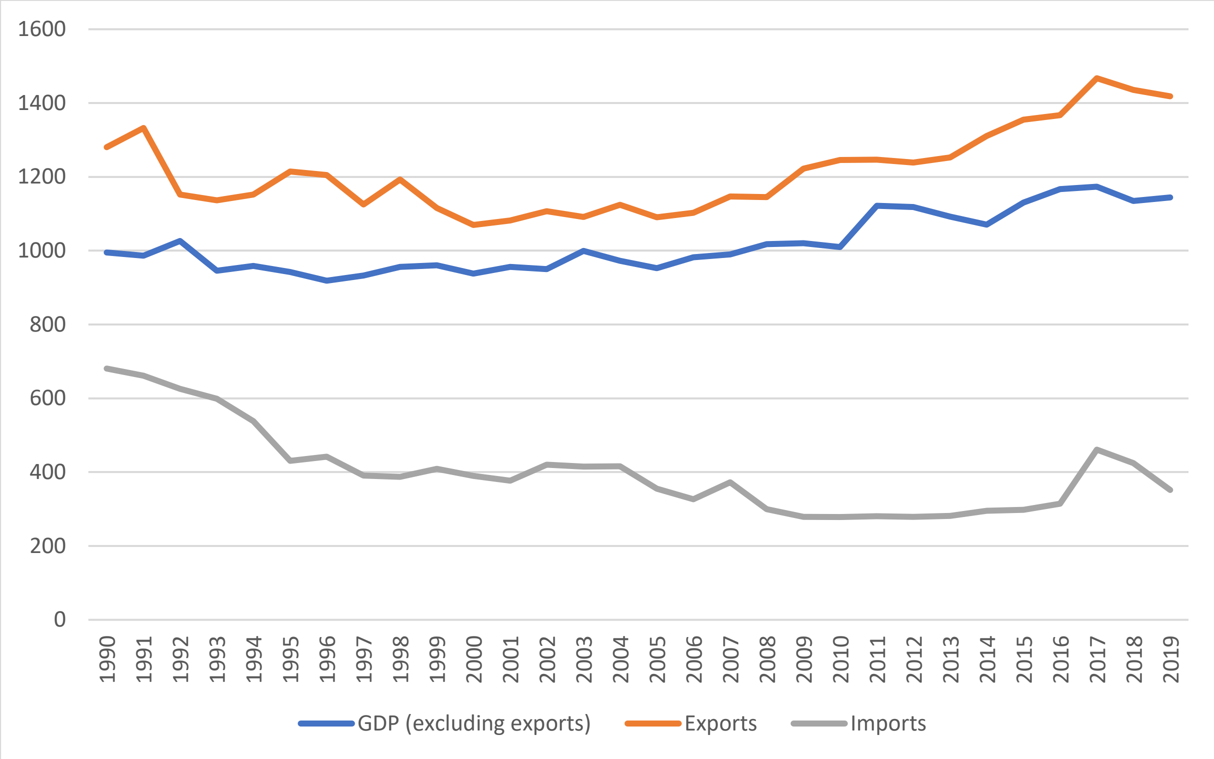


Source: author's elaboration based on data from WU-Vienna (2024)

Part of the variation in domestic extraction and domestic material consumption is also explained by changes in the natural resource intensity of GDP, exports, and imports. Graph 3 illustrates their evolution over the last three decades. Consistent with the findings of the studies presented in the previous subsection, Brazilian exports exhibit a higher environmental footprint than goods and services produced for the domestic market. On average, exports require 19.2% more natural resources per BRL produced than the overall GDP (excluding exports). Both indicators show a similar trend, decreasing up to the late 1990s, after which the natural resource intensity of GDP and exports move into a crescent trajectory, following a modest increase until 2005 and a sharp increase thereafter. Despite a similar trajectory, the natural resource intensity of exports increased significantly more between 2000 and 2019, rising by 32.6% compared to a 21.9% increase in Brazilian GDP.

Conversely, the natural resource intensity of Brazilian imports consistently declined, dropping by 48.3% in the 1990s and by a further 9.8% between 2000 and 2019. This resulted in a widening gap between the natural resource intensity of exports and imports, especially after 2000. On average, the natural resource intensity of the Brazilian export basket was more than three times higher than that of imports, and roughly 2.6 times greater than the Brazilian GDP.

Graph 3 - Brazilian GDP and export intensity in natural resources – at 2010 prices



Source: author's elaboration based on data from WU-Vienna (2024)

V.1.2. The Brazilian GHG emission pattern

Natural resource extraction is closely connected to commodity production (Figure 4), which is often highly intensive in GHG emissions. Agricultural commodities contribute significantly to methane emissions through enteric fermentation, rice cultivation, and manure management, and they are responsible for substantial CO_2 emissions when forests are converted into croplands and pastures (Rajão *et al.*, 2020; MAPBIOMAS, 2024). Industrial commodities require substantial energy to transform mineral ores into their manufactured forms, such as pig iron, steel, and other metal alloys (SEEG, 2024). Therefore, one possible consequence of the regressive specialization that took place in the Brazilian economy is an increasing specialization in GHG-intensive activities.

Figure 4 - Brazilian domestic extraction by material group (2019)

Source: WU-Vienna (2024)

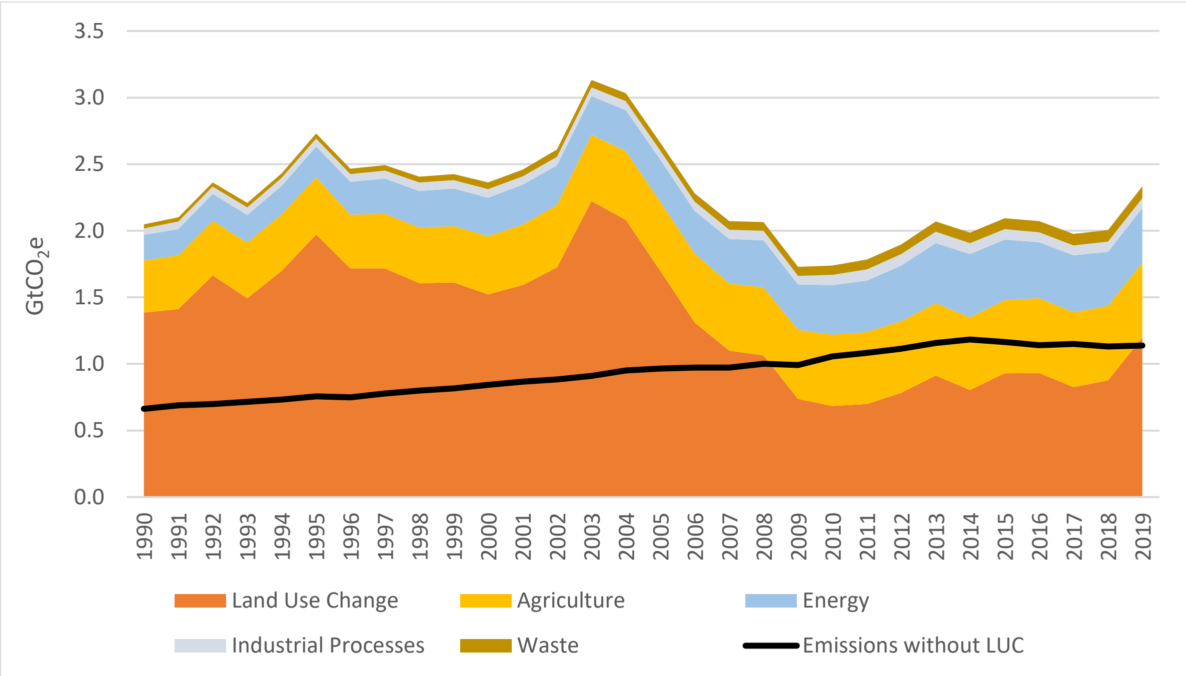
In 2019, Brazil emitted 2.2 $GtCO_2e$, ranking seventh in the list of top-emitting countries. Graph 4 shows the evolution of GHG emissions by sector. The first characteristic that stands out is the high relevance of land use and agriculture in total emissions. While the former category accounted for 58.7% of all GHG emitted by Brazil between 1990 and 2019, the latter was responsible for 21.4%.

It is important to highlight that land use and agriculture emissions are intertwined, as forest clearing in Brazil has been primarily driven by the expansion of the agricultural frontier.[19] The sharp expansion of pastures and croplands over the three decades under discussion put enormous pressure on forested areas. In this period, the country's cattle herd grew from 147.1 million to 214.7 million head, and 87.1% of this expansion took place in municipalities of the

[19] According to data from Mapbiomas (2024), forest conversion into agricultural land reached 75.8 million hectares between 1990-2019, with more than 73.2% accounted for by pastures expansion and the rest by crop expansion. Using the share of land given to crops in total deforested areas tends to underestimate the weight of crop cultivation in total land use change, as capital-intensive agriculture often expands over less productive pastureland, instead of over areas of primary vegetation. Indeed, over the last three decades, pastures lost about 14.3 million hectares to agriculture (Mapbiomas, 2024). Alvarenga (2014) showed that instead of losing area, cattle ranching was being displaced by intensive agriculture. This fact is particularly important when we consider the increase over this period in the weight of soybean in the Brazilian export basket.

Brazilian Amazon [20] (IBGE, 2024). To accommodate these additional cattle, 75.8 million hectares of forest were converted into pasture. Meanwhile, the expansion of croplands involved the conversion of an additional 20.2 million hectares. Combined agriculture resulted in the deforestation of 75.8 million hectares, which represented roughly 95.6% of total forest loss. (Mapbiomas, 2024). Mining and construction accounted for another 1.1%, and other natural developments for 3.3%.

Graph 4 - GHG emissions by sector



Source: SEEG (2024)

In terms of their trajectory, emissions from land use change (LUC) exhibited a very marked downward trend after 2004. In that year, the Brazilian government launched the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). This initiative significantly enhanced environmental governance in the Brazilian Amazon by improving inter-institutional coordination among public bodies responsible for deforestation control, integrating satellite imagery with deforestation surveillance, and expanding protected areas in regions under high pressure from deforestation. The PPCDAm achieved its most significant results between 2005 and 2012, reducing deforestation rates in the Brazilian Amazon by 82%. During this period, the increasing pressure on forested land posed by the

[20]According to IBGE data, 87.1% of the growth in the Brazilian cattle herd took place in the Brazilian Amazon. For more, see Pesquisa Pecuária Municipal: https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9107-producao-da-pecuaria-municipal.html?=&t=series-historicas

expansion of agricultural activities was counterbalanced by a successful environmental policy. This allowed for a 19.6% increase in agriculture GDP with falling deforestation rates and emissions.

From 2012 onward, deforestation rates rebounded due to changes in the Brazilian Forest Code that relaxed legal requirements for Areas of Permanent Preservation (APPs) and granted amnesty to landowners who had carried out illegal deforestation prior to 2008 (Sant'Anna and Costa, 2019). Additionally, environmental governance and surveillance weakened due to successive budget cuts to environmental management that led to resource shortages for institutions like the IBAMA and ICMBio. These cuts began in 2013 and worsened after 2015, due to Brazil's fiscal crisis and the primary expenditure cap established by Constitutional Amendment 95 (Alvarenga et al., 2019). Changes to emissions from LUC responded to this situation and increased by 53% between 2012 and 2019. Despite the sharp increase in deforestation rates in the Amazon in this period, land use was the only category to present lower emissions in 2019 than in 1990.

In addition to growing emissions from LUC, Brazil in this period had large amounts of GHG emissions from agricultural activities such as enteric fermentation, the manuring process and soil management, lixiviation, and the decomposition of biomass in flooded cultivation, among others (SEEG, 2024). In total, agriculture`s emission increased by 43.9%, or by 171.7 $MtCO_2e$, with cattle ranching being the primary culprit of this increase, accounting for an additional 107.9 $MtCO_2e$, primarily due to the large amounts of methane produced in the process of enteric fermentation by herds. In absolute terms, cumulative emissions from enteric fermentation in this period totaled 10.1 $GtCO_2e$, as reported by the Greenhouse Gas Emissions and Removals Estimation System (SEEG, 2024). This aspect will be further analyzed in Chapter 3, which will provide an estimate of emissions by industry.

Table 2 - Emissions from the agriculture sector 1990-2019

Sector/Subsector	Total emissions			
	1990	2000	2010	2019
1. Livestock	**349,654,131**	**384,002,986**	**456,531,620**	**457,648,216**
1.1 Cattle ranching	321,989,339	359,464,181	429,116,963	425,524,631
1.1.1 Enteric fermentation	283,407,696	312,377,489	368,532,736	366,842,714
2. Crops	**41,498,088**	**54,125,872**	**77,859,106**	**105,204,999**
2.1 Soy	1,834,179	3,025,431	6,337,999	10,537,721
2.2 Rice	9,686,510	10,930,674	11,418,704	11,029,200
2.3 Corn	1,682,085	2,546,273	4,361,908	7,966,609
2.4 Sugar cane	2,039,660	2,382,190	4,505,801	4,049,253
3. Agriculture	**391,152,219**	**438,128,859**	**534,390,726**	**562,853,215**
Sector/Subsector	**Share of agriculture emissions**			
	1990	**2000**	**2010**	**2019**
1. Livestock	89.4%	87.6%	85.4%	81.3%
1.1 Cattle ranching	82.3%	82.0%	80.3%	75.6%
2. Crops	10.6%	12.4%	14.6%	18.7%
2.1 Soy	0.5%	0.7%	1.2%	1.9%
Agriculture (% of Brazilian emissions)	19.1%	19.2%	30.7%	24.1%
Agriculture (% of Brazilian emissions excluding LUC)	59.0%	52.1%	50.6%	49.5%

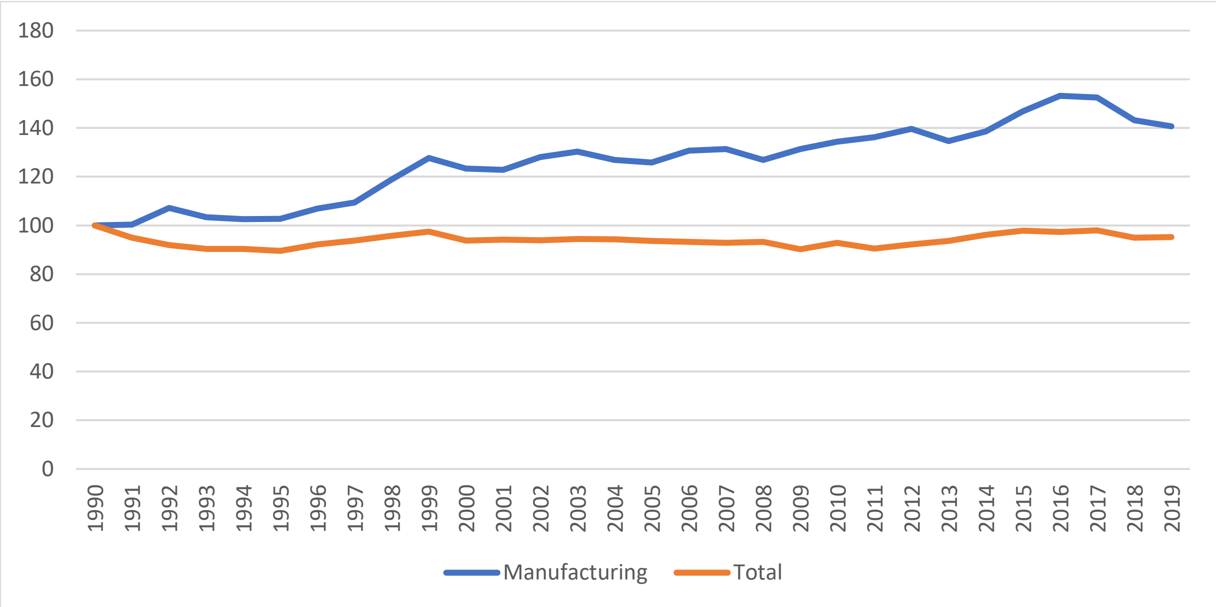
Source: author`s elaboration based on data from SEEG (2024).

The emissions from crop production during this period (including soil management, use of fertilizers, lixiviation, and other activities) more than doubled, increasing their share of total agricultural emissions by 8.1 percentage points. Soybean was the culture presenting the greatest emission increase, growing 474.5% between 1990 and 2019. In this period, Brazilian soybean production rose by 711%, while the area dedicated to its cultivation expanded by 279.3% (CONAB, 2024). Around 80% of production was destined for exportation (MAPA, 2024), and the expansion was primarily driven by an increase in Chinese demand, especially after the early 2000s (Costa and Fraga, 2021).

The Brazilian emission pattern, largely dominated by agriculture and LUC, differed significantly from the one presented globally. While in Brazil, 75% of all GHG emissions between 1990 and 2019 came from agriculture and LUC, 73.2% of global emissions in this period came from the energy sector, and one-third was due to energy use in industrial activities (Climate Watch, 2020).

In Brazil, on average, energy used accounted for around 14.8% of total emissions when emissions from LUC were included and 33.9% otherwise. During this period, energy emissions increased by 113.4%, significantly outpacing total emission growth of 14% (or 71.6% when LUC emissions are disregarded). Therefore, the share of energy emissions in total emissions increased from 9.4% to 17.5% between 1990 and 2019, and from 28.9% to 35.9% when LUC emissions are not considered. Aside from the impact of economic growth and changes in the energy matrix, evidence suggests that energy emissions were also related to worsening energy efficiency. Graph 5 reveals a marked upward trend in the energy intensity of manufacturing, especially after 1995. According to Altomonte et al. (2011), the increase in the manufacturing energy intensity after 1995 was related to an increasing specialization of manufacturing in natural-resource-based industries, as the latter often required more energy per unit of output. The energy intensity of the Brazilian economy also increased after 1995, though more modestly.

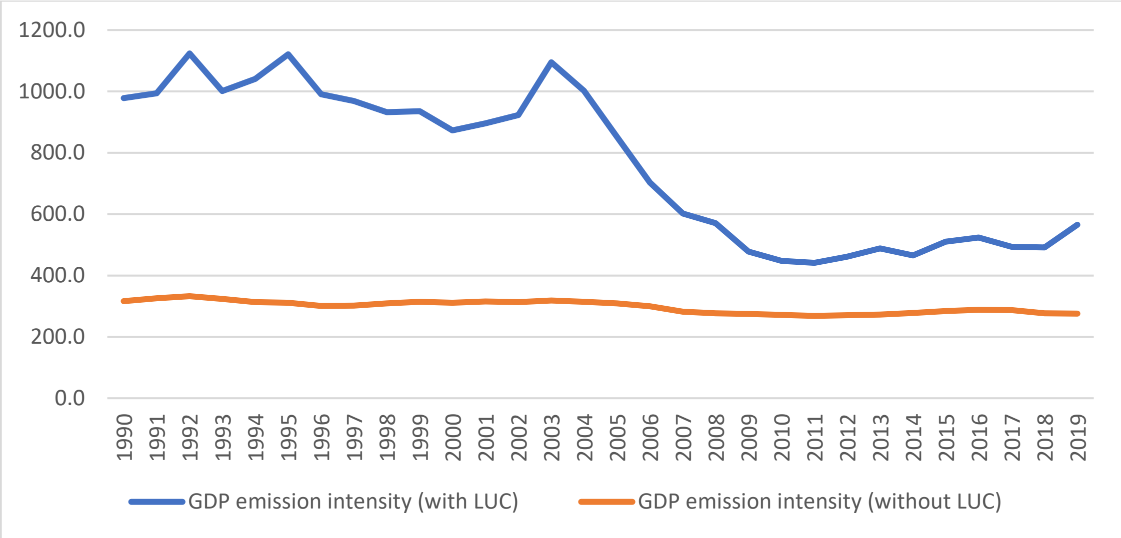
Graph 5 - Energy intensity – MJ/thousand GDP (at 2015 prices)



Source: author`s elaboration from World Bank (2024) and EIA (2024) data

Finally, Graph 6 displays GDP intensity in GHG emissions. The overall trend (blue line) is quite dependent on deforestation rates, given the already mentioned high relevance of LUC to Brazilian emissions. Indeed, it can be seen that after the PPCDAM, GDP intensity dropped significantly and then rebounded in 2012. From an environmental sustainability standpoint, such a trend shows how environmental policy can be used to counterbalance the potentially harmful effects of agricultural commodity production. When LUC change is excluded, though, Brazilian GDP exhibits a modest decline in GHG intensity up to 2010. The reasons for that will be addressed in Chapters 3 and 4.

Graph 6 - Brazilian GDP intensity in GHG emissions – with and without LUC



Source: author's elaboration from SEEG (2024) and World Bank (2024) data

VI. CONCLUDING REMARKS

Structural change must point in the right direction and happen at a specific pace to trigger a sustained process of capital accumulation, productivity, and per capita income growth that accompanies economic development. At the same time, economic development promotes a series of structural transformations that may reinforce trends towards a more diversified economic structure with a higher participation of more technologically sophisticated industries. This interdependency between structural change and economic development has been widely covered by the development economics literature at least since the 1940s.

This chapter has presented the debate on the interconnection between these two elements to set the ground for introducing a new dimension into the discussion of economic development: the sustainability dimension. It is imperative to understand how structural change, economic development, and the environment interact with one another, given the accumulating evidence of a rapid degradation of natural capital, a process that accelerated in the twentieth century. For instance, science presents unshakable evidence that climate change is tightly connected to the economic development process of a few countries, even though many developing economies also make relevant contributions to GHG emissions.

The debate on economic development and the environment has been significantly influenced by the Environmental Kuznets Curve (EKC) hypothesis. In general terms, the hypothesis posits that economic development will endogenously create the necessary conditions to reverse environmental degradation generated in the initial stages of this process. In other words, the EKC hypothesis suggests that it is possible to grow out of environmental issues.

However, the evidence supporting this hypothesis is, at best, controversial. Several factors challenge its validity, including the possibility of emissions leakage between countries through trade relations. Another relevant point is that the process of deindustrialization, which allegedly will relieve environmental pressures due to the smaller material base of services, often involves a high degree of complementarity between services and the manufacturing sector. In other words, if there is no necessary substitution of activities with higher material content, the conditions for an absolute decoupling between growth and environmental emissions are unlikely to occur.

This debate on how structural change, development, and the environment interact with one another is critical for analyzing the recent transformation of the Brazilian economy, as various studies suggest that the country has undergone a process of regressive specialization. The literature review on the topic has revealed an unsettled discussion about the timing and intensity of this regressive specialization process. Some studies point to intensive regressive specialization for both the productive structure and exports, beginning as early as the 1990s. Others find that this process gained momentum during the second half of the 2000s, being much more intensive for the Brazilian trade pattern.

In both streams of this debate, the environmental repercussions of these changes have been largely ignored. Indeed, the literature review conducted in this chapter has drawn on only a handful of studies available about the nexus between the recent structural change in Brazil and the country's environmental performance, all of them covering the period up to the mid-2000s. This means that insufficient attention has been paid to analyzing environmental repercussions in the most recent period, during which part of the literature on structural change points to an intensification of the regressive specialization process.

Given this lack of studies, this chapter has analyzed some environmental indicators for the period 1990-2019. The analysis revealed some worrying trends during this period, especially from the 2000s onwards. Taken together, the literature gap and the worsening of the environmental indicators underscore the relevance of the analyses that will be carried out in the next chapters to investigate the impact of recent structural changes on Brazilian GHG emissions.

CHAPTER 2 – BUILDING GHG EMISSION VECTORS AND INTEGRATING THEM INTO AN ENVIRONMENTALLY EXTENDED INPUT-OUTPUT MODEL

I. INTRODUCTION

Chapter 1 presented an extensive literature review on the interconnection between structural change, economic development, and the environment. Its last sections delved into the Brazilian case and revealed a fruitful debate on recent structural changes in Brazil. This debate was pretty much centered on the discussion of whether Brazil had entered a path of regressive specialization. The majority of the literature converged on the existence of regressive specialization, even though some controversies persisted about when this process began and its intensity for the productive structure and export basket. However, the sustainability dimension is the elephant in the room, as the literature largely ignored the environmental implications of increasing the material basis of economic growth as a result of the regressive specialization process.

Using input-output matrices to analyze how productive structure and environmental issues interact is not new. In 1970, Leontief published his article "*Environmental repercussions and the economic structure: an input-output approach*", in which he proposed extending such models to analyze the emissions of air pollutants resulting from final demand shocks. Yet, this type of analysis seems to have only recently taken off. This late awakening may result from an increase in data availability. Over the last two decades, the lack of environmentally related data has been gradually reduced. Before that, many databases were outdated in this respect, presenting severe time discontinuities and low levels of disaggregation, which may have hindered the integration of environmental variables into input-output tables (IOTs).

Another factor that may help to explain the recent diffusion of environmentally extended input-output analyses is that the climate agenda has been lifted to a top priority position in political and academic debates. The narrowing window of opportunity to avoid the most disruptive impacts of climate change has given the problem a sense of urgency. In such a context, environmentally extended IOTs can assist policymakers in understanding each country's emission profile, revealing their industries' emission intensities and shares in total emissions, which industries pull and propagate more emissions from and to other sectors, and how emissions respond to changes in pace and composition of economic growth. Such information is critical to identifying opportunities for decoupling economic growth from GHG emissions and designing decarbonization pathways tailored to each country's development and environmental challenges. This debate is even more critical for developing countries because their catching-up strategies must face a climate constraint that was absent when developed countries industrialized.

In Brazil, databases with annual information on greenhouse gas (GHG) emissions and land use changes are relatively new. The first national communication on Brazilian anthropogenic emissions dates back only to 2004. This initiative reflects the country's commitment to the United Nations Framework Convention on Climate Change (UNFCCC) in conducting emission inventories and reporting them to the international community every five years. However, since 2013, this information has been unofficially released annually by the System for Estimating Greenhouse Gas Emissions (SEEG)[21]. As we will see in the coming sections, this information is critical for constructing emission satellite accounts – hereafter referred to as Brazilian emission vectors.

Given the absence of emission vectors that match Brazilian IOTs and the relevance of incorporating an environmental dimension into the debate on recent structural changes in Brazil, the first objective of this chapter is to build a time series of GHG emission vectors. These vectors cover the period 2000-2019 for 42 industries and 91 commodities and match the IOT developed by Passoni and Freitas (2022). They will support Chapters 3 and 4, which will shed light on the structural pattern of Brazilian emissions and analyze how recent structural changes in the country have impacted its emissions in the period under review. The second objective of this chapter is precisely to present the structural decomposition analysis (SDA) methods that will be used on Brazilian GHG emissions. Chapter 4 will carry out SDA analyses for Brazil's production-based emissions: two on Brazilian domestic production as a whole, and the other one focusing only on exports.

II. ENVIRONMENTALLY EXTENDED INPUT-OUTPUT TABLES: A BRIEF OVERVIEW

In 1970, Leontief published his article "*Environmental repercussions and the economic structure: an input-output approach*", proposing to incorporate a new industry into the IOT as a way to account for the pollution arising from the productive process. While the output of the industries hitherto included in such tables had actually been 'economic goods', the new industry

[21] For more on the methodology used to estimate Brazilian GHG emissions and removals, see Azevedo et al. (2018)

was responsible exclusively for producing air pollution, i.e., a negative environmental externality. As recalled by the author:

> *The technical interdependence between the levels of desirable and undesirable outputs [for instance, negative environmental externalities] can be described in terms of structural coefficients similar to those used to trace the structural interdependence between all the regular branches of production and consumption. As a matter of fact, it can be described and analyzed as an integral part of that network.* (Leontief, 1970; p.262)

The extension proposed by Leontief consisted of incorporating a row and a column (in grey) into the original technical coefficient matrix (in yellow) to represent the interrelations between the pollutant-producing industry and all other industries in the economy (Figure 5). The extra row shows how the pollution is 'demanded' as input to the production of each industry`s output. Conversely, the additional column shows how the polluting industry demands the output from other industries to undertake its own production.

Figure 5 - Leontief's approach to extending IOTs for air pollution accounting

Industry	Agriculture	Manufacture	Air pollution
Agriculture	0.25	0.4	0
Manufacture	0.14	0.12	0
Air pollution	0.5	0.2	0

Source: adapted from Leontief (1970)

Through this approach, the total air pollution level can be estimated as follows:

$$p = (\boldsymbol{I} - \boldsymbol{A}^{*})^{-1}\boldsymbol{F}^{*} \qquad (1)$$

p is the pollution level

$A^* = [a_{i,j}]_{n+1,n+1}$ is the direct technical coefficient augmented matrix to account for air pollution

$F^* = [f_{i,j}]_{n+1,1}$ is the final demand vector, where the element in the n+1 row represents the polluting sector's final demand (which is presumably zero).

Interestingly, Leontief presented his environmentally extended model in physical units. Thus, he avoided the need to work with hybrid input-output tables (IOTs) that combined monetary and physical units of measure (Miller and Blair, 2009).

Besides air pollution, environmentally extended input-output tables (EEIOT) have been used to analyze the correlation between economic structure, production, and many other environmental issues, ranging from GHG emissions and energy use to natural resource depletion, deforestation, and ecosystem services. As Leontief (1970) recalled, IOTs can be applied to analyzing any output that has a linear correlation with the production level.

While Leontief's proposal of including a single polluting sector is algebraically correct, its logic can lead to some confusion, especially regarding emissions inventory analysis. The inventories report an industry's and individual companies' emissions divided into three scopes (GHG Protocol, 2004). Scope 1 reports all direct emissions from factors and assets controlled by the industry or firm. For example, a company in the agricultural sector should report enteric fermentation emissions for inclusion in Scope 1. Scope 2 relates to indirect emissions from the purchase of energy. Finally, Scope 3 reports all indirect emissions from the company's supply chain (not covered in Scope 2).

These inventories are mainly used to report emissions at the microeconomic level, that is, for companies to report their direct and indirect emissions. However, sector-level analyses are also relatively common (CDC, 2022). In both cases, it is easy to see that the author's proposal generates problems for allocating emissions between Scopes 1 and 3. At the sectoral level, it is evident that the way Leontief extended its matrix left barely any room to report scope 1 emissions, given that all emissions (or pollution) would all be produced by the "polluting industry" and consumed as an input to the output production of all other industries. As a result, these emissions would all be reported in Scope 3. At the firm level, companies often need to resort to environmentally extended input-output tables, given the scarcity of information on their suppliers` emission factors. Concretely, a firm is unlikely to know the emission factors per unit of output of each of its suppliers. Therefore, it is important to consider ways to integrate emissions into matrices that do not obscure direct or indirect emission accounting analyses or sectors and firms' accountabilities.

There is a second approach to extending IOTs to take account of environmental issues that differs from the one in Leontief's proposal and seems less troubling. Instead of adding a row and a column representing an environmental sector, this inclusion can be made through environmental satellite accounts, as proposed in Miler and Blair (2009). These satellite accounts are vectors containing each industry`s intensity of pollution. This intensity can also be expressed in terms of GHG emissions, energy consumption, or natural resource use per unit of output (Figure 6). Through this approach, estimating the level of air pollution can be done, as in Equation 2:

$$p = \widehat{\boldsymbol{P}}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \tag{2}$$

p is the total pollution level;
$\widehat{\boldsymbol{P}}$ is a diagonal matrix with the pollution intensities in the main diagonal;
$(\boldsymbol{I} - \boldsymbol{A})^{-1}$ = is the Leontief inverse matrix;
f is the final demand vector.

Figure 6 -Environmentally extended IOT structure

Industries	Intermediate consumption				Final demand				Gross output
	S1	S2	S3	Sn	C	I	G	X	
S1									
S2									
S3									
Sn									
Value added									
Imports									
Gross output									
GHG emissions									
Local pollutant									
Primary energy consumption									
Natural resource use									

Source: author's elaboration

Given its advantage, this thesis will draw on the second approach to matching GHG emissions into Brazilian IOT tables. Another advantage of great interest to this thesis is that the second approach allows for easier visualization of emissions interrelations between industries by estimating an environmental Leontief inverse matrix (see Section 4). The data used, and the methodological steps for building the GHG emission vectors are presented in the next section.

III. BUILDING THE GHG EMISSION VECTORS

III.1 Data

This section outlines the methodological steps followed to estimate Brazil's gross GHG emission vectors. The database built here covers the period 2000-2019,[22] and the data are expressed in GWP-100, according to the IPCC Fifth Assessment Report (IPCC AR-5) guidelines. The vectors represent the gross emission intensity[23] of each of 42 industries and are expressed in tCO_2e per BRL millions of outputs (at 2010 prices). To create these vectors, we drew on three different databases (see Table 3 below).

[22] New vectors are expected to be released as more recent IOTs are published.
[23] By gross emissions we mean that the vector built in this Chapter does not account for emission removals.

Table 3 - Sources and variables used in the model

Database	Specifications	Source
Annual input-output tables (IOT)	The database covers the period 2000-2020 for two disaggregation levels: (i) 42 industries and 91 products; (ii) 67 industries and 127 products. The monetary values in the IOT tables are expressed at: current prices, previous year prices, and 2010 constant prices.	Passoni and Freitas (2022)
SEEG	The database uses the IPCC guideline to estimate the Brazilian GHG emission inventory from 1970 to 2021. The information can be filtered by (i) emission sector (energy, agriculture, industrial processes, waste, and land-use change); (ii) type of greenhouse gas; (iii) carbon equivalent metric (Global Warming Potential or Global Temperature Change Potential); (iv) Geographic region, covering all states, federal districts and municipalities; (v) type of emissions (net or gross emissions)	System for Estimating Greenhouse Gas Emissions (SEEG)[24]
Land use change	The MAPBIOMAS database provides information on land cover and land use change. This information is displayed in a land use transition matrix whose rows and columns present the different kinds of land cover (in hectares) in the years t-1 and t. Therefore, the entries in this matrix provide information on the area that was under a certain type of land cover in year t-1 and transitioned to another type of land cover in year t.	MAPBIOMAS (2024)

Source: author's elaboration.

III.2. Methods

III.2.1. General steps

The SEEG database displays Brazilian emissions across the five emitting sectors that feature in IPCC reports: energy, waste, industrial processes, agriculture, and land use. Therefore,

[24] For more on the methodological steps used in SEEG`s database, see Azevedo *et al*. (2018)

creating emission vectors at this point involves allocating emissions from all emitting sectors to the 42 industries of the input-output matrices developed by Passoni and Freitas (2022).

The information on Brazilian emissions is presented at different levels of detail, with the possibility of reaching a sixth tier of disaggregation (Figure 3). The first tier, referred to as the "emission category," corresponds to the IPCC emitting sectors. Meanwhile, tiers two to six are called “emissions subcategories” and complement the information in tier one by subcategorizing the GHG emissions within the five IPCC sectors.

Based on the six tiers of information, it is possible to build a matching matrix (M_p) to identify whether an IOT commodity is associated with a specific emission category and its related subcategories. This matrix assigns a value of 1 to all commodities directly associated with a certain category and subcategory of emission and 0 otherwise. Figure 3 exemplifies how this correspondence between emission categories, subcategories, and IOT commodities is made. For instance, it is reasonable to assume that emissions from enteric fermentation are related to the production of live cattle, other animals, and meat, while emissions from the burning of agricultural residues from sugarcane are associated with sugarcane production. It is important to note that: (i) each commodity can be associated with many different emissions categories and subcategories (i.e., there can be multiple 'ones' in a column), and (ii) each emission category or subcategory can be associated with the production of more than one commodity (i.e., there can be multiple 'ones' in a row), as is the case with emissions from enteric fermentation (see Figure 7).

Figure 7 - Example of a matching matrix for integrating SEEG emissions categories and subcategories into IOT commodities

Tier 1 (Category)	Emissions Subcategories					Emission (TCO2e)	IOT Commodities						
	Tier 2	Tier 3	Tier 4	Tier 5	Tier 6		Sugar Cane	Soybean Production	Cellulose	Bovine and other live animals, products of animal origin	Beef and veal and other meat products	Pig iron and ferroalloys	Cement
Agricultural	Enteric Fermentation	Direct	Other	Animal	Bovines	9.2	0	0	0	1	1	0	0
Agricultural	Waste burning	Direct	Other	Crop	Sugarcane	3	1	0	0	0	0	0	0
Waste	Liquid effluente treatment	Industrial effluent	Pulp production	-	-	4	0	0	1	0	0	0	0
Waste	Liquid efluente treatment	Industrial effluent	Bovine Production	-	-	2	0	0	0	0	1	0	0
Industrial Processes	Cement Production	-	-	-	-	5.5	0	0	0	0	0	0	1
Industrial Processes	Production of Pig Iron and Steel	-	-	-	-	7.2	0	0	0	0	0	1	0
Energy	Biofuel Consumption	Soy	-	-	-	7.1	0	1	0	0	0	0	0
Energy	Agriculture self-consumption	Animal Fat	-	-	-	3	0	0	0	1	0	0	0

Source: author`s elaboration

If one wants to work with an industry-by-industry model, then the matching matrix above needs to be multiplied by the market-share matrix (D'). The entries in the market-share matrix show the share of each industry in the production of each commodity. Therefore, the multiplication of the matching matrix (M_p) by market-share (D') will result in a non-binary matrix, M_s, in which entries will not only identify whether an industry is associated with a certain category or subcategory of emissions but also give a hint as to what extent they are associated to one another. In other words, the market share matrix will weigh how each industry can be held accountable for emissions from each commodity production.[25]

$$M_s = M_p * D' \qquad (3)$$

So far, the methodological steps described above apply to all emissions categories. However, some particularities pertaining to each emissions category may require specific criteria to refine the allocation of emissions to the 42 IOT industries. For that reason, we use three different weighting criteria for allocating emissions among the IOT industries: one for agriculture and waste emissions, one for energy and industrial processes emissions, and one for land use change (LUC) emissions.

[25] Once again, a certain category and subcategory of emissions can be associated with multiple industries. This happens when more than one industry produces a given commodity. Analogously, one industry can be associated with more than one category of emissions, notably when this industry produces than one commodity.

III.2.2. Allocating emissions from agriculture and waste across the IOT industries

Even after applying the market-share matrix, an industry's contribution to the emissions reported in a certain subcategory may remain unclear. For instance, emissions from urea application in agriculture may be associated with both the agriculture and the livestock sectors. When a particular subcategory of emissions is associated with two different industries, we follow the method proposed by Gramkow (2011). This allocates emissions according to each industry's share in their combined output. For example, suppose the combined output of agriculture and livestock equals R$ 100 billion, with agriculture accounting for 40% of this value. In that case, 40% of the emissions from urea use are allocated to agriculture, and the remaining 60% to livestock production.

III.2.3. Allocating energy and industrial processes emissions across the IOT industries

The matrix Ms above identifies the industries associated with a particular emission category and its related subcategory. As in agriculture, very often, a line of energy and industrial processes categories may be related to more than one industry. In such cases, an allocating criterion for these emissions is needed. Usually, tier five of the energy category displays information about the energy source (such as natural gas, firewood, or petroleum) that resulted in such emissions. Similarly, tier five of the industrial processes category provides information about the input (for instance, mineral coal coke) whose use resulted in a certain amount of GHG emission.

Once again, we follow the methodological steps proposed by Gramkow (2011) to allocate emissions from energy and industrial processes associated with multiple industries. This method consists of allocating emissions proportionally to each industry's share in the intermediate consumption of the type of energy or input responsible for such emissions. For example, in the case of oil consumption by the food industry in the SEEG database, the associated emissions are allocated to "slaughter, meat, and dairy products," "production and refining of sugar," "other food products," and "beverage production" according to their share in the intermediate consumption of oil.

The only emissions allocated to energy-producing industries stem from their own energy consumption. For instance, if the biofuel industry consumes a certain amount of biofuel in its own production process, then the emissions from this consumption will be allocated to this industry. However, let's say that the textile industry also requires some amount of biofuel to produce its output. In this case, the emissions from biofuel use for the textile industry will be attributed to the textile industry itself.

III.2.4. Allocating land use change emissions across the IOT industries

To allocate the emissions from land use change, we draw on the MAPBIOMAS land use and land cover transition matrix for the period 2000-2019.[26] This matrix shows how each land cover changed in the review period.

Figure 8 presents a hypothetical example of a land cover transition matrix. The rows show the land cover in year t-1, while the columns display the land cover in year t. In this hypothetical matrix, one should notice that, out of the 1,560 hectares of forest that existed in year t-1, in year t, 1,000 hectares remain as forested land, 100 hectares have turned into non-forested natural formation, 400 hectares have been converted into agricultural land (200 hectares have been converted into pasture, 100 hectares into temporary crops, and the remaining 100 into other agricultural uses), another 50 hectares have shifted to non-vegetated land, and 10 hectares have become water surface. The organization of the other rows is similar: it represents what was under a particular land cover category in year t-1 and has shifted to different land cover categories in year t.

The column entries show how each category of land cover contributes to the total area under a specific land cover. For instance, for the forested area, we see that out of the 1040 hectares under this category in year t, 1000 hectares is the forest remnant of year t-1, 10 hectares has come from non-forest natural formation, 25 from the conversion of agricultural land into forest, and the other 5 hectares from non-vegetated land.

Figure 8 - Land cover transition matrix

Land cover categories and subcategories	1. Forest (t)	2. Non-Forest Natural Formation (t)	3. Farming (t)	3.1. Pastures (t)	3.2. Temporary Crops (t)	4. Non-Vegetated Land (t)	4.1. Mining (t)	4.2. Urban Area (t)	5. Water (t)	5.1. Aquaculture (t)	Total (t)
1. Forest (t-1)	1000	100	400	200	100	50	15	25	10	2	1560
2. Non-Forest Natural Formation (t-1)	10	100	0	0	0	0	0	0	0	0	110
3. Farming (t-1)	25	0	600	0	0	0	0	0	0	0	625
3.1. Pastures (t-1)	15	0	0	100	100	0	0	0	0	0	15
3.2. Temporary Crops (t-1)	3	0	0	150	150	0	0	0	0	0	3
4. Non-Vegetated Land (t-1)	5	0	0	0	0	50	0	0	0	0	55
4.1. Mining (t-1)	4	0	0	0	0	0	15	0	0	0	4
4.2. Urban Area (t-1)	1	0	0	0	0	0	0	25	0	0	1
5. Water (t-1)	0	0	0	0	0	0	0	0	70	22	70
5.1. Aquaculture (t-1)	0	0	0	0	0	0	0	0	0	22	0
Total (t-1)	1040	200	1000	200	100	100	15	25	80	24	2420

Source: author's elaboration

[26] For more, see Mapbiomas (2024) and Souza (2020).

To allocate land use change emissions, we are particularly interested in the portion of forested land in year t-1 that has changed to other categories of land cover in t. However, we are not interested in all the land covers that have succeeded the forest, only those that can be directly related to the expansion of economic activities, such as (i) farming, which includes croplands and pasture, (ii) non-vegetated areas, specifically mining and urban areas, and (iii) water, notably aquaculture. These transitions give us a proxy for forest loss (deforestation) due to productive purposes and exclude those related to natural processes. In the example displayed in Figure 4, we see that forest loss due to productive purposes totals 442 hectares.[27] Based on this information, we allocate land use emissions proportionally to the share of farming and mining, urban areas, and aquaculture in the forest loss area, assuming that:

i. All emissions related to forest conversion into farming and aquaculture go to agriculture
ii. All emissions from converting forests into urban areas can be assigned to the construction sector
iii. All emissions from forest loss due to mining expansion can be assigned to the "extraction of iron ore, including processing and agglomeration", and "other mining and quarrying" industries.

While the IO model implies a direct, steady, and linear relationship between inputs and outputs, the relationship between land (and thus land-use change emissions) and agricultural output may not behave as such. As pointed out by Young (1997), on the Brazilian agricultural frontier, quasi-open access to land prevails, a situation in which property rights are established only after land occupation, and the most common way to show land occupation is through converting forested areas into extensive pastures. Therefore, on the agricultural frontier, deforestation is commonly driven by speculation aimed at the capital gains economic agents expect to earn from selling their lands when the property rights are officially recognized (Young, 1997, 2018; Alvarenga, 2014).

In other words, institutional aspects such as deforestation surveillance and land tenure governance influence landowners' decisions on how to increase agricultural output. This can be done either by increasing deforestation, productivity, or both. This means that higher output

[27] This is the sum of the areas that have been converted from forest to farming, mining, urban areas, and aquaculture.

levels can be achieved either with more, less, zero, or even with negative deforestation (and therefore emissions from LUC).

This situation does not imply that one should not take into account land use emissions while working with input-output modeling. The weight of LUC in total Brazilian emissions is too large (around 50% of the country's total GHG emissions) to be disregarded, and not all deforestation in Brazil is driven by agents claiming land property rights. Nevertheless, environmentally extended input-output analyses should be carried out very carefully when LUC emissions are incorporated.

Indeed, the methodological issue seems to be even more vital for output projection analysis: for instance, if one were interested in estimating what quantity of LUC emissions would be generated if the final demand for agricultural goods were doubled. However, the analysis carried out in this thesis looks backward to check the quantity of emissions actually generated by the level of economic activity in a given year. Whether or not deforestation in that particular year was driven by land speculation, new land was incorporated into the production process and changed the agricultural 'cooking recipe.' Therefore, this is no longer a matter of how much land was needed to produce a given output but how productively this land was used in that particular year.

III.2.5. Combining the three criteria for allocating emissions

Based on the three allocation criteria mentioned in the previous subsections, it was possible to build a matrix of sectoral participation (SE) in the inventoried emissions on the SEEG database, which was estimated according to Equation 4:

$$\boldsymbol{SE} = (\boldsymbol{M_s} \otimes \boldsymbol{VR}) \oslash [(\boldsymbol{M_s} \otimes \boldsymbol{VR}) * v' * v] \quad (4)$$

SE is a matrix of dimension SxI, where S is the number of rows in the SEEG emissions inventory table and I is the number of industries (which, in our case, equals 42). VR is a SxI dimension matrix whose values reflect the weights created from the criteria established in the previous three subsections. For example, for the lines referring to emissions inventoried in the agriculture and waste sectors, the values of the VR matrix reflect the participation of each industry in the sum of the gross output of a set of industries associated with a given emission. For the energy and industrial process emissions, the entries in the matrix's rows reflect the industry's share in the intermediate consumption of a given fuel or input responsible for generating such emissions. Finally, in the lines referring to the land use sector, the values reflect the participation of each industry in the deforested area from year t-1 to year t, where v is a summation vector of dimension *1xI*, v' equals v transposed, and $\otimes$ and $\oslash$ represent Hadamard cell-by-cell multiplication and division.

From SE, it is possible to estimate the total emissions by industry, as in Equation 5:

$$\boldsymbol{e_i} = \sigma' * (\widehat{\boldsymbol{GHG_s}} * \boldsymbol{SE}) \tag{5}$$

$\widehat{\boldsymbol{GHG_s}}$ is a diagonal matrix whose main diagonal entries represent the inventoried emissions in the SEEG table; and σ' is the summation vector of dimension Sx1. By multiplying $\widehat{\boldsymbol{GHG_s}} * \boldsymbol{SE}$, we obtain a matrix of dimension SxI containing the emissions for each row of inventoried emissions per industry. The pre-multiplication of this matrix by the summation vector results in the total emission by industry (e_i). Therefore, the emission vector of emission intensities (tCO_2e/BRL million of output) can be obtained, as in Equation 6, where $\boldsymbol{x_i}$ corresponds to the gross output by industry:

$$\widehat{\boldsymbol{E}} = \widehat{\boldsymbol{e_i}} \oslash \widehat{\boldsymbol{x_i}} \tag{6}$$

IV. The structural GHG emissions profile

Chapter 3 will present a structural profile of Brazil for the period 2000-2019, focusing on questions such as:

(i) How are Brazilian GHG emissions distributed across Brazilian industries, and how did these emissions evolve between 2000 and 2019?

(ii) What is the contribution of each final demand to Brazilian GHG emissions?

(iii) Which are the most carbon-intensive industries and final demand components?

(iv) Which industries have the highest potential to pull emissions from and propagate emissions to other sectors?

To answer these questions, the emission vectors generated above will be applied to Equation 2. However, instead of using a generic pollutant indicator ($\widehat{\boldsymbol{P}}$), a diagonal matrix[28] will be used ($\widehat{\boldsymbol{E}}$), with the main diagonal composed of the elements from the emission vector ($\widehat{\boldsymbol{E}}$), as shown in Equation 7:

$$\boldsymbol{e} = \widehat{\boldsymbol{E}}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \tag{7}$$

[28] $\widehat{\boldsymbol{E}} = \boldsymbol{\vartheta I}$, where I is an identity matrix of dimension 42x42.

As previously mentioned, one major advantage of specifying the model, as in Equation 7, rather than using the Leontief approach, is that it provides a clearer understanding of how industries demand emissions from or propagate them to one another. This can be done through the Leontief environmentally extended inverse matrix ($\tilde{\boldsymbol{L}}$), which can be obtained by multiplying $\widehat{\boldsymbol{E}}$ by $(\boldsymbol{I}-\boldsymbol{A})^{-1}$. In this matrix, cell $\widetilde{l_{ij}}$ represents the direct and indirect impact on the emissions of activity j resulting from a unit increase in the output of activity i.

Therefore, analogously, we can define the emission backward linkage ($\widetilde{BL}$) as the summation of the elements in column j. This indicator can be estimated as in Equation 8 and measures the total emissions generated when the final demand for output from industry j increases by one unit (see Equation 8). Conversely, the summation of the n elements in row i represents what we call emission forward linkage ($\widetilde{FL}$), which is a measure of total emissions generated by industry i when the demand for output from all other industries increases by one unit (see Equation 9).

$$\widetilde{BL_j} = v\,\tilde{L} = \sum_{i=1}^{42} \tilde{L}_{ij} \tag{8}$$

$$\widetilde{FL_i} = \tilde{L}\,v' = \sum_{j=1}^{42} \tilde{L}_{ij} \tag{9}$$

Where v is a diagonal matrix with ones in the main diagonal and v' equals v transposed.

Based on these indicators, we can obtain the power of dispersion of emissions ($\widetilde{PD_j}$) and the sensitivity of dispersion of emission ($\widetilde{SD_i}$), as in Equations 10 and 11. The former is a relative measurement of the impact of an increase of one unit in the final demand of industry j on other industries' emissions. In other words, the power of dispersion of emissions provides a measurement of the capacity of industry j to drive emissions in other industries. An industry with $\widetilde{PD_j}$> 1 has a stronger-than-average capacity to pull emissions from other industries when its production increases. Conversely, the sensitivity of dispersion of emissions provides a relative measurement of how sensitive emissions from industry i are to a unit increase in the demand of all other industries. An industry with $\widetilde{SD_i}$> 1 exhibits a higher-than-average increase in emissions when the demand for production across all industries rises.

$$\widetilde{PD_j} = \frac{\sum_{i}^{42} \tilde{\boldsymbol{L}}_{i,j}}{\frac{1}{42}\sum_{j=1}^{42}\sum_{i=1}^{42} \tilde{\boldsymbol{L}}_{i,j}} \tag{10}$$

$$\widetilde{SD_i} = \frac{\sum_{j=1}^{42} \tilde{\boldsymbol{L}}_{ij}}{\frac{1}{42}\sum_{i=1}^{42}\sum_{j=1}^{42} \tilde{\boldsymbol{L}}_{i,j}} \tag{11}$$

V. Structural decomposition analysis of GHG emissions

Chapter 4 conducts three structural decomposition analyses of Brazilian GHG emissions. Two of them concentrate on the country's total emissions, aiming at identifying the main drivers of emissions changes between 2000 and 2019. The first decomposition will focus on investigating the contribution of changes in output level and composition to the country`s emissions. The second will investigate aspects such as changes in technology and inter-industry density, both in final demand and in deforestation rates. The final SDA will analyze emissions from Brazilian exports. The methodological steps of each SDA are presented below.

V.1 Structural decomposition analysis of Brazilian GHG emissions

V.1.1. The impact of changes in emission intensity and output scale and composition changes

Equation 12 defines the total emissions, where $\boldsymbol{e}$ is a 42x1 vector denoting total GHG emissions by industry, $\widehat{\boldsymbol{E}}$ is a 42x42 diagonal matrix with elements on the main diagonal representing each industry's emission intensity (GHG emissions per unit of output) and $\boldsymbol{x}$ is the 42x1 vector of output by industry.

$$\boldsymbol{e} = \widehat{\boldsymbol{E}}.\boldsymbol{x} \quad \textbf{(12)}$$

Now, let $\boldsymbol{x}$ be written as $\boldsymbol{x} = (\boldsymbol{i}.\boldsymbol{x})\boldsymbol{x}(\boldsymbol{i}.\boldsymbol{x})^{-1}$, where i` is the summation vector with all its elements equaling 1. Defining $\boldsymbol{k} = \boldsymbol{x}.(i.\boldsymbol{x})^{-1}$, $s = (\boldsymbol{i}.\boldsymbol{x})$, we have $\boldsymbol{e} = \widehat{\boldsymbol{E}}.\boldsymbol{k}.s$, where $\boldsymbol{k}$ and s represent the share of each industry in total gross output and the magnitude of gross output, respectively.

There are many ways to decompose the variations in **e**, and each of them will result in different values for the contribution of $\widehat{\boldsymbol{E}}$, $\boldsymbol{k}$, and s. However, a commonly accepted approach to avoid extensive decompositions is to take the average of two polar decompositions (Dietzenbacher and Los,1998), as shown in Equation 13.

$$\Delta \boldsymbol{e} = \frac{1}{2}\Delta\widehat{E}(\boldsymbol{k_1}.\boldsymbol{s_1} + \boldsymbol{k_0}.\boldsymbol{s_0}) + \frac{1}{2}\left(\widehat{\boldsymbol{E}}_0.\Delta\boldsymbol{k}.\boldsymbol{s_1} + \widehat{\boldsymbol{E}}_1.\Delta\boldsymbol{k}.\boldsymbol{s_0}\right) + \frac{1}{2}(\widehat{\boldsymbol{E}}_0.\boldsymbol{k_0} + \widehat{\boldsymbol{E}}_1.\boldsymbol{k_1}).\Delta\boldsymbol{s} \quad \textbf{(13)}$$

This equation shows that the total emission changes can be decomposed into three elements: (i) the intensity effect, which results from a variation in the industries' emission intensities; (ii) the structure effect, which measures the variation in total emissions due to changes in gross output composition; (iii) the scale effect, which measures the emissions changes resulting from variations in the gross output scale. Table 4 presents the algebraic form and description of each decomposition term.

Table 4 - Structural decomposition of Brazilian GHG emissions

Effects	Algebraic form	Description
Emission intensity effect	$\frac{1}{2}\Delta\hat{\boldsymbol{E}}(\boldsymbol{k}_1.\boldsymbol{s}_1 + \boldsymbol{k}_0.\boldsymbol{s}_0)$	Measures GHG emission changes due to alteration in industries\` emission intensity (including LUC emissions). A positive (negative) sign means the industries require more (fewer) emissions to produce one unit of gross output.
Structure effect	$\frac{1}{2}(\hat{\boldsymbol{E}}_0.\Delta\boldsymbol{k}.\boldsymbol{s}_1 + \hat{\boldsymbol{E}}_1.\Delta\boldsymbol{k}.\boldsymbol{s}_0)$	Measures emission changes due to variations in output composition. A positive (negative) sign means that more (fewer) emissions are being generated as the economic structure approaches (moves away from) more emission-intensive industries.
Output scale effect	$\frac{1}{2}(\hat{\boldsymbol{E}}_0.\boldsymbol{k}_0 + \hat{\boldsymbol{E}}_1.\boldsymbol{k}_1).\Delta\boldsymbol{s}$	Measures emission changes due to variations in the scale of domestic output. A positive (negative) sign means that more (fewer) emissions are being generated due to an increase (decrease) in total output.

Source: author's elaboration

V.1.2. The impact of changes in emission intensities, final demand structure, demand leakage and technology

The decomposition above allows a clear view of how changes in industries\` emission intensity, economic activity level, and output composition affect GHG emissions. Even though it helps to provide important evidence on whether the recent structural changes in the Brazilian economy dealt with in Chapter 1 are pushing the country towards emission-intensive sectors, some other aspects may remain unseen, such as how demand forces interact with each industry\`s technology and environmental efficiency, with the interindustry fabric and trade pattern to generate emissions. More precisely, this second decomposition allows us to understand how changes in these components leads to emissions in the analyzed period.

Departing from the Equation 12, we can write $\boldsymbol{x}$ as $\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}.\boldsymbol{f}$, where $\boldsymbol{A}$ is the domestic direct coefficient matrix, $(\boldsymbol{I} - \boldsymbol{A})^{-1} = \boldsymbol{L}$, which is the Leontief inverse matrix, and $\boldsymbol{f}$ is the vector of final demand for domestic production. Therefore, we can decompose $\boldsymbol{e}$ as follows:

$$\Delta \boldsymbol{e} = \Delta \widehat{E}.\frac{1}{2}(\boldsymbol{L_0 f_0} + \boldsymbol{L_1 f_1}) + \frac{1}{2}\left(\widehat{\boldsymbol{E}}_1 \Delta \boldsymbol{L f_0} + \widehat{\boldsymbol{E}}_0 \Delta \boldsymbol{L f_1}\right) + \frac{1}{2}(\widehat{\boldsymbol{E}}_1 \boldsymbol{L_1} + \widehat{\boldsymbol{E}}_0 \boldsymbol{L_0})\Delta \boldsymbol{f} \quad \textbf{(14)}$$

V.1.2.1 Elements behind changes in the sectoral emission intensity matrix

Let's define $\widehat{\boldsymbol{E}} = \widehat{\boldsymbol{G}}.\widehat{\boldsymbol{\beta}}$**,** then $\Delta\widehat{\boldsymbol{E}}$ can be written as a result of weighted changes in $\widehat{\boldsymbol{G}}$ and $\widehat{\boldsymbol{\beta}}$, as in Equation 15**.**

$$\Delta \widehat{\boldsymbol{E}} = \frac{\boldsymbol{1}}{\boldsymbol{2}}\Delta \widehat{\boldsymbol{G}}(\widehat{\boldsymbol{\beta}}_{\boldsymbol{0}} + \widehat{\boldsymbol{\beta}}_{\boldsymbol{1}}) + \frac{\boldsymbol{1}}{\boldsymbol{2}}(\widehat{\boldsymbol{G}}_{\boldsymbol{0}} + \widehat{\boldsymbol{G}}_{\boldsymbol{1}})\Delta \widehat{\boldsymbol{\beta}} \quad \textbf{(15)}$$

Matrix $\widehat{\boldsymbol{G}}$ is analogous to matrix $\widehat{\boldsymbol{E}}$. However, the elements in the main diagonal in the former matrix represent emission intensity by industry, excluding land use change emissions. $\widehat{\boldsymbol{\beta}}$ is a diagonal matrix where the elements in the main diagonal represent the augmenting factor for each industry's emission intensity due to the inclusion of emissions from land use change. In other words, Equation 16 breaks the variation in emission intensity ($\Delta\widehat{\boldsymbol{E}}$**)** into two other effects: (i) carbonization effect ($\Delta\widehat{\boldsymbol{G}}$); (ii) deforestation effect ($\Delta\,\widehat{\boldsymbol{\beta}}$**)**.

The carbonization effect measures how total GHG emissions change due to gains (or losses) in environmental efficiency,[29] which may result from changes in the energy matrix (towards a less pollutant or more efficient source of energy), increases in the productivity of livestock production, the installation of more efficient filters to deal with fugitive emissions from industrial processes, improvements in the conditions of landfilling, and the construction of waste-to-energy plants that reduce emissions from waste, among other factors. Conversely, the deforestation effect measures the "*extra emissions*" generated by land use change in industries` emission intensities.

Despite the already mentioned methodological difficulties in dealing with land use change in input-output modeling, this source of emissions is too large (around 50% of the total) to be disregarded. Nevertheless, due to its high share of Brazilian emissions, land use change can dominate the trend of total emissions and overshadow important developments, such as changes in energy intensity or in the energy matrix. As seen in Chapter 1 (Graph 4), Brazilian emissions went through a steep decline between 2005 and 2012, when deforestation control policies became more stringent. However, when the land use sector was excluded, Brazilian emissions revealed an increasing trend during the entire period under review for all other emitting sectors.

[29] Environmental efficiency here is expressed only in terms of GHG emissions per unit of output.

Here, a trade-off emerges. On the one hand, land use change should be taken into account, due to its high relevance for Brazilian emissions. On the other, it is precisely this high relevance that can obscure other transformations impacting either aggregate or sectoral emissions. To deal with this problem, we propose a decomposition that isolates the effect of deforestation on both total emissions and on emission intensity by industry. This is done by incorporating $\widehat{\boldsymbol{\beta}}$ as a term for environmental inefficiency caused by deforestation.

V.1.2.2 Elements behind changes in output

As seen in Chapter 1, one of the main issues highlighted in the literature analyzing Brazilian deindustrialization is the de-densification of the productive structure, driven by a marked process of import penetration. To investigate the impact of this on Brazilian GHG emissions, we can express changes in L as a result of changes in A, more specifically as: $\Delta \boldsymbol{L} = \boldsymbol{L_1} \Delta \boldsymbol{A} \boldsymbol{L_0}$.[30]

Now, let us define $\boldsymbol{A} = \boldsymbol{\Lambda} \otimes \boldsymbol{A^t}$, where the domestic technical coefficient matrix, $\boldsymbol{A}$, is written as a portion of the total direct coefficient matrix $\boldsymbol{A^t}$, which includes both domestic and imported inputs. The term $\boldsymbol{\Lambda}$ is the matrix of domestic content of $\boldsymbol{A^t}$, i.e., the share of total inputs that are domestically produced and $\otimes$ is the cell-by-cell product. Then, using the additive decomposition form proposed by Rose and Casler (1996), we can decompose changes in $\boldsymbol{A}$ as in Equation 16:

$$\Delta \boldsymbol{A} = \frac{1}{2}(\Delta \boldsymbol{\Lambda} \otimes \boldsymbol{A_1^t} + \Delta \boldsymbol{\Lambda} \otimes \boldsymbol{A_0^t}) + \frac{1}{2}(\boldsymbol{\Lambda_0} \otimes \Delta \boldsymbol{A^t} + \boldsymbol{\Lambda_1} \otimes \Delta \boldsymbol{A^t}) \qquad \textbf{(16)}$$

Therefore, changes in emissions due to variations in intermediate coefficients ($\Delta \boldsymbol{A}$) result from alterations in share of domestic content of inputs ($\Delta \boldsymbol{\Lambda}$), and in technology ($\Delta \boldsymbol{A^t}$). The variation in the share of domestic inputs will be use as a proxy for changes in the interindustry density[31], in line with studies such as Morceiro (2012), Morceiro and Guilhoto 2020, Marcato, Dweck and Montanha (2022) and Montanha, Dweck and Summa (2022).

V.1.2.3. Elements behind changes in the final demand vector

Changes in final demand can result either from variations in factors relating to domestic absorption or from demand leakage to imports. When it comes to emission changes due to

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[30] For a demonstration of the algebraic steps followed to achieve Equation 6, see Miller and Blair (2009)

[31] As put by Montanha, Dweck and Summa (2022: p.15), changes in the share of domestic content of input "*It quantifies the capacity of domestic production chains to meet the consecutive stages through which intermediates are transformed. In other words, how much and to what extent intersectoral linkages are supplied by the national productive structure*."

domestic absorption, this can stem from the scale of final demand, its sectoral composition, or changes in the share held by each final demand component, as they exhibit quite different emission intensities per dollar spent[32].

To isolate these effects, we can express the domestic final demand vector $\boldsymbol{f}$, of dimension 42x1, as a result of the multiplication of $\boldsymbol{F^c}$ by $\boldsymbol{j}$, where the former element is a 42x5 matrix of final demand distributed across its c components, and the latter is a summation vector of dimension cx1 (see Equation 17). Analogously, we can write $\boldsymbol{f}$ as a result of the multiplication of the matrix of the share of each industry in the c categories of final demand, $\boldsymbol{F^m}$, by a vector of the total value of final demand by category $\boldsymbol{f^{cs}}$, as in Equation 18.[33] Finally, we can write $\boldsymbol{f}$ as a result of the multiplication of $\boldsymbol{F^m}$ by $\boldsymbol{f^{cm}}$ and f^s, where $\boldsymbol{f^{cm}}$ represents a cx1 vector of the shares of each of the c categories of final demand in the total final demand, and f^s is the scalar of total final demand (see Equation 19).

$$\boldsymbol{f} = \boldsymbol{F^c}.\boldsymbol{j} \tag{17}$$

$$\boldsymbol{f} = \boldsymbol{F^m}\boldsymbol{f^{cs}} \tag{18}$$

$$\boldsymbol{f} = \boldsymbol{F^m}.\boldsymbol{f^{cm}}.f^s \tag{19}$$

Breaking down the final demand to isolate the effects of import penetration is particularly relevant to the purposes of this thesis, given that an important stream of literature on recent structural changes in Brazil attributes to this factor the poor performance of the Brazilian manufacturing sector both domestically and in the country's exports.[34]

As seen in Chapter 1, from an environmental standpoint, demand leakages from imports result in cross-boundary pollution displacement, meaning that whenever a country substitutes domestic production for imports, its emissions tend to fall at the cost of emissions rising elsewhere. The net environmental impact of this displacement will depend on the GHG emission intensity of each industry engaged in the production of this particular good or service in the importer country and exporter country.

To investigate the impact of import penetration on Brazilian GHG emissions between 2000-2019, we can express $\boldsymbol{F^m}$ as a proportion of the total final demand, which includes demand for

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[32] Chapter 3 will present GHG emission intensities for all final demand components, with and without land use change.

[33] $\boldsymbol{F^m}$is a matrix of dimension 42xc, while $\boldsymbol{f^{cs}}$is a vector of dimension cx1.

[34] For more on the debate on deindustrialization, see Chapter 1.

final goods and services whether produced domestically or imported. In Equation 20, $\boldsymbol{F^m}$ is written as the result of a cell-by-cell multiplication between $\boldsymbol{F^i}$, a 42xC matrix with the share of the domestic content of final demand by industry of each of the c categories, and $\boldsymbol{F^{mt}}$, a 42xC matrix whose entries correspond to the share of each industry in the c categories of total final demand, which includes both domestically produced and imported final goods and services.

$$\boldsymbol{F^m} = (\boldsymbol{F^i} \otimes \boldsymbol{F^{mt}}) \tag{20}$$

Therefore, we can write final demand as $\boldsymbol{f} = (\boldsymbol{F^i} \otimes \boldsymbol{F^{mt}})\boldsymbol{f^{cm}} f^s$, which allows its decomposition as follows in Equation 21.

$$\Delta \boldsymbol{f} = \frac{1}{2}\left[(\Delta \boldsymbol{F^i} \otimes \boldsymbol{F})\boldsymbol{f_0^{cm}} f_0^s + (\boldsymbol{F_1^i} \otimes \Delta \boldsymbol{F^{mt}})\boldsymbol{f_0^{cm}} f_0^s + (\boldsymbol{F_1^i} \otimes \boldsymbol{F_1^{mt}})\Delta \boldsymbol{f^{cm}} f_0^s + (\boldsymbol{F_1^i} \otimes \boldsymbol{F_1^{mt}})\boldsymbol{f_1^{cm}} \Delta f^s\right] + \frac{1}{2}\left[(\Delta \boldsymbol{F^i} \otimes \boldsymbol{F_1^{mt}})\boldsymbol{f_1^{cm}} f_1^s + (\boldsymbol{F_0^i} \otimes \Delta \boldsymbol{F^{mt}})\boldsymbol{f_1^{cm}} f_1^s + (\boldsymbol{F_0^i} \otimes \boldsymbol{F_0^{mt}})\Delta \boldsymbol{f^{cm}} f_1^s + (\boldsymbol{F_0^i} \otimes \boldsymbol{F_0^{mt}})\boldsymbol{f_0^{cm}} \Delta f^s\right] \tag{21}$$

V.1.2.4. Final decomposition

Substituting 15, 16, and 21 into Equation 14, we obtain a final decomposition. As a result, changes in Brazilian GHG emissions can be written as the sum of the following effects, whose algebraic form is expressed in Table 5.

$$\Delta e = \Delta e_c + \Delta e_d + \Delta e_\Lambda + \Delta e_T + \Delta e_{fdl} + \Delta e_{dp} + \Delta e_{ds} \tag{22}$$

Table 5 - Structural decomposition of Brazilian GHG emissions

Effects	Algebraic form	Description
Carbonization effect ($\Delta \boldsymbol{e_c}$)	$\frac{1}{4}\Delta\widehat{\boldsymbol{G}}(\widehat{\boldsymbol{\beta}}_0 + \widehat{\boldsymbol{\beta}}_1)(\boldsymbol{L_0 f_0} + \boldsymbol{L_1 f_1})$	Measures emission changes due to alteration in industries` emission intensity (excluding LUC emissions). A positive (negative) sign means the industries require more (fewer) emissions to produce one unit of gross output.
Deforestation effect ($\Delta \boldsymbol{e_d}$)	$\frac{1}{4}(\widehat{\boldsymbol{G}}_0 + \widehat{\boldsymbol{G}}_1)\Delta\widehat{\boldsymbol{\beta}}(\boldsymbol{L_0 f_0} + \boldsymbol{L_1 f_1})$	Measures emission changes due to augmentation of industries` emission intensity when LUC emissions are considered. A positive (negative) sign means the economy's industries are becoming more (less) intensive in emissions due to deforestation rates increasing (decreasing).

Productive de-densification effect (Δe_{Λ})	$\frac{1}{4}\left\{\hat{E}_0[L_1([\Delta\boldsymbol{\Lambda} \otimes (A_0^t + A_1^t)])L_0]f_1 + \hat{E}_1\left[L_1\left(\frac{1}{2}[\Delta\boldsymbol{\Lambda} \otimes (A_0^t + A_1^t)]\right)L_0\right]f_0\right\}$	Measures emission changes due to variations in intermediate demand domestic content. A positive (negative) sign means that more (fewer) emissions are being generated due to an increase in the share of domestic inputs. The higher the domestic share, the higher the production of inputs and, thus, of related emissions.
Technological effect (Δe_T)	$\frac{1}{4}\left\{\hat{E}_0[L_1([(\boldsymbol{\Lambda}_0 + \boldsymbol{\Lambda}_1) \otimes \Delta A^t])L_0]f_1 + \hat{E}_1\left[L_1\left(\frac{1}{2}[(\boldsymbol{\Lambda}_0 + \boldsymbol{\Lambda}_1) \otimes \Delta A^t]\right)L_0\right]f_0\right\}$	Measures emission changes due to variations in the efficiency of the use of inputs. A negative (positive) sign means that fewer (more) inputs are now required to produce a given amount of output, thereby resulting in fewer(more) emissions.
Final demand leakage effect (Δe_{fl})	$\frac{1}{4}(\hat{E}_0L_0 + \hat{E}_1L_1)\{[(\Delta f^i \otimes f_1^{mt})f_1^{cm}f_1^s + (\Delta f^i \otimes f_0^{mt})f_0^{cm}f_0^s]\}$	Measures emission changes due to variations in the share of final demand met by imported goods and services. A positive (negative) sign means that more (fewer) emissions are being generated as a higher (lower) share of final demand is met by domestic production.
Final demand scale effect (Δe_{ds})	$\frac{1}{4}(\hat{E}_0L_0 + \hat{E}_1L_1)\{[(f_0^i \otimes f_0^{mt})f_0^{cm} + (f_1^i \otimes f_1^{mt})f_1^{cm}]\Delta f^s\}$	Measures emission changes due to variations in the scale of final demand. A positive (negative) sign means that more (fewer) emissions are being generated due to an increase (decrease) in final demand.
Change in final demand product mix (Δe_{dp})	$\frac{1}{4}(\hat{E}_0L_0 + \hat{E}_1L_1)\{[(f_0^i \otimes \Delta f^{mt})f_1^{cm}f_1^s + (f_1^i \otimes \Delta f^{mt})f_0^{cm}f_0^s]\}$	Measures emission changes due to variations in the sectoral composition of final demand. A positive (negative) sign means that more (fewer) emissions are being produced because final demand is shifting towards sectors with higher (lower) carbon emission intensities.
Change in final demand composition	$\frac{1}{4}(\hat{E}_0L_0 + \hat{E}_1L_1)\left\{\frac{1}{4}[(f_0^i \otimes f_0^{mt})\Delta f^{cm}f_1^s + (f_1^i \otimes f_1^{mt})\Delta f^{cm}f_0^s]\right\}$	Measures emission changes due to variations in the shares of each final demand component. A positive (negative) sign means more (fewer) emissions are being produced as final demand is shifting towards (away from) more emission-intensive components.

Source: author`s elaboration

V.2. Structural decomposition analysis of export emissions

As seen in Chapter 1, various studies point to an intense process of regressive specialization of Brazil's export basket. To assess the impact of this process on Brazil's environmental performance, we shall undertake an analysis of the emissions from the country's exports. This analysis will be conducted in Chapter 4, where the results of a decomposition of export-related emissions will shed light on whether Brazil's regressive specialization in its export basket has impacted the country's emission levels, to what extent, and during which periods this process was most intense.

In this section, we present the methodology employed in this decomposition. Let`s denote the emissions from exports, as $\boldsymbol{e_{\Phi}}$, $\boldsymbol{L}$ is the Leontief inverse matrix**,** and where $\boldsymbol{\Phi}$ represents a 42x5 matrix of Brazilian exports opened by the following trading partners: China, the United States, the European Union, Latin America, and the Caribbean, and the rest of the world (Equation 23). We break down exports by trading partners, recognizing that the Brazilian export basket varies by country and region.[35]

$$\boldsymbol{e_{\Phi}} = \boldsymbol{\hat{E}.L.\Phi} \tag{23}$$

Thus, emissions from exports can be decomposed as in Equation 24.

$$\Delta \boldsymbol{e_{\Phi}} = \left(\frac{1}{2}\right)(\Delta\boldsymbol{\hat{E}})(\boldsymbol{L_0\Phi_0} + \boldsymbol{L_1\Phi_1}) + \left(\frac{1}{2}\right)\left[\boldsymbol{\hat{E}}_0(\Delta\boldsymbol{L})\boldsymbol{\Phi_1} + \boldsymbol{\hat{E}}_1(\Delta\boldsymbol{L})\boldsymbol{\Phi_0}\right] + \left(\frac{1}{2}\right)\left[\boldsymbol{\hat{E}}_0\boldsymbol{L_0} + \boldsymbol{\hat{E}}_1\boldsymbol{L_1}\right)\Delta\boldsymbol{\Phi} \tag{24}$$

The decomposition of $\Delta\boldsymbol{\hat{E}}$ follows the same methodological steps already presented in Equation 15. As earlier, $\Delta\boldsymbol{\hat{E}}$ is broken into carbonization and deforestation effects. The former measures how industries` emission intensities and deforestation influence exports' emissions.

Meanwhile, as in the previously shown Equation 16, we can express changes in $\boldsymbol{L}$ as $\Delta\boldsymbol{L} = \boldsymbol{L_1}(\Delta\boldsymbol{A})\boldsymbol{L_0}$. Now, let $\boldsymbol{\mu}$ be the matrix of domestic content of the total direct coefficient. This means that **A** can be written as $\boldsymbol{A} = \boldsymbol{\mu} \otimes \boldsymbol{A^T}$**,** where $\mathbf{A^T}$ is the matrix of total technical coefficients (including both imported and national inputs) and ⊗ is the product of Hadamard, obtained by the cell-by-cell multiplication between two matrixes. As a result, changes in $\boldsymbol{A}$ can be decomposed as in Equation 25.

$$\Delta\boldsymbol{A} = \frac{1}{2}\Delta\boldsymbol{\mu} \otimes \left(\boldsymbol{A_1^T} + \boldsymbol{A_0^T}\right) + \frac{1}{2}(\boldsymbol{\mu_1} + \boldsymbol{\mu_0}) \otimes \Delta\boldsymbol{A^T} \tag{25}$$

[35] Castilho et al. (2017) highlighted that the Brazilian exports to countries in Latin America is profoundly different that the exports to other trading partners such as China, the EU and the US.

Therefore, we can write $\Delta \boldsymbol{L}$ as it follows in Equation 26, where the two terms on the right-hand side of the equation measure how changes in the input to output ratio (technology effect) and in the domestic content of inputs to produce exported Brazilian goods and services (productive de-densification effect) impact export emissions.

$$\Delta \boldsymbol{L} = \boldsymbol{L_1}\left[\frac{1}{2}\Delta\boldsymbol{\mu}\otimes\left(\boldsymbol{A_1^T} + \boldsymbol{A_0^T}\right)\right]\boldsymbol{L_0} + \boldsymbol{L_1}\left[\frac{1}{2}(\boldsymbol{\mu_1} + \boldsymbol{\mu_0})\otimes \Delta\boldsymbol{A^T}\right]\boldsymbol{L_0} \tag{26}$$

Finally, we can decompose $\Delta\boldsymbol{\Phi}$ by defining $\boldsymbol{\Phi} = [\boldsymbol{\varphi_1}, \dots, \boldsymbol{\varphi_5}]$, where $\boldsymbol{\varphi_1}$ represents the exports by industry destined to trading partner 1. Then, we have:

a) $\boldsymbol{\Phi i} = \boldsymbol{\varphi}$, a 1xn vector of exports by industry

b) $\boldsymbol{i'\Phi i} = \boldsymbol{i'\varphi} = \alpha$, which represents the level of total exports

c) $(\boldsymbol{i'\Phi})' = \lambda$, where λ_1 corresponds to total exports destined for trading partner 1.

We define $\boldsymbol{\eta}$ as a vector of the shares of each trading partner in Brazilian exports, as given in Equation 27:

$$\boldsymbol{\eta} = \left(\frac{1}{\varphi}\right)\lambda = \begin{bmatrix} \lambda_1/\alpha \\ \vdots \\ \lambda_5/\alpha \end{bmatrix} \tag{27}$$

Therefore, the sectoral composition of exports can be obtained, as in Equation 28:

$$\boldsymbol{\Psi} = \boldsymbol{\Phi}(\widehat{\nu\boldsymbol{\eta}})^{-\boldsymbol{1}} \tag{28}$$

Thus, $\Delta\boldsymbol{\Phi}$ is a result of three elements: (i) changes in the scale of Brazilian exports, $\Delta\alpha$; (ii) changes in the composition of the country's export basket, $\Delta\boldsymbol{\Psi}$; and (iii) changes in the weight of each trading partner in the Brazilian export basket $\Delta\boldsymbol{\eta}$.

$$\Delta\boldsymbol{\Phi} = \left(\frac{\boldsymbol{1}}{\boldsymbol{2}}\right)(\Delta\alpha)(\boldsymbol{\Psi_0\eta_0} + \boldsymbol{\Psi_1\eta_1}) + \left(\frac{\boldsymbol{1}}{\boldsymbol{2}}\right)[\alpha_0(\Delta\boldsymbol{\Psi})\boldsymbol{\eta_1} + \alpha_1(\Delta\boldsymbol{\Psi})\boldsymbol{\eta_0}] + \left(\frac{\boldsymbol{1}}{\boldsymbol{2}}\right)[\alpha_0\boldsymbol{\Psi_0} + \alpha_1\boldsymbol{\Psi_1})\Delta\boldsymbol{\eta} \tag{29}$$

Substituting Equations 15, 26, and 29 into Equation 24, we obtain the final decomposition for the emissions of exports. The algebraic form is presented in Table 6.

$$\Delta \boldsymbol{e_\Phi} = \boldsymbol{\Delta e_{\Phi c}} + \boldsymbol{\Delta e_{\Phi d}} + \boldsymbol{\Delta e_{\Phi \mu}} + \boldsymbol{\Delta e_{\Phi T}} + \boldsymbol{\Delta e_{\Phi \nu}} + \boldsymbol{\Delta e_{\Phi}} + \boldsymbol{\Delta e_{\Phi\Psi}} + \boldsymbol{\Delta e_{\Phi\eta}} \tag{30}$$

Table 6 - Structural decomposition of GHG emissions from Brazilian exports

Effects	Algebraic form	Description
Carbonization effect ($\Delta e_{\Phi c}$)	$\left(\frac{1}{4}\right)[\Delta\hat{G}(\hat{\beta}_0 + \hat{\beta}_1)](L_0\Phi_0 + L_1\Phi_1)$	Measures emission changes due to alteration in industries` emissions intensity (excluding LUC emissions). A positive (negative) sign means the industries require more (fewer) emissions to produce one unit of gross output.
Deforestation effect ($\Delta e_{\Phi d}$)	$\frac{1}{4}[(\hat{G}_0 + \hat{G}_1)\Delta\hat{\beta}](L_0\Phi_0 + L_1\Phi_1)$	Measures emission changes due to augmentation of industries` emissions intensity when LUC emissions are considered. A positive (negative) sign means Brazilian industries are becoming more (less) intensive in emissions due to an increase (decrease) in deforestation rates).
Productive de-densification effect ($\Delta e_{\Phi\mu}$)	$\left(\frac{1}{4}\right)[\hat{E}_0[L_1(\Delta\mu\otimes(A_1^T + A_0^T))L_0]\Phi_1 + \hat{E}_1[L_1[\Delta\mu\otimes(A_1^T + A_0^T)]L_0]\Phi_1]$	Measures emission changes due to variations in the intermediate demand domestic content. A positive (negative) sign means that more (less) emissions are being produced due to an increase in the share of domestic inputs used to produce exports. The higher the domestic share, the higher the production of inputs and, thus, of related emissions.
Technology effect ($\Delta e_{\Phi T}$)	$\left(\frac{1}{4}\right)[\hat{E}_0[L_1((\mu_1 + \mu_0)\otimes\Delta A^T)L_0]\Phi_1 + \hat{E}_1[L_1((\mu_1 + \mu_0)\otimes\Delta A^T)L_0]\Phi_0]$	Measures emission changes due to variations in the efficiency of use of inputs. A negative (positive) sign means that fewer (more) inputs are now required to produce a given amount of output, thereby resulting in fewer (more) emissions.
Scale effect ($\Delta e_{\Phi v}$)	$\left(\frac{1}{4}\right)(\hat{E}_0L_0 + \hat{E}_1L_1)[(\Delta\alpha)(\Psi_0\eta_0 + \Psi_1\eta_1)$	Measures emission changes due to variations in the scale of exports. A positive (negative) sign means that more (fewer) emissions are being generated due to an increase (decrease) in total export value.
Export Basket effect ($\Delta e_{\Phi\Psi}$)	$\left(\frac{1}{4}\right)(\hat{E}_0L_0 + \hat{E}_1L_1)[(\alpha_0(\Delta\Psi)\eta_1 + \alpha_1(\Delta\Psi)\eta_0)]$	Measures emission changes due to variations in the sectoral composition of exports. A positive (negative) sign means that more (fewer) emissions are being produced because the export basket is shifting towards sectors with higher (lower) emission intensities.
Trading partner effect ($\Delta e_{\Phi\eta}$)	$\left(\frac{1}{4}\right)(\hat{E}_0L_0 + \hat{E}_1L_1)[(\alpha_0\Psi_0 + \alpha_1\Psi_1)\Delta\eta]$	Measures emission changes due to variations in the shares of each trading partner in Brazilian exports. A positive (negative) sign indicates that Brazil is

		strengthening (weakening) its trade relations with countries for which exports in its basket are more (less) intensive in GHG emissions.

Source: author's elaboration

V.3. Period and sectoral aggregation

As mentioned, this thesis's analysis covers the period 2000-2019. The next chapter will present the trajectory of GHG emission across industries and final demand components, their emission intensities, and the emission backward and forward linkages for the Brazilian economy in the period under review. Based on the trends revealed in Chapter 3, Chapter 4 will investigate the main drivers of emission changes using the three structural decompositions presented above, two for total Brazilian emissions and the other focusing on emissions from Brazilian exports.

For the structural decomposition analysis, we break the entire period into five subperiods:

(i) **2000-2005:** a subperiod marked by modest economic growth mainly pulled by external factors and growing deforestation rates

(ii) **2005-2010:** a subperiod characterized by more robust economic growth mainly pulled by household consumption, which was reinforced by the expansion of public and private investments and the good performance of Brazilian exports, accompanied by a sharp decline in deforestation

(iii) **2010-2014:** a subperiod of economic deacceleration due to both internal and external factors and rising deforestation rate.

(iv) **2014-2019:** a subperiod of economic stagnation and rising deforestation rates.

(v) **2000-2019:** encapsulating the whole period and aiming to show which factors contributed the most to the emission changes during the two decades analyzed in this thesis.

Finally, we group the 42 industries into six industry groups based on the taxonomy proposed by Torraca and Kupfer (2014). Table 7 presents the industries belonging to each of the groups below:

(i) **agriculture, fishing, and related (AGR) group:** includes all activities associated with farming, fishing, hunting and forestry

(ii) **processed agricultural commodities (AC) group:** includes industries with high requirements of natural resources and energy that process and transform agricultural goods into highly homogeneous manufactured goods

(iii) **industrial commodities (IC) group:** includes natural-resource-intensive industries producing mineral ores, metal alloys, and basic chemical goods

(iv) **traditional manufacturing (TM) group:** includes industries engaging in the production of less technologically sophisticated manufactured goods with low production scale requirements, such as manufactured consumer goods, wage goods, industrial parts, and complements

(v) **innovative manufacturing (IM) group:** includes all activities producing more technologically sophisticated goods that are capable of leading the process of technology diffusion in the economy

(vi) **services (SR) group:** includes all industries engaged in service production.

Although this taxonomy was originally based on a discussion of competitive patterns, it is also convenient for the purpose of this thesis, as its sectoral aggregation puts together industries with similar environmental characteristics. For instance, the ARG and AC industry groups comprise industries whose production largely relies on living and renewable natural resources. Their direct emissions predominantly derive from some sort of organic matter transformation, such as deforestation, fertilizer use, enteric fermentation, and so on. In contrast, the IC Group deals with the extraction and industrial transformation of inorganic natural resources or non-living and non-renewable organic resources, such as oil. Most of the latter's direct emissions are associated with energy consumption and the release of fugitive gases during the industrial processing of these resources. When it comes to traditional and innovative manufacturing, the value added by these industries tends to be less intensive in terms of natural resources than the ARG, AC, and IC groups and most of their direct emissions come from energy use.

Table 7 - Industry aggregation groups

Industry groups	Industries
Agriculture, fishing, and related group	Agriculture, forestry, livestock and fisheries
Industrial commodities group	Extraction of oil and gas, including support activities
	Extraction of iron ore, including processing and agglomeration
	Other mining and quarrying
	Oil refining and coking plants
	Manufacture of biofuels
	Manufacture of other organic and inorganic chemicals, resins, and elastomers
	Cement and other non-metallic mineral products
	Manufacture of steel and its derivatives
	Metallurgy of nonferrous metals
	Metal products - exclusive machinery and equipment
Processed agricultural commodities group	Manufacture of tobacco products
	Manufacture of wood products
	Manufacture of pulp, paper, and paper products
Traditional industry group	Food and beverages
	Manufacture of textiles
	Manufacture of wearing apparel and accessories
	Manufacture of footwear and leather goods
	Printing and reproduction of recordings
	Perfumery hygiene and cleaning
	Manufacture of pesticides, disinfectants, paints, and various chemicals
	Rubber and plastics
	Furniture and products of various industries and machinery and equipment*
Innovative industry group	Pharmaceutical products
	Furniture and products of various industries and machinery and equipment*
	Household appliances and electronic material
	Automobiles, trucks, and buses
	Parts and accessories for motor vehicles
	Other transportation equipment
Services group	Electricity generation and distribution of gas, water, sewage, and urban cleaning
	Construction
	Trade
	Accommodation and food services
	Transport warehousing and mail
	Information services
	Financial intermediation insurance and supplementary pension and related services
	Real estate activities and rentals
	Business and family services and maintenance services
	Public administration, defense, and social security
	Public education
	Private education
	Public health
	Private health

Source: adapted from Torracca and Kupfer (2014) and Passoni (2019)

VI. Concluding remarks

As previously seen, an intense debate has emerged regarding recent structural changes in Brazil. Despite valuable contributions from the extensive literature on this topic, the environmental implications of these transformations have largely been overlooked. The few studies that have attempted to address these environmental repercussions are outdated and do not cover the period of greatest concern, during which, the literature suggests, the Brazilian economy experienced an accelerating process of regressive specialization.

To investigate the environmental repercussions of these structural changes, this thesis employs an input-output model extended to take account of GHG emissions resulting from Brazilian output production. This chapter presents the data sources and methodological steps used to construct emission vectors for Brazil and match them with the Brazilian IOTs estimated by Passoni and Freitas (2022). These emission vectors cover the period 2000-2019 and are disaggregated into 42 industries, which are subsequently grouped into six industry groups based on the taxonomy proposed by Torracca and Kupfer (2014). These vectors will be used in the analyses presented in Chapters 3 and 4.

Additionally, this chapter introduces three structural decomposition analyses to examine the impact of recent structural changes on Brazilian emissions. The first decomposition investigates the main drivers of total emission changes, considering factors such as variations in industries' emission intensity, output composition, and scale. This analysis aligns with the literature review on the environmental impacts of structural changes presented in Subsection III.1.2 of Chapter 1. Many studies explore changes in output composition to infer how structural change affects environmental sustainability, often using emissions and energy indicators.

The second decomposition analyzes how variations in domestic demand interact with changes in each industry`s technology and emission efficiency, as well as in the domestic content of intermediate and final demand to generate emissions. As seen in Chapter 1, some works point to an import penetration process in the manufacturing sector as one of the culprits of Brazilian deindustrialization with potential de-densification impacts on the Brazilian productive structure. Therefore, an SDA that deals with intermediate and final demand leakages to import can provide evidence of the impacts of import penetration on Brazilian GHG emissions. Analyzing the impact of final demand is also quite relevant for shedding light on the possible impact of variations in economic and export growth on emissions during the period under review.

The third decomposition investigates the main drivers of changes in emissions from Brazilian exports, focusing on factors such as scale, sectoral composition, and export destinations, acknowledging that Brazilian exports vary by trade partner. This decomposition aimed to assess the impact of regressive export specialization on the emissions embodied in Brazilian exports.

CHAPTER 3. THE BRAZILIAN STRUCTURAL PROFILE OF GHG EMISSIONS

I. INTRODUCTION

The extensive literature review conducted in Chapter 1 drew attention to a concerning structural change trajectory for the Brazilian economy towards an increasing regressive specialization for both productive structure and trade pattern. Even though many studies addressing this topic have found evidence of increasing specialization in natural-resource-intensive industries, the environmental repercussions of these structural changes have remained largely unheeded by the literature.

This thesis uses GHG emission-based indicators to investigate the environmental sustainability of recent structural changes in Brazil. During the period covered by this work, all IPCC sectors increased their emissions, except for land use change. Indeed, the emission decline experienced by the latter sector was just enough to compensate for the 39% emission increase from the other four sectors, so the total emission level in 2019 was roughly the same as the one observed in 2000.

Even though displaying emissions by IPCC sectors provides valuable information regarding the Brazilian emission trajectory, it falls short of informing whether and how the Brazilian economy is decarbonizing. Emission reductions can result from factors such as changes in the level of economic activity or even temporary shifts in a country's energy and power matrices. On the other hand, decarbonization is the process through which countries plan to achieve their carbon neutrality (IPCC, 2018). This process requires great structural transformation to support a permanent shift of old emission trajectories downwards, in alignment with the goals of the Paris Agreement (Altenburg and Assmann, 2017).

Chapter 2 presented a methodology for matching GHG emissions with the system of national accounts, allowing a clear view of how Brazil's economic structure and emissions relate to one another. This chapter draws on the previously created GHG emission vectors to investigate the Brazilian structural profile of GHG emissions between 2000 and 2019. By 'structural emissions profile,' we mean a characterization of Brazilian emissions based on their interconnection with the productive structure and demand forces. That is to say, this chapter unveils the emissions generated by the economic activity, based on how industries are interrelated rather than by IPCC emitting sectors. More specifically, this chapter seeks to answer the following questions:

(v) How are Brazilian GHG emissions distributed across industries, and how did industries` emissions evolve between 2000 and 2019?
(vi) What is the contribution of each final demand to Brazilian GHG emissions in the period under review?
(vii) Which are the most carbon-intensive industries and final demand components?
(viii) Which industries have the highest potential to pull emissions from and propagate emissions to other sectors?
(ix) What trends do emissions embedded in exports exhibit?

Addressing these allows for a better understanding of how the driving forces of economic growth in this period interact with the interindustry fabric and industries' emissions intensity to generate emissions. Doing this makes it possible to identify potentially concerning trends for Brazilian GHG emissions in this period, such as an increasing emission trajectory or emission intensity for a specific industry or particular final demand component.

One of these components, exports, is of particular interest to this thesis. As many studies maintain that Brazil has been through a reprimarization trajectory of its export baskets[36], this chapter provides an in-depth exploration of Brazilian export emissions to investigate how they changed over the analyzed period. This exploration complements the analysis of exports carried out in the section on emission trends by final demand components by breaking down export emissions by five trade partners, namely: China, the European Union (EU), the United States (US), Latin America and the Caribbean (LAC), and the rest of the world (RoW). Such an approach provides valuable information on whether and how shifts in trade patterns with specific partners impacted overall trends in emissions embedded in exports – an important consideration given the emergence of China as a global driving force of reprimarization.

Finally, given the great influence of deforestation on the trajectory of Brazilian emissions, land use change can overshadow other important elements and trends (for instance, the scale of final demand or a reduction in the emission intensity of agriculture due to the adoption of better technologies). Therefore, this chapter will present the results with and without land use change emissions to offer a more comprehensive view of the underlying factors at play.

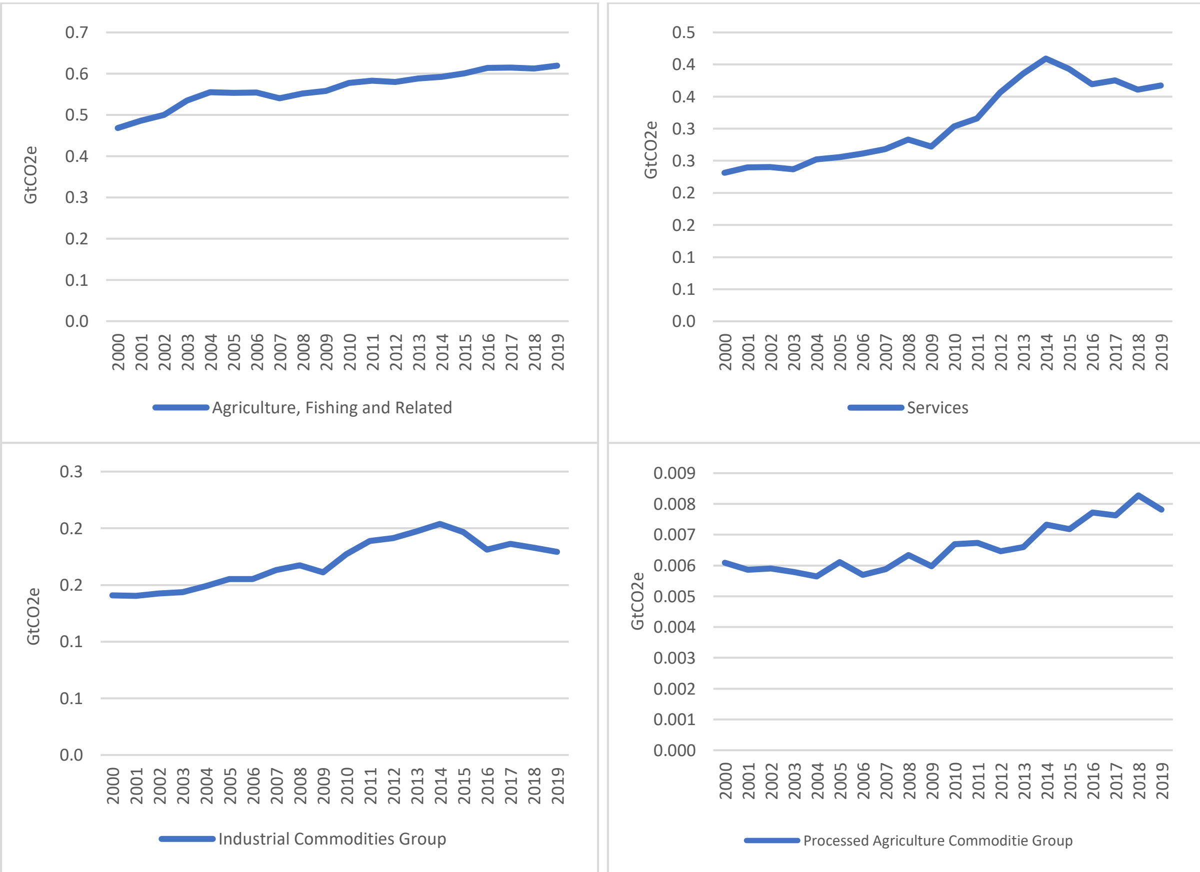
[36] For more on the literature about export reprimarization in Brazil, see Chapter 1, section IV.2.

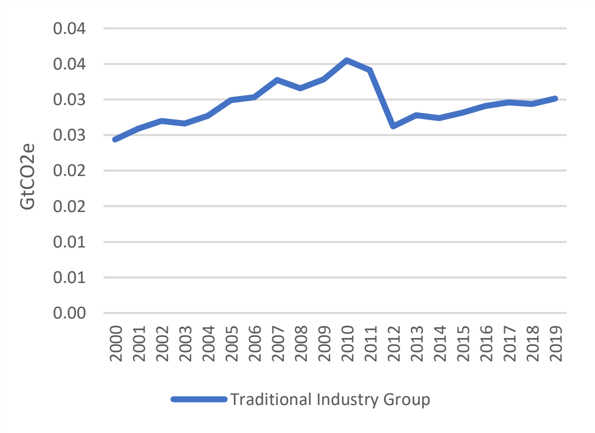
II. GHG emissions by industry group, excluding land use change emissions

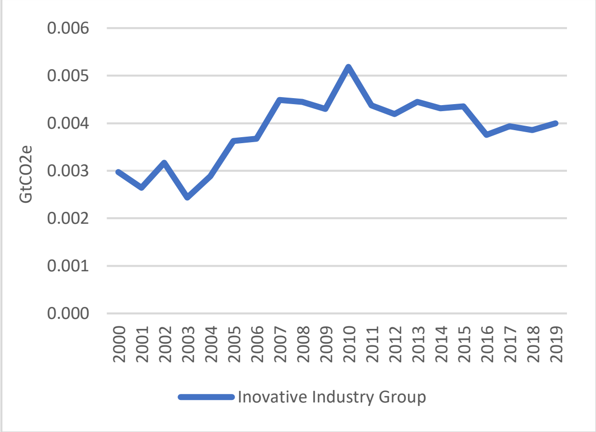
This section presents the GHG emissions for the six industry groups defined by Torraca and Kupfer (2014). It also examines the GHG emission intensity of each group and tracks how this intensity evolved over the period 2000–2019.

A common element across all industry groups during this period is that they all increased their emissions. However, these upward trajectories departed from very distinct emission levels and greatly differed in terms of acceleration phases, inflection points, and retraction stages (see Graph 7).

Graph 7 - GHG emissions by industry group







Source: author`s elaboration

The agriculture, fishing, and related (ARG) group began from the highest initial level of emission (around 0.5 $GtCO_2e$) and showed a steady increase over the entire period. ARG emissions grew particularly fast between 2000 and 2005, expanding by 18.3% compared to 4.3% in 2005-2010, 2.5% between 2010 and 2014, and 4.6% from 2014 to 2019. Interestingly, AGR emissions grew faster precisely when exports reached their greatest contribution to GDP growth (Graph 8). This is not a coincidence but reflects the fact that agriculture's share in total exports is higher than that of total GDP. So, whenever exports lead the process of economic growth, AGR emissions will tend to increase faster.

As Table 18 shows, from a demand-side perspective, AGR exports were the primary driver of total emission increases between 2000 and 2005. This also applies to 2014-2019, when the Brazilian economy slowed down, and exports remained as roughly the only final demand component growing at positive rates. We can see that AGR exports were the main factor driving emissions during the period covered by this thesis, accounting for 44.9% of all emission increases between 2000 and 2019.

The service sector emission trajectory was slightly flat in the first years and then accelerated from 2004 onward. This ascending trajectory accompanied a shifting of the economic growth engine from exports to the domestic market in the second half of the 2000s. However, the emissions from the services sector really took off from 2010 and 2015, a period marked by a cooling trend in the Brazilian economy.[37] The counterintuitive upsurge in emissions for this industry group is the combined result of a still good performance of household consumption, and an increasing reliance on thermoelectric plans for power generation. The latter fact is the

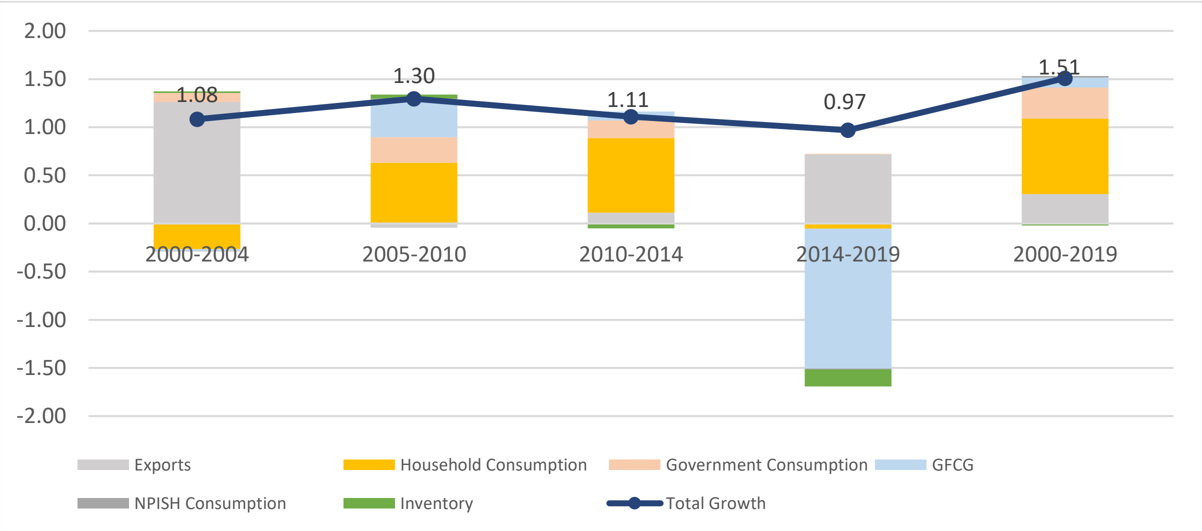
[37] While the average growth rate between 2005 and 2010 was 4.3% per year, it declined to 2.2% between 2010 and 2015 and dropped further, to -0.6%, from 2015 to 2019.

result of the rainfall regime consistently under the expected levels from 2010 and 2015, which culminated in a severe water crisis in 2014 and 2015 (ANA, 2014; Marengo et al., 2015). As water levels in hydroelectric reservoirs were greatly impacted, the country was pushed towards alternative and more polluting sources of power. The share of thermal power in the Brazilian power matrix more than doubled from 2010 to 2015 (EPE, 2021), while the emission factor per GWh increased by 87.3% (IEA, 2022).

It is important to remember that the methodology developed in Chapter 2 allocates energy-related emissions proportionally to each industry's intermediate consumption of the energy source responsible for those emissions. So, when thermal plants burn fossil fuel to produce power, the corresponding emissions are assigned to the service group, precisely to the "production and distribution of electricity, gas, water, sewage, and urban cleaning" industry. This means that shifts in the power matrix directly impact this industry group.

After the water crisis subsided in 2016, emissions from the service sectors went down a trend that was also reinforced by the poor performance of the Brazilian economy. Given the strong deceleration of domestic absorption between 2016 and 2019 (Graph 8), services emissions decreased across all final demand components, except for exports, between 2014 and 2019 (Table 8).

Graph 8 - Demand side growth accounting



Source: author`s elaboration

The emission trajectory of the industrial commodity (IC) group increased steadily from 2000 to 2015 (Graph 7). However, the IC emission drivers changed from one period to another. Between 2000 and 2005, IC emissions increased under a great influence of external factors, with exports accounting for 125.8% of all the emission growth for this industry group (Table 8). In the subsequent period, the domestic market took the lead in driving the IC emissions. During this period, gross fixed capital formation increased at higher rates, responding to investments undertaken in the Economic Acceleration Plan (PAC I), launched in 2007.[38] A second phase of PAC was announced in 2010, projecting investments for the 2011 and 2014 period. However, the contribution of gross fixed capital formation in driving IC emission during this period was moderated, as the Brazilian economy was already showing signs of economic slowdown, which brought private investments to lower levels.

Nevertheless, despite the deceleration of the Brazilian economy, IC emissions remained in an increasing trajectory up to 2015. The explanation for this trajectory in the first half of the 2010s cannot be found on the demand side. Despite the slight recovery of exports during this period, which indeed contributed to increasing IC emissions (Table 8), the evidence suggests that the already-mentioned water crisis exerted a great influence on the IC emissions trend by increasing the emission factor for power generation. Given the large amount of energy embedded in this industry group's output, the increase in emissions per kW resulted in a much higher emission intensity per million units of output produced.[39]

After 2015, the water crisis subsided as a result of improved rainfall levels, allowing hydroelectric power to recover its share in power generation. Meanwhile, domestic absorption dropped, alleviating the pressure of economic growth on this group's emission levels. In fact, exports were the only demand force acting for IC emission increase in this period (Table 8).

Emissions from the processed agricultural commodities (AC) group initially declined during the first five years of the series, driven primarily by reductions in household consumption and GFCF. However, in 2005, emissions rebounded and began a sustained upward trajectory that continued until the end of the period. In the late 2000s, this increase was largely fueled by domestic absorption as economic growth accelerated. However, from 2011 onward, as domestic absorption cooled down, exports began to play an increasingly dominant role in driving emissions from this industry group. Indeed, between 2014 and 2019, exports had become the only final demand component contributing positively to AC emissions.

[38] According to Alvarenga et al. (2024), GHG emissions from public investments surged during this period due to increased demand for cement and metal alloys. This rise was driven by public investment growth, particularly after 2007 with the launch of the Growth Acceleration Plan (PAC). This trend lasted up until 2015, when the fiscal situation in Brazil deteriorated, and the country underwent sizable cuts in investment spending in an attempt to address fiscal imbalances.

[39] Table 9 shows that IC`s emission intensity increased 32.5% between 2008 and 2015.

Regarding the emissions from traditional manufacturing (TM) and innovative manufacturing (IM), both accelerated after 2004 and kept an upward trajectory up to 2010 (Graph 7). These industry groups` performance tends to rely more heavily on the dynamism of Brazilian internal markets (Passoni, 2019). Therefore, their emissions usually behaved procyclically, which helps to explain why emissions rose faster during period 2005-2010 and then dropped after 2011 for both groups.

After 2014, emissions from the traditional manufacturing (TM) group showed a slight recovery, while the emission trajectory of the IM group continued to decline. These divergent trends appear to stem from differences in demand for each group's output. Data show that while TM's gross output fell by 3.2% during this period, IM experienced a sharper decline of 14.9%.[40] Although both industry groups saw an increase in emissions intensity during this period, the decline in final demand appears to have outweighed the rise in emissions intensity for the IM group, leading to a reduction in its emissions. In contrast, the opposite occurred for the TM group, where the increase in emissions intensity more than offset the drop in final demand, resulting in overall emissions growth.

Table 8 - Demand-side emission growth accounting

Industry Group	2000-2005						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.559	0.010	0.001	0.049	0.033	0.101	0.753
IC	0.161	0.007	0.001	0.015	-0.009	-0.048	0.128
AC	0.002	0.000	0.000	0.000	0.000	-0.002	0.000
TM	0.029	0.001	0.000	0.021	0.000	-0.003	0.048
IM	0.004	0.000	0.000	0.001	0.001	0.000	0.006
Services	0.134	0.023	0.003	0.044	0.025	-0.015	0.214
Total	0.889	0.042	0.005	0.130	0.051	0.033	1.15
Industry Group	2005-2010						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	-0.050	0.021	-0.001	0.163	0.048	0.078	0.259
IC	-0.088	0.009	0.000	0.052	0.211	0.055	0.238
AC	-0.001	0.001	0.000	0.005	0.002	0.000	0.006
TM	-0.004	0.003	0.000	0.041	0.005	0.014	0.058
IM	-0.003	0.001	0.000	0.008	0.013	0.002	0.019
Services	-0.056	0.066	0.002	0.356	0.120	0.033	0.520
Total	-0.204	0.100	0.001	0.625	0.398	0.180	1.101

[40] Data from the input-output tables estimated by Passoni and Freitas (2022)

Industry Group	2010-2014						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.268	-0.020	-0.001	-0.031	-0.082	-0.016	0.119
IC	0.073	0.005	0.000	0.090	0.058	-0.009	0.216
AC	0.003	0.000	0.000	0.003	0.000	0.000	0.005
TM	-0.014	-0.003	0.000	-0.039	-0.003	-0.007	-0.066
IM	-0.002	0.000	0.000	-0.001	-0.003	-0.001	-0.007
Services	0.080	0.129	0.003	0.588	0.069	-0.010	0.859
Total	0.407	0.111	0.001	0.609	0.040	-0.044	1.125
Industry Group	2014-2019						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	1.507	-0.036	0.001	-0.388	-0.040	-0.334	0.710
IC	0.397	-0.028	-0.001	-0.243	-0.624	-0.150	-0.649
AC	0.031	-0.001	0.000	-0.006	-0.006	-0.006	0.013
TM	0.035	0.001	0.000	0.042	-0.006	0.000	0.073
IM	0.004	0.000	0.000	-0.003	-0.010	-0.001	-0.010
Services	0.161	-0.164	-0.008	-0.672	-0.365	-0.060	-1.107
Total	2.137	-0.227	-0.008	-1.270	-0.551	-1.051	0.970
Industry Group	2000-2019						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.617	-0.003	0.000	0.009	-0.014	0.017	0.626
IC	0.141	0.005	0.000	0.035	0.008	-0.030	0.159
AC	0.006	0.000	0.000	0.003	0.000	-0.002	0.007
TM	0.010	0.001	0.000	0.012	-0.001	0.000	0.023
IM	0.000	0.000	0.000	0.002	0.002	0.000	0.005
Services	0.107	0.076	0.002	0.350	0.036	-0.009	0.562
Total	0.884	0.079	0.002	0.411	0.031	-0.024	1.382

Source: authors` elaboration
*GFCF and NPISH consumption stand for: gross fixed capital formation and consumption of non-profit institutions serving households

Table 9 presents emission intensities by industries for the period 2000-2019. The first element that stands out is the great disparity of emission intensities across different industry groups. The AGR group was by far the most emission-intensive industry group in the Brazilian economy, followed by the IC group. Putting this disparity into perspective, these two groups exhibited average emission intensities 248.6 and 24.8 times bigger than that of innovative industry group.

Nevertheless, these two groups were the only one to experience sizable reduction in emission intensity over the analyzed period. While the AGR reduced its emissions by 19.9% between 2000 and 2019, the IC group saw a decline in its emission intensity of 27.7%.

The consistent drop in emission intensity in agriculture throughout the period 2000-2019 may result from a combination of factors, such as (i) productivity gains (Costa, 2022; World Bank, 2023), (ii) the adoption of low-carbon agricultural practices when the Low Carbon Agriculture Plan was launched (MAPA, 2023)[41]; and (iii) important sectoral output composition changes within agriculture.

Regarding the latter factor, Brazil has been experiencing a re-composition of land cover over the last two decades. Due to its high profitability, the soybean production area has been expanding rapidly. Compared to pasturelands, soy crops can yield a profit per hectare that is ten times higher in some areas of the country (ANUALPEC, 2014). Therefore, soybean production is taking over areas once dedicated to cattle ranching (Alvarenga, 2014), which seems to be contributing to a reduction in agriculture emission intensities through two channels. First, soy crops use land more productively, producing higher output per hectare – that is, the higher the share of soybean cultivation in total land cover, the higher the AGR output. Second, livestock production is associated with large quantities of methane emissions due to enteric fermentation. So, when soy crops replace pastureland, a higher share of AGR output is produced, decoupled from methane emissions.[42] As we will see later, reducing the emission intensity of the agriculture group can bring about a significant decarbonization effect throughout the economy, given its high emission forward linkages.

As for the IC group, its intensity dropped up until 2008, when the share of thermoelectric power began to increase. The IC group is very energy-intensive, so shifts in the energy or power matrices tend to impact greatly the emission factors of this group. Indeed, according to the SEEG (2024) database, the ICs' emissions stemming from the intermediate consumption of energy increased by over 20% between 2009 and 2015. This helps to explain the 32.9% increase in this group`s emission intensity in this period (Table 9).

[41] According to official data, between 2010 and 2020, the ABC Plan contributed to lowering emissions by 193.7 $MtCO_2e$.

[42] It is important to note that land use change emissions are not taken account of in this section. Otherwise, these calculations would need to consider the indirect influence of soybean cultivation on deforestation, which occurs when livestock is displaced by it into forested areas (Young, 1996; 2018; Alvarenga, 2014).

Table 9 - Emission intensity by industry group

Year	AGR	IC	AC	TM	IM	Services
2000	2,282.9	270.2	78.3	41.3	8.1	77.5
2001	2,288.3	254.1	80.1	43.5	6.8	80.2
2002	2,065.6	243.7	75.7	45.4	8.2	79.2
2003	1,961.0	216.7	67.7	42.4	6.1	81.4
2004	1,986.0	205.9	60.2	40.9	6.2	84.0
2005	2,234.2	201.4	70.5	44.7	7.6	81.3
2006	2,290.4	196.2	67.3	45.7	7.5	78.9
2007	2,081.7	201.4	67.3	47.4	8.5	75.9
2008	1,895.6	188.7	73.6	43.8	7.8	77.7
2009	2,027.1	219.7	76.7	47.4	8.5	70.8
2010	2,119.1	219.5	73.9	49.2	9.0	73.5
2011	1,933.1	219.0	77.9	45.7	7.7	73.6
2012	1,913.4	222.8	75.5	34.3	7.7	80.2
2013	1,812.7	223.9	77.4	35.8	7.8	84.3
2014	1,860.2	231.5	85.4	35.9	8.2	87.7
2015	1,853.4	250.1	86.9	38.3	9.6	86.5
2016	1,798.9	261.6	95.1	40.0	9.2	83.3
2017	1,851.6	260.0	92.0	40.9	9.1	83.7
2018	1,812.9	220.0	91.2	40.2	8.4	81.1
2019	1,827.9	211.5	87.5	40.8	8.6	81.2

Source: author`s elaboration.

The IM and TM groups, despite their low emission intensities, performed quite poorly. The former group presented a rather cyclical emission intensity from 2000 to 2019, ending the period with a higher emission intensity than it started. A concerning upward trend emerged for IM after 2011, despite the slight decrease in its emission intensity in the two last years. Meanwhile, the traditional manufacturing group (TM) reached its lowest emission intensity between 2011 and 2014 but then rebounded to approximately the same level as in 2000.

As mentioned above, the growth in emission intensity for the service group seems to be related to the increase in thermoelectric production during the first half of the 2010s. Indeed, a rise of 17.7% in the GHG intensity of services occurred between 2010 and 2015, coinciding with the period of escalating water scarcity.

Taking a broader view, it becomes clear that, aside from AGR and IC, all other groups performed relatively poorly in reducing emission intensity, achieving only modest reductions or even increasing emissions per unit of output. In other words, the groups more closely tied to exports saw the sharpest declines in emission intensity over the analyzed period.

The AGR and IC groups' superior performance may be the result of more stringent environmental regulation and growing scrutiny by international markets regarding the environmental standards for exported goods and services, which may have exerted pressure on the firms in these industry groups to innovate and adopt more sustainable techniques. The work of Porter and Van der Linde (1995) was pioneering in proposing environmental regulation as a potential driver of innovation and efficiency gain for regulated firms. Lustosa and Young (2001) tested the Porter Hypothesis for Brazil and found that industries more closely tied to exports were the most likely to engage in green innovation efforts, responding to the growing environmental concerns of external markets.

Another way to look at the divergent trends across different industry groups is by focusing on those groups that have been outperformed in terms of emission intensity reduction, such as the IM and TM groups. One possible hypothesis is that recent structural changes in the Brazilian economy featured not only a regressive specialization process but also an adverse selection within the manufacturing groups, in which firms with higher capacity to access natural resources and energy at low prices and evade environmental compliance costs outcompeted others. However, both hypotheses require a firm-level analysis, which is beyond the scope of this work.

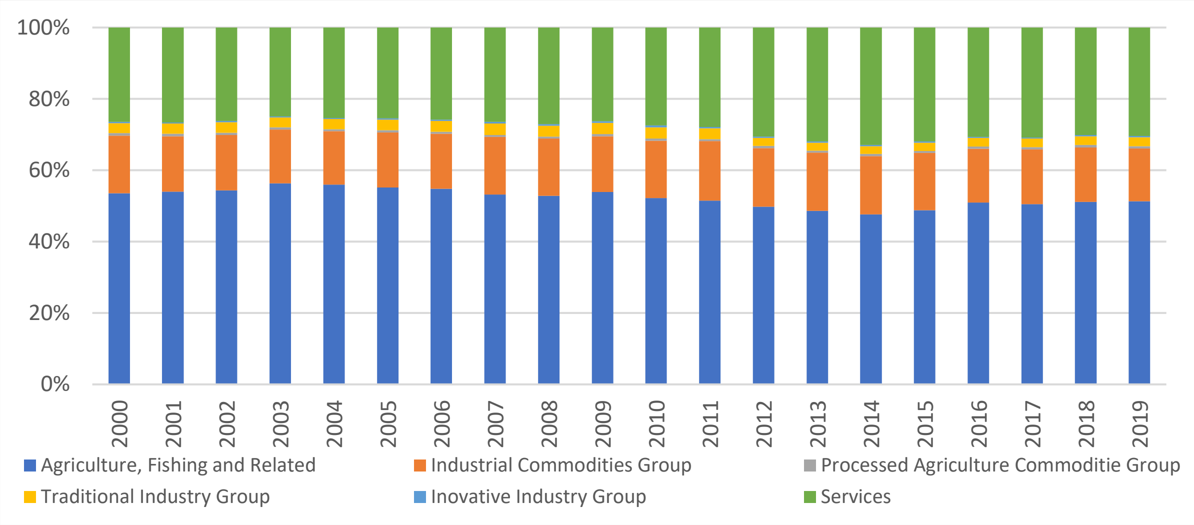
Regardless of their poor performance, IM and TM remained by far the least emission-intensive industry groups in the Brazilian economy. Conversely, the most natural-resource-intensive groups exhibited the highest emission intensities (Table 9). This result underscores the relevance of analyzing the recent structural change in Brazil from an environmental perspective since a regressive specialization may not only be a problem for Brazilian economic development, as signaled by the numerous studies analyzed in Chapter 1, but also for the country's decarbonization.

Finally, Graph 9 shows each industry group's share of total Brazilian emissions. The AGR group's average share amounted to 52.3% between 2000 and 2019, way above its average share in the Brazilian GDP, which stood at 6.1%.[43] The mismatch between these two shares is the result of high emission intensities for this industry group as compared to those for the other group. As one can observe, this industry group increased its participation in Brazilian emissions over the first half of the 2000s, kept it stable up to 2010, and was then overtaken by the

[43] According to the FAO (2018), in 2018, Brazil was the third-largest emitter in the agricultural sector, only behind India and China. However, when land use emissions are taken into account, Brazil takes the lead in this ranking.

increasing share attributed to services, especially during the water crisis period. Another 15.7% of all GHG emissions came from the production of industrial commodities. As for traditional and innovative manufacturing, those two groups combined responded to 3.1%.

Graph 9 - Emission share of the Brazilian industry groups



Source: author's elaboration

III. GHG emissions by final demand component, excluding land use change emissions

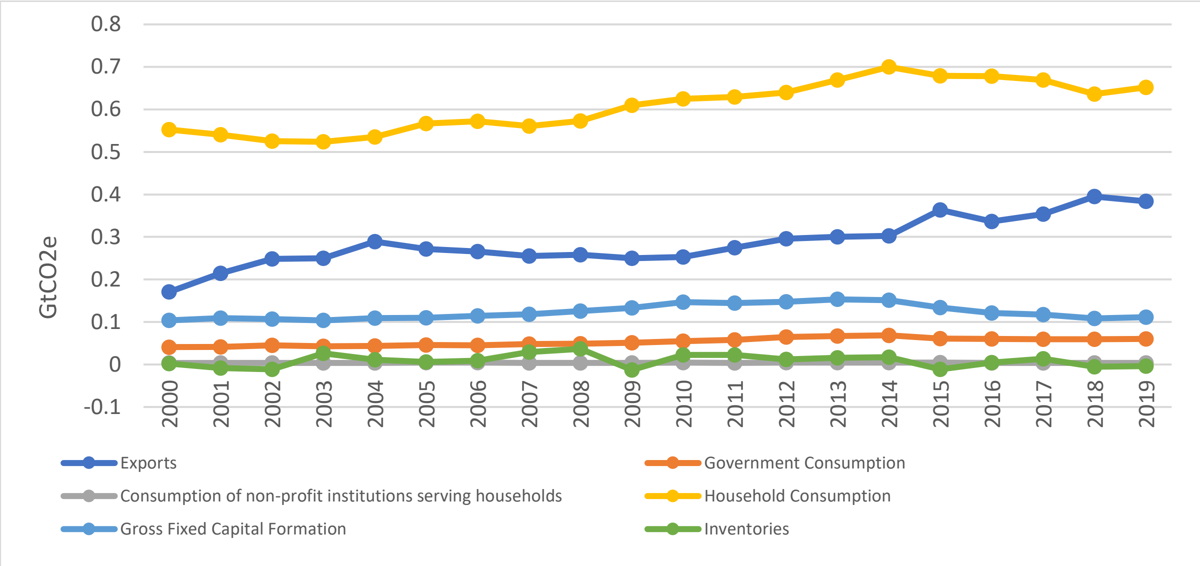
As Graph 10 illustrates, household consumption is the larger emitter among all final demand categories. This predominance stems from household consumption's significant share of the Brazilian GDP, averaging 50.8% during the period analyzed. Its emission trajectory is closely tied to the economic cycle, turning upward in 2004 as GDP growth blossomed and unemployment rates shrunk. In this period, social policies became a top priority for the central government. The policies, initially fragmented into multiple income transfer programs in the early 2000s, were later unified and expanded in scope. During the same period, the government implemented a consistent increase in the real minimum wage.[44] These measures, combined with the expansion of microcredit, strengthened the role of household consumption as a driver of economic growth, pushing this final demand emissions upward.

This upward trend came to a halt in 2014 with the reversal of the economic cycle. The subsequent period was marked by two consecutive years of severe economic recession (2015 and 2016), followed by three years of sluggish growth and the gradual dismantling of the real

[44] For more on growth-oriented social policy in Brazil, see Kerstenetzky (2012).

wage appreciation policy (Carvalho, 2018; Rossi, Dweck, and Oliveira, 2019). Against this backdrop, emissions from household consumption declined by 9.7% between 2014 and 2019.

Graph 10 - Emissions by final demand component



Source: author's elaboration

Many studies view the abrupt shift in fiscal policy conduction, occurring amid an ongoing economic slowdown, as a catalyst for the 2015-2016 economic crisis and the subsequent sluggish growth. (Rossi, Dweck, and Oliveira 2018; Carvalho, 2018; Passoni and Miguez, 2021). According to Dweck, Tonon, and Krepsky (2022), fiscal balances began to deteriorate as a result of both a decline in fiscal revenues – due to the economic slowdown that followed the 2008 financial crisis – and the adoption of countercyclical fiscal policies to mitigate the immediate impact of this crisis.

As fiscal balances eroded, political pressure mounted to shift the direction of fiscal policy. In 2011, the government put the brakes on fiscal expansion, further weakening aggregate demand, which was already decelerating due to declining international trade and household consumption – the latter affected by the rising interest rates and the adoption of restrictive macroprudential policies that limited access to credit. Still, in the early 2010s, the government increased the subsidies and tax exemptions aimed at stimulating private investment and economic growth. The policy not only did not produce the expected outcomes, as aggregate demand was already decelerating, but it also ended up aggravating the fiscal situation by reducing the tax revenue (Summa and Serrano, 2015).

In 2015, in an attempt to address the growing fiscal imbalance, the government implemented an unprecedented fiscal cut of BRL 70 billion, equivalent to around 1% of Brazilian GDP that year (Miguez and Passoni, 2021). One year later, still facing severe fiscal difficulties, Brazil passed a constitutional amendment establishing a new fiscal regime, which capped primary expenditure in real terms for the next 20 years (Brasil, 2016).

The abrupt shift in fiscal policy directly impacted emissions from government consumption but also indirectly influenced the emission trajectory of other components of final demand. After a decade of continuous growth, emissions from government consumption began to decline in 2014. It is likely that this deceleration would have occurred earlier if not for the increased use of thermal electricity generated by fossil fuels in the early 2010s. As Graph 10 shows, the emission intensity of government consumption rose by 14.9% between 2009 and 2014. Therefore, two opposing effects were at play during this period: a decelerating fiscal spend, which pushed government consumption emissions downward; and an increasing emission intensity, which pushed emissions upward.

Fiscal adjustment also impacted GFCF emissions both directly and indirectly through both public and private investment. Given its essentially discretionary nature, public investments are at the forefront of fiscal adjustment efforts, often being disproportionately affected by them. Alvarenga et al. (2024) estimated the emissions from public spending between 2000 and 2019 and found that between 2014 and 2016, emissions stemming from public investment decreased by 35.5%, way above the 11.9% drop for government consumption's emissions. As of 2017, when the new Brazilian fiscal regime came into effect, public expenditure emissions plateaued due to the real-term cap on primary expenditure

Regarding its indirect effects on GFCF, the reversal of fiscal policy exacerbated the ongoing slowdown trends in aggregate demand. The reduction in public investment, along with cuts in government consumption that brought social transfers and minimum wage appreciation policies to a halt, created a highly discouraging environment for private investment. Between 2014 and 2019, gross fixed capital formation (GFCF) declined by 27.1%,[45] leading to a 26.4% decrease in its emissions.

Among the final demand components, the most remarkable growth in emissions was observed in exports. Over the analyzed period, emissions from this component surged by 125.5%, largely outpacing the 46.6% increase in emissions from household consumption, the 17.9% rise in

[45] Data from the IOT series estimated by Passoni and Freitas (2022).

government consumption emissions, and the 7.2% growth in emissions from gross fixed capital formation.

When breaking down this trajectory by subperiods, we observe a significant surge in export emissions between 2000 and 2004, followed by a plateau from 2005 to 2010, and a renewed acceleration from 2011 onward. Two key factors likely contributed to this trend: the growth in the total value of exports and a shift in Brazil's export basket toward emission-intensive industries. Both dynamics are intrinsically linked to China`s growing relevance as a Brazilian trade partner. As we will see later, not only did Brazilian exports to China surge during this period, but their composition has also consistently been highly concentrated in commodities.

These factors may also explain the trajectory of export emission intensity. By 2000, exports were already the most emission-intensive component of final demand, reflecting the higher share of emission-intensive goods and services in their composition compared to other categories of final demand. The difference in emission intensities across final demand components widened between 2008 and 2019, as the emission intensity of exports increased by 26.4%, while all other final demand components showed a decreasing trend in their intensities.

This widening intensity gap takes place precisely in the period when the literature indicates the aggravation of the reprimarization trend for Brazilian exports. As highlighted by Amaral, Freitas, and Castilho (2020), from 2008 to 2011, the Brazilian sectors engaged in resource-based manufacturing and primary goods were the only ones to gain external competitiveness. However, from 2011 onward, these gains were concentrated exclusively in primary goods. As discussed in Chapter 1, the production of these goods is typically associated with higher emissions due to factors such as land-use change, enteric fermentation, energy consumption, and industrial processes. From an environmental standpoint, Young (2016) argues that Brazil's integration into international trade is increasingly based on *spurious environmental competitiveness*[46] – i.e. a competitiveness pattern in which the country's ability to compete internationally largely relies on its access to low-cost natural resources and energy, at the expense of mounting environmental degradation.

This increasing emission intensity for exports may also be a result of Brazil turning to thermoelectric power from the late 2000s to the mid-2010s, given the rising presence of energy-

[46] This term was originally used by Fayjzilber (1988: p.12) to describe "*a country's capacity to sustain and expand its share of international markets (...) by making use of the available cheap manpower and of subsidized lines of credit*".

intensive goods in the Brazilian export basket, such as those from the industrial commodities (IC) group. The next chapter will elucidate the contributions of changes in the scale, composition, and emission intensity of exports to these trends.

Household consumption is the second most emission-intensive component of final demand, largely due to the significant presence of goods directly or indirectly associated with deforestation, such as processed and unprocessed agricultural commodities, products from the food industry, and others.

Regarding Gross Fixed Capital Formation (GFCF), it is noteworthy that its emission intensity decreased during the water crisis period despite the heavy reliance on highly energy-intensive goods such as cement, steel, and metal alloys. Alvarenga et al. (2024) demonstrated that the emission intensity of public investment actually increased between 2010 and 2015, indicating that the overall reduction in GFCF intensity was driven by changes in private investment. Also, according to the authors, the low emission intensity of government consumption can be attributed to the fact that a significant portion of it consists of wage bills (*ibid.*).

Table 10 - Emission intensity by final demand component

Year	Emission intensity (tCO2e/BRLmillion)				
	Exports	Government consumption	NPISH consumption	Household consumption	GFCF
2000	608	80	76	375	236
2001	630	78	82	372	247
2002	627	82	82	369	245
2003	605	83	85	373	261
2004	608	83	82	374	250
2005	601	82	83	382	248
2006	592	77	79	368	243
2007	574	77	74	339	225
2008	543	76	71	337	216
2009	649	74	71	335	223
2010	599	75	69	326	208
2011	589	77	66	315	197
2012	608	86	70	309	198
2013	606	84	71	311	198
2014	650	85	71	316	205
2015	699	76	71	315	212
2016	686	75	69	317	222
2017	703	73	69	306	225
2018	685	74	67	293	207

2019	680	74	68	295	207

Source: author's elaboration
*GFCF and NPISH consumption stands for: gross fixed capital formation and consumption of non-profit institutions serving households

When it comes to the share of each final demand component in Brazil`s emissions, household consumption clearly stands out, given its high weight in the Brazilian GDP and relatively high emission intensity, followed by exports, GFCF, government consumption, and NPISH consumption. These shares greatly varied according to the characteristics of the economic growth that prevailed in each period. A surging ascending trajectory emerged for exports between 2000 and 2005, as this period's growth was mainly driven by external demand (Graph 8). In this particular period, exports saw their share jumping from 19.5% to 29.1%, which put a squeeze on other final demand components' share in total emissions.

From 2005 to 2014, as domestic absorption became the main driving force of economic growth, household consumption and GFCG increased their combined emission share from 64.9% to 68.7%, after peaking at 69.8% in 2010. Government consumption also increased its weight in total emissions by 1.1 percentage points in this period. This scenario is pretty much reversed in the last subperiod when domestic absorption entered a falling trajectory. In this context, export share in total emissions regained ground, expanding from 24.3% to 31.8% between 2014 and 2019.

Table 11 - Emission share of final demand components

Year	Exports	Government consumption	NPISH consumption	Household consumption	GFCF	Inventories
2000	19.5%	4.7%	0.4%	63.2%	11.9%	0.3%
2001	23.8%	4.6%	0.4%	60.0%	12.1%	-0.9%
2002	27.1%	4.9%	0.4%	57.2%	11.7%	-1.2%
2003	26.3%	4.5%	0.4%	55.1%	10.9%	2.8%
2004	29.1%	4.4%	0.4%	53.9%	11.0%	1.1%
2005	27.0%	4.5%	0.4%	56.5%	10.9%	0.6%
2006	26.3%	4.5%	0.4%	56.6%	11.3%	0.9%
2007	25.1%	4.7%	0.4%	55.2%	11.6%	2.9%
2008	24.7%	4.7%	0.4%	54.8%	12.0%	3.5%
2009	24.2%	4.9%	0.4%	58.9%	12.8%	-1.2%
2010	22.9%	5.0%	0.4%	56.5%	13.3%	2.0%
2011	24.3%	5.1%	0.3%	55.6%	12.7%	2.0%
2012	25.4%	5.6%	0.4%	55.0%	12.7%	1.0%
2013	24.8%	5.6%	0.4%	55.3%	12.7%	1.3%
2014	24.3%	5.5%	0.3%	56.2%	12.2%	1.4%
2015	29.5%	4.9%	0.3%	55.2%	10.9%	-0.9%

2016	27.9%	5.0%	0.3%	56.3%	10.1%	0.4%
2017	29.1%	4.9%	0.3%	54.9%	9.7%	1.1%
2018	33.0%	4.9%	0.3%	53.1%	9.1%	-0.4%
2019	31.8%	5.0%	0.33%	54.0%	9.2%	-0.3%

Source: author's elaboration
*GFCF and NPISH consumption stands for: gross fixed capital formation and consumption of non-profit institutions serving households

IV. GHG emissions by industry group, including land use change emissions

Land use change is Brazil's primary driver of greenhouse gas (GHG) emissions. Based on the methodology elaborated in Chapter 2, the great majority of these emissions (around 99%) were assigned to the AGR group.[47] Thus, when land use emissions are included, an average of 1.18 $GtCO_2e$ is added to AGR group emissions, raising these by over 190%. Moreover, the AGR group's emission trajectory also changes. In Section II, we saw that AGR emissions exhibited a sustained upward trend during the entire period. However, when land use change emissions are included, a sharp decrease in this group's emissions can be observed between 2004 and 2012 (Graph 11), as a result of the 82% reduction in deforestation rates in the Amazon brought about by the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm).[48]

After that, a marked upward trend emerged for the AGR group's emissions, mirroring the deforestation trajectory of the Brazilian Amazon for this period. After 2012, several factors contributed to rekindling deforestation rates. The first was the approval, in 2012, of a new Brazilian Forest Code, which loosened legal requirements for Permanent Preservation Areas (APPs) and granted amnesty to landowners guilty of illegal deforestation before 2008. According to Sant'Anna and Costa (2019), these changes encouraged further deforestation by fostering expectations among settlers that APP regulations would be further eased or that new amnesties might be granted in the future.

Another factor that seemed to have contributed to the deforestation increase was the successive budgetary cuts dedicated to environmental management functions, which undermined the

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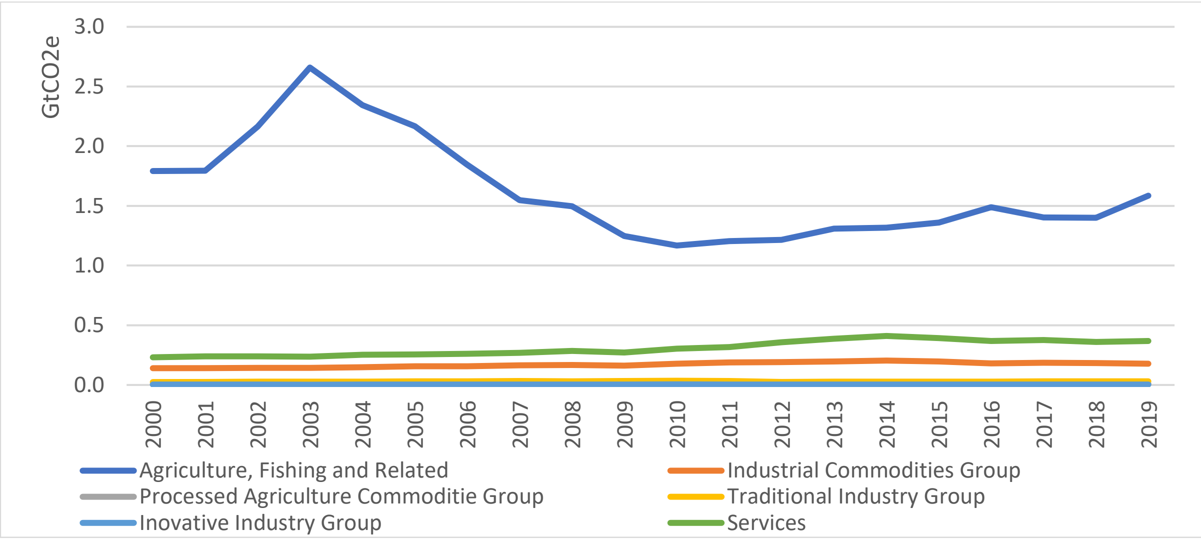
[47] Land use change emissions were distributed across the 42 industries proportionally to their participation in the conversion of forest and other natural areas for economic purposes.

[48] The PPCDAm was launched in 2004 by Brazil's federal government as an interministerial effort targeting the reduction of deforestation rates in the Amazon region. Among the main policies introduced by the Plan are: (i) the creation and expansion of protected areas in locations under high pressure from deforestation; (ii) the "real-time monitoring of deforestation, generating alerts for the institutions responsible for environmental inspection and surveillance" (iii) the restriction of credit for farms embargoed by illegal deforestation. (Medeiros et al., 2017, Assunção, Gandour and Rocha, 2013).

ability of the responsible agencies to carry out their duties effectively – particularly by causing a growing shortage of personnel and lowering their capacity to invest in or replace equipment used for the environmental surveillance. (Alvarenga et al., 2019). Finally, a slowing in the pace at which protected areas can also be observed in this period in the Amazon region (Young et al., 2017). All these factors combined made land-grabbing strategies more likely to pay off.

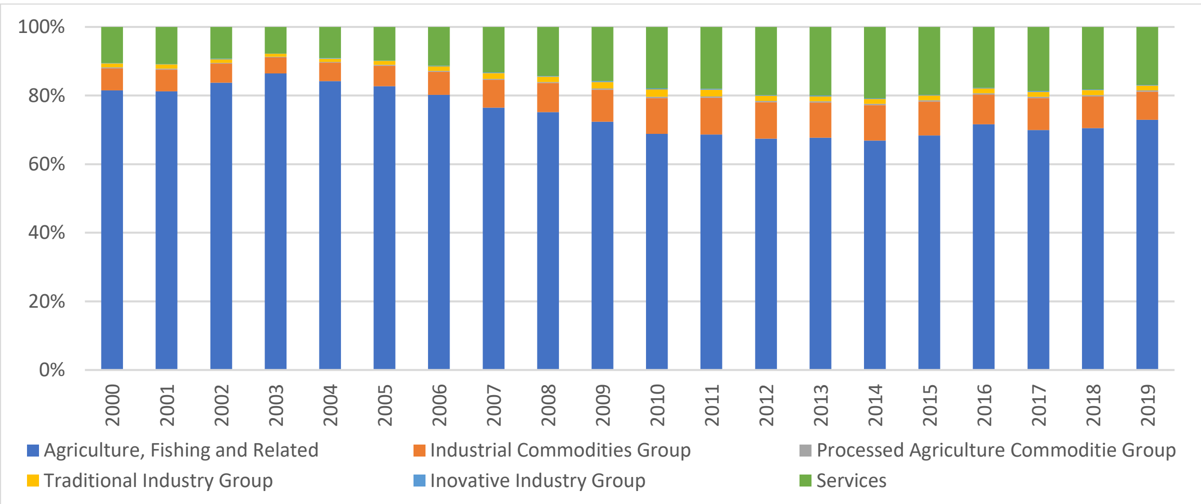
Graph 11 - GHG Emissions by industry group



Source: author's elaboration

When land-use change emissions are included, the AGR group's average share of Brazil's total emissions rises to 74.8% (Graph 12), an increase of more than 22.5 percentage points compared to scenarios that exclude these emissions. In this context, the three most natural resource-intensive industry groups - AGR, IC, and AC - accounted for an average of 84% of Brazil's GHG emissions, reaching a striking peak of 91.3% in 2003.

Graph 12 - Emission share by industry group (LUC emissions included)



Source: author's elaboration

Finally, when it comes to emission intensities, one can see that the average value for the AGR group nearly tripled when land use emissions are accounted for. Not only that but its emission intensity trajectory is largely driven by deforestation trends. For the other industry groups, however, no significant changes are observed. The IC and services sectors experienced only a slight increase in emission intensities, as a minimal portion of land use change is linked to mining, and the associated emissions were consequently allocated to the "*Extraction of iron ore, including processing and agglomeration*" and "*Other mining and quarrying" industries*".[49] This indicates that the gap between the AGR group's emission intensity and that of other industry groups widens substantially when deforestation is taken into account. For every million Brazilian reals' worth of goods produced, the AGR group generated, on average, 26.1 times more emissions than the industrial commodities group, 75.9 times more than the agricultural commodities group, 140.2 times more than traditional industry, 737.3 times more than innovative industry, and 73.7 times more than the services sector (Table 12).

Table 12 - Emission intensity by industry group (including emissions from LUC)

Year	Emission Intensities by Industry Group					
	AGR	IC	AC	TM	IM	Services
2000	8,738.8	271.6	78.3	41.3	8.1	77.5
2001	8,454.6	254.9	80.1	43.5	6.8	80.2
2002	8,947.7	244.2	75.7	45.4	8.2	79.3
2003	9,746.0	217.2	67.7	42.4	6.1	81.9
2004	8,384.8	206.3	60.2	40.9	6.2	84.6
2005	8,748.0	201.8	70.5	44.7	7.6	81.5
2006	7,624.8	196.6	67.3	45.7	7.5	78.9
2007	5,969.9	201.8	67.3	47.4	8.5	76.1
2008	5,136.0	189.0	73.6	43.8	7.8	77.9
2009	4,532.2	220.3	76.7	47.4	8.6	71.0
2010	4,283.5	220.0	73.9	49.2	9.0	73.7
2011	3,997.6	219.5	77.9	45.7	7.7	74.0
2012	4,009.9	223.2	75.5	34.5	7.7	80.6
2013	4,035.0	224.6	77.4	35.9	7.8	84.5
2014	4,139.4	232.2	85.4	35.9	8.2	88.0
2015	4,197.6	250.6	86.9	38.3	9.6	86.6
2016	4,365.1	262.1	95.1	40.0	9.2	83.4
2017	4,223.1	260.4	92.0	40.9	9.1	83.9
2018	4,143.3	220.4	91.2	40.2	8.4	81.2
2019	4,682.5	211.6	87.5	40.8	8.6	81.3

Source: author's elaboration

[49] As seen in Chapter 2,Table 7, both industries belong to the IC group.

V. GHG emissions by final demand component, including land use change emissions

The previous section revealed that the inclusion of LUC emissions considerably impacts the AGR group's emission intensity. This in turn impacts final demand components' emissions in two ways. First, the greater the participation of the AGR group in a given final demand component, the higher its emissions. Second, the release of emissions by deforestation propagates higher emissions to downstream sectors through its forward linkages (see section vi).

Overall, the most impacted final demand component is exports, whose average emission more than doubles when LUC emissions are considered. The rising restrictions of external markets on products linked to deforestation pose increasing risks for Brazilian exports. Consumers and firms are becoming increasingly demanding regarding the socio-environmental conditions under which the goods and services they consume or resell are produced, leading to strategies such as boycotts and the banning of transactions with companies that fail to comply with minimum sustainability criteria. For instance, more than 500 companies involved in supply chains with forest risks have committed to zero deforestation goals (Bager and Lambin, 2022). On a macro level, the European Union has signaled its intention to ban the import of agricultural commodities associated with deforestation (European Union, 2023). As we will see in section VII, EU imports from Brazil are indeed heavily reliant on AGR exports, and the emissions embodied in these imported goods are significantly affected by deforestation.

Meanwhile, in the period under review, emissions from household consumption rose by 110%. It is interesting to note that during the first subperiod, household consumption was the final demand component most affected by emissions from LUC. This lead position was later taken by exports, driven by the AGR group's increasing share of the Brazilian export basket (see Section VII). All other final demand components were also significantly affected as well, revealing deforestation's strong capacity to spread emissions across the economy.

Table 13 - Increasing emission factors for final demand emission intensities when LUC emissions are included

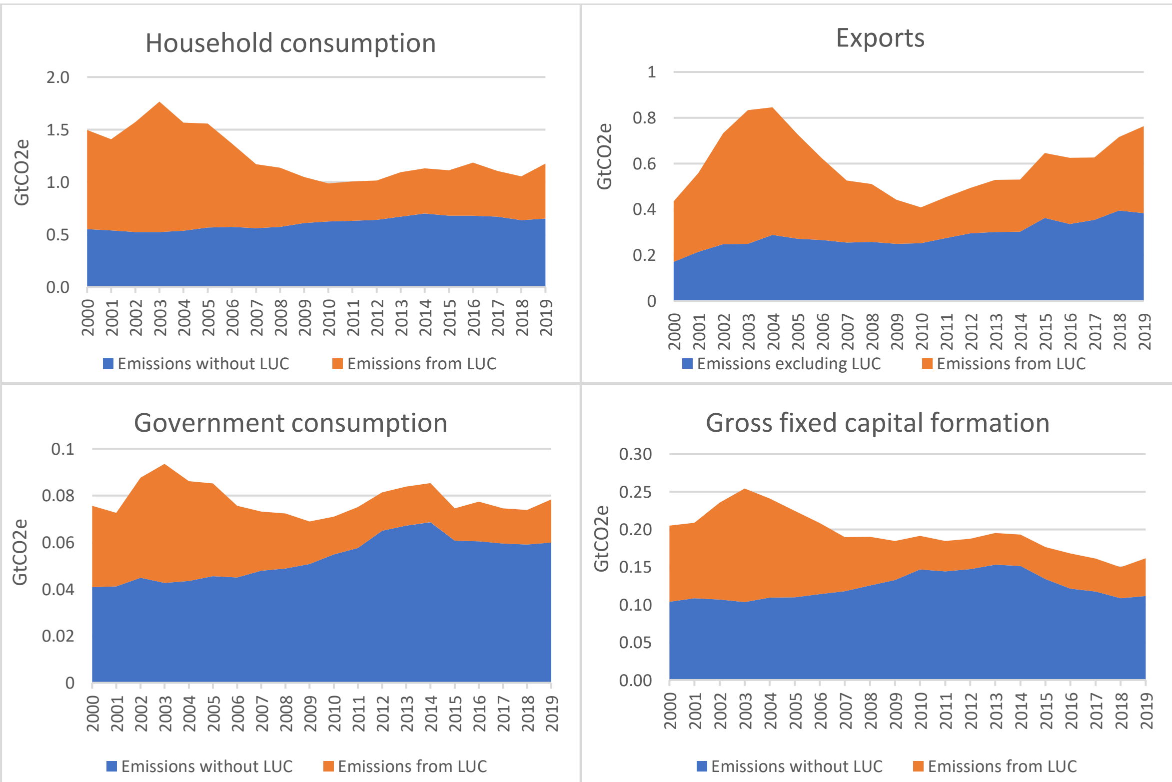
Period	Exports	Government consumption	NPISH consumption	Household consumption	GFCF
2000-2005	187%	95%	63%	192%	115%
2005-2010	108%	53%	36%	108%	61%
2010-2015	70%	26%	18%	61%	29%
2015-2019	84%	26%	20%	70%	38%
2000-2019	114%	52%	35%	110%	62%

Source: author's elaboration

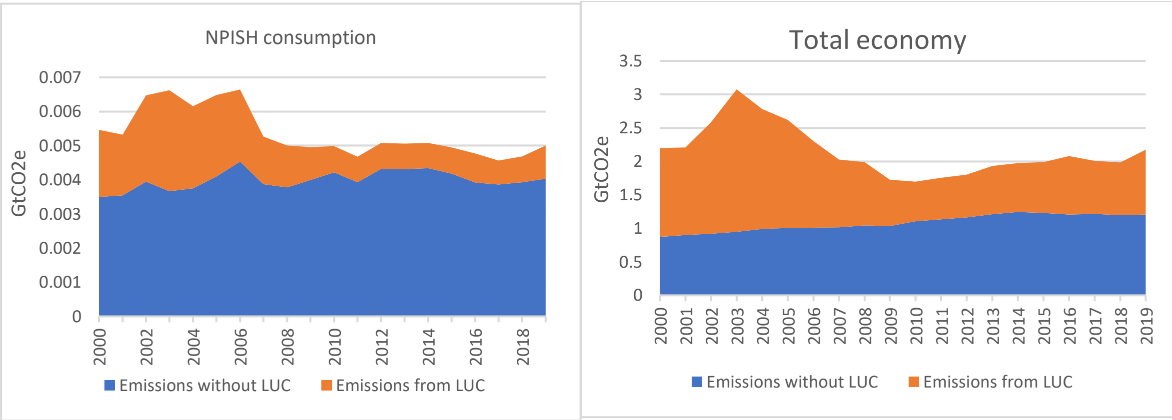
Graph 13 shows the trajectory of the emission of final demand components. The blue area represents the emissions of each component, disregarding those from LUC, while the orange area shows the emissions from LUC. All final demand components` emissions exhibit an increasing trajectory up to 2003, due to accelerating deforestation rates in the Amazon region. On the other hand, from 2004 to 2010, despite higher economic growth in this period, overall emissions drop for all final demand components, mainly thanks to the decrease in LUC emissions (orange area). As a result, the emission intensity of the Brazilian GDP in the period falls by 53.9%,[50] attesting to the importance of deforestation control policies for decarbonizing the Brazilian economy.

After 2012, the emissions from LUC embodied in each final demand component increase as the reduction in deforestation rates in the Amazon ceases. For all final demand components but exports, the economic recession of 2015 and 2016 and the low economic growth of the following years seem to have at least partially compensated for the increasing LUC emissions, as displayed in the shrinking blue areas of Graph 13.

Graph 13 - Emissions by final demand component (with and without LUC emissions)



[50] When land use change emissions are not taken into account, the reduction in emission intensity in the period is much more modest: approximately 15%.



Source: authors' elaboration

Table 14 shows the emission intensities of final demand components of the Brazilian economy in this period when LUC emissions are included. As one can observe, exports remain the most emission-intensive component of final demand, followed by household consumption. Both components demand high amounts of agriculture output whose production is closely linked to deforestation.

Interestingly, the decarbonization of Brazilian exports was interrupted in 2010, years before the deforestation rates in the Brazilian Amazon turned upward. Two factors may have contributed to this reversal: (i) the already mentioned water crisis that led to higher dependence on thermoelectric energy; or (ii) a re-composition of the Brazilian export basket that became more evident in the late 2000s.[51] One should note that the latter factor reinforced the effect of the former on export emission intensity. Given the high energy embodied in industrial commodities, their increasing participation in the Brazilian export basket tended to push export average emission intensity upward.

[51] Section VII presents the co-evolution of the Brazilian export basket and export-related emissions disaggregated by trade partner. Chapter 4 will complement this analysis by estimating the variation in exports-related emissions in response to changes in exported value and in the share of each industry group and trade partner in total exports.

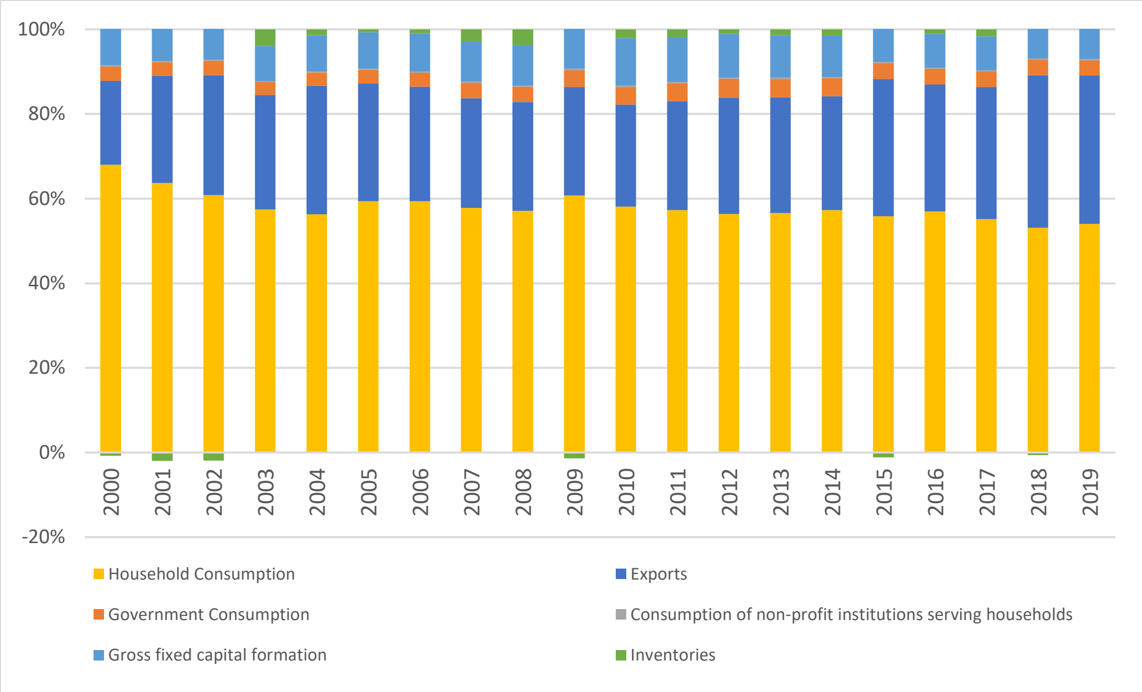
Table 14 - Emission intensities by final demand component, including emissions from LUC

Year	Emission intensities by final demand component				
	Exports	Government consumption	NPISH consumption	Household consumption	GFCF
2000	1,549.1	148.1	119.0	1,015.5	465.4
2001	1,639.8	138.0	123.1	970.2	475.5
2002	1,847.6	160.6	134.4	1,103.2	539.5
2003	2,016.5	181.7	153.3	1,256.6	641.2
2004	1,778.1	164.2	134.8	1,093.9	551.9
2005	1,613.9	153.9	132.0	1,047.4	507.0
2006	1,386.6	128.7	116.0	880.3	443.9
2007	1,183.2	117.0	100.4	708.2	361.9
2008	1,075.1	111.8	94.5	669.4	326.9
2009	1,148.1	100.0	88.2	576.8	310.0
2010	967.4	96.5	81.2	514.3	271.9
2011	969.3	100.1	78.7	504.1	251.6
2012	1,015.0	107.5	81.8	491.0	251.6
2013	1,065.6	105.3	83.4	508.4	252.6
2014	1,137.9	105.6	83.6	509.9	261.2
2015	1,244.0	93.3	83.6	515.3	279.4
2016	1,274.1	95.9	84.6	553.3	308.9
2017	1,243.3	91.6	81.6	506.0	308.7
2018	1,239.6	92.6	79.7	486.7	286.3
2019	1,350.2	97.0	84.2	532.6	300.5

Source: author's elaboration

Finally, we can see the effect of incorporating LUC emission as an ever-increasing contribution to exports' share of total emissions, going from 19.8% in 2000 to more than 36% in 2019 (Graph 14). As mentioned earlier, this growth was not continuous, but rather occurred in two phases. One that went from 2000 to 2004 and the other starting in 2011. Different factors may have been involved in increasing export-related emissions. It is very likely that that a sharp increase in exported value is one of them along with the rising deforestation rated up to 2004 and then from 2012 onwards. Another potential catalyzing factor for export-related emissions may be linked to the reprimarization, especially if the Brazilian exports is increasing its reliance on AGR group or placed downstream These points will be elucidated in Chapter 4, through a decomposition of the emissions embodied in Brazilian exported goods and services.

Graph 14 - Share of final demand components in total GHG emissions, including emissions from LUC



Source: author's elaboration

VI. Inter-industry emission linkages

In 2015, as a means of avoiding the most disruptive effects of climate change, the Paris Agreement (PA) set as one of its goals to limit the increase in global average temperature by the end of this century to within a range of 1.5°C to 2.0°C compared to pre-industrial levels. Each country that is a signatory to the PA is required to communicate its medium-term climate commitments to the international community through its Nationally Determined Contributions (NDCs) and update them every five years, incorporating increasingly ambitious climate targets. These decarbonization efforts can also be complemented by adherence to Long-Term Strategies (LTSs), voluntary documents in which countries present deeper decarbonization strategies, generally aimed at achieving carbon neutrality by 2050.

Transition pathways to meeting the goals set in NDCs and LTSs involve major structural transformations, requiring decarbonization both across and within economic sectors. In the first case, decarbonization occurs through shifts in productive structures towards less carbon-intensive industries, for example, by phasing out oil-producing industry while phasing in a renewable energy sector. In the second, decarbonization happens through the replacement of carbon-intensive technologies with low-emission ones, such as the substitution of electric engines for combustion ones within the automotive industry. (Buttazzoni, Delgado, and Alvarenga, 2024)

The emission intensities of each industrial group presented earlier provide an important indicator to support discussion on the transition to decarbonized economies. In fact, emission-intensity-based indicators have been widely used by green and sustainable taxonomies as a way to inform private investors and the public sector about which activities can be classified as low-emission and should, therefore, be prioritized in resource mobilization endeavors.

However, despite valid classification efforts, these indicators are insufficient, as they do not consider how activities are interrelated through emission flows. In this sense, activities with low-emission intensity (direct emissions/gross production value) may demand inputs from carbon-intensive activities. Similarly, carbon-intensive activities can compromise the decarbonization opportunities of industries by propagating their emissions through the inputs they produce.

Emission linkages[52] can provide valuable information for planning a transition to decarbonization. Emission backward linkage (EBL) provides information on how each industry pulls emissions from all industries by consuming their inputs. Conversely, emission forward linkage (EFL) measures how each industry propagates emissions by supplying inputs to all industries.

Table 15 displays each industry group's EBL and EFL for different years, with LUC emissions included. The AGR group exhibits the highest emission linkages among all industry groups. Interestingly, the AGR group's EBL and EFL scored their highest values in 2005, dropped in 2010 and 2015, and then slightly increased again in 2019. The AGR group largely relies on self-produced inputs, so when deforestation increases (decreases), more (fewer) LUC emissions are incorporated into its production processes.[53] In addition to that, the emission reductions (increase) due to changes in deforestation rates are passed on to other industries placed downstream – i.e., those consuming AGR goods as inputs. This is precisely why the AC, IC, and TM groups significantly reduced their EBL when deforestation dropped. While the reasons for the decline in the AC group's EBL are intuitive, what explains the impact of deforestation reduction in the latter two groups is the strong reliance of the food and beverage and biofuel manufacture industries[54] on AGR inputs.

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[52] For more on the methodology for estimating emission linkages, see Chapter 2.

[53] While the total backward linkage of agriculture in 2000 was 1.61, the net backward linkage (calculated after the deduction of the main diagonal elements of the inverse Leontief matrix) was 0.54. This difference highlights the group's direct and indirect dependence on the inputs it produces internally.

[54] These two industries belong to the IC and TM groups, respectively.

Table 15 - Emission backward and forward linkages by industry group

Industry group	Emission backward linkage					Emission forward linkage				
	2000	2005	2010	2015	2019	2000	2005	2010	2015	2019
AGR	9,487	9,537	4,671	4,561	5,076	27,385	30,258	13,457	13,147	14,558
IC	998	913	691	767	737	548	488	464	508	457
AC	1,657	2,414	1,059	1,067	1,128	84	75	74	75	76
TM	1,007	1,051	491	479	502	49	48	47	38	37
IM	220	228	182	195	173	12	11	13	12	10
Services	295	313	215	243	227	312	304	287	358	310

Source: author's elaboration

Conversely, the IM group is neither pulling nor propagating large quantities of emissions from or to other industries. In fact, this group presents the lowest EBL and EFL among all groups in all the years analyzed. The low EBL results from a cleaner production process (i.e., low dependence on emission-intensive sectors) and technology internal to the group. Meanwhile, the low EFL can be explained by the IM's low emission intensity and because a relevant portion of its output flows directly towards final demand (Passoni, 2019). This latter fact also explains the low EFL for traditional manufacturing and processed agricultural commodities.

Services, otherwise, present a relatively high EFL, which can be attributed to the high demand of all industries for power generation and distribution and for transportation. The highest EFL value for this industry group was in 2015, precisely during the period when the country's reliance on thermoelectric power plants peaked.

Table 16 presents the emission power of dispersion $(\widetilde{PD})$ and emission sensitivity of dispersion $(\widetilde{SD})$ for the period under investigation. These indicators provide the normalized form for EBL and EFL, yielding an average value equal to 1. This way, it is possible to more clearly observe which industrial groups have the capacity to pull and propagate emissions above the economy's average.

A very relevant finding is that the IM industrial group is the only one with $\widetilde{PD}$ and $\widetilde{SD}$ below the economy's average (1). This means that this group drives fewer emissions both upstream and downstream than the average for the economy, whether by not relying on highly emission-intensive inputs or by not supplying highly emission-intensive inputs to other sectors. With the AGR group, on the other hand, given its high emission intensity, self-consumption, and position as an input supplier for other industries, both its $\widetilde{PD}$ and $\widetilde{SD}$ are well above the economy's average. It is important to mention that, through its forward linkages, AGR propagates large amounts of deforestation emissions to other groups. Once again, this underscores (i) how industries downstream get "contaminated" by deforestation and (ii) the importance of deforestation control policies for reducing emissions across different industries.

Table 16 - Normalized emission backward and forward linkages by industry group

Industry Group	Emission power of dispersion ($\widetilde{PD}$)					Emission sensitivity of dispersion ($\widetilde{SD}$)				
	2000	2005	2010	2015	2019	2000	2005	2010	2015	2019
AGR	10.5	10.0	8.6	8.0	8.9	30.3	31.7	24.8	23.2	25.4
IC	1.4	1.2	1.6	1.6	1.3	2.1	2.0	2.0	1.9	2.0
AC	2.4	3.2	2.4	2.3	3.1	0.3	0.3	0.3	0.3	0.3
TM	1.5	1.4	1.1	1.0	1.4	0.2	0.2	0.2	0.1	0.2
IM	0.3	0.3	0.4	0.4	0.5	0.05	0.05	0.06	0.05	0.05
Services	0.4	0.4	0.5	0.5	0.3	2.3	2.3	2.3	1.4	1.3

Source: author's elaboration

VI.1. Emission linkages clusters and transition opportunities for Brazil

Even though Table 16 provides valuable information on the capacity of each industry group to pull and propagate emissions as compared to the average, there is much heterogeneity in the backward and forward linkages within these groups. For this reason, it is convenient to analyze the information disaggregated by industries. Based on the information provided by the emission power and sensitivity of dispersion, industrial sectors have been clustered according to their capacity to support transition to a low-carbon economy.

It is important to emphasize that the cluster analysis here is based on the Brazilian structure as it was in 2019. However, as previously mentioned, transition to a decarbonized economy requires deep structural transformations encompassing the substitution of high-emitting industries and technologies for low-emitting ones. Such changes are likely to alter the sectoral composition of output, inter-industry linkages, industries' emission intensities, and thus their $\widetilde{PD}$ and $\widetilde{SD}$ values.

Therefore, the sectors that spearhead transition today may not have the same protagonism in the future. With that disclaimer in mind, Figure 9 presents the four clusters based on the 2019 values for EBL and EFL.

Figure 9 - Emissions linkages clusters

Industry clusters		Emission sensitivity of dispersion	
		Low (<1)	High (>1)
Emission power of dispersion	Low (<1)	Transition-enabling industries	Emission-propagating industries
	High (>1)	Emission-dependent industries	Transition-preventing industries

Source: author's elaboration

(i) **Transition-enabling industries:** These are industries that currently present a high potential for inaugurating and leading the process of transitioning to a low carbon economy, since they do not depend on large amounts of emissions to produce their output; nor do they propagate larger amounts of emissions to other industries' production processes. Therefore, if economic growth moves towards these industries, the Brazilian economy will experience an increasing decoupling from emissions.

(ii) **Emission-propagating industries:** These industries rely on relatively clean inputs, but their own emission intensity is sufficiently high to propagate emissions downstream. This cluster decarbonization depends on within-industry measures, i.e., it depends on moving toward less-emission-intensive technologies.

(iii) **Emission-dependent industries:** These industries rely on highly emission-intensive inputs. Nevertheless, they have a relatively low emission propagating effect, as a larger share of their output flows directly toward final demand. In order not to block transition processes, these industries require either to change their production techniques so as to shift their intermediate consumption towards low carbon inputs or connect with suppliers that engage in a within decarbonization process.

(iv) **Transition-preventing industries:** These industries rely on high emission-intensive technologies and very emission-intensive inputs that carbonize their production process. Therefore, in order not to pose obstacles to the decarbonization process, these industries need to shift their intermediate consumption towards low carbon inputs or connect with cleaner suppliers, and adopt better technologies to deploy a within-sector decarbonization, avoiding emissions to be passed on to downstream industries.

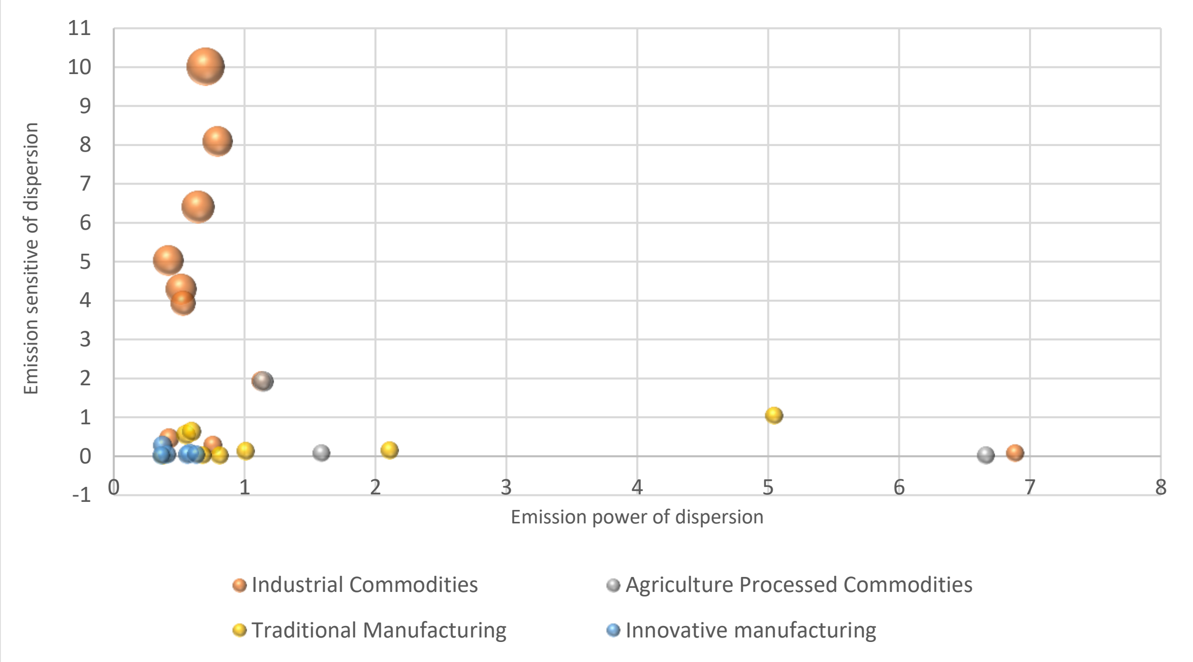
Graph 15 displays the Brazilian industries according to the clusters above. Due to difficulties in visualizing information, given the disparities in the scale of $\widetilde{PD}$ and $\widetilde{SD}$ for the agriculture and service sectors compared to manufacturing, these clusters were plotted in Graph 16. The size of the bubbles represents each industry's emissions due to self-consumption.

One can observe that all the innovative industries are contained in the quadrant with both their $\widetilde{PD}$ and their $\widetilde{SD}$ below 1, accompanied by most (six out of eight) of the traditional manufacturing industries. This is a very relevant finding, as it shows that a structural change that privileges the IM group has a multiple dividend. Besides the importance of manufacturing to the economic development process, as previously presented in Chapter 1, this kind of industry can also assist the country with its transition towards a low-carbon economy.[55]

As for the IC group, most of its industries fall in the emission-propagating cluster. Even though IC industries do not rely so much on emission-intensive inputs, they are often energy-intensive. Indeed, Graph 15 shows that the majority of IC industries exhibit a very high capacity to propagate emissions to other sectors. The great challenge these industries pose for transition is that their emissions are usually very hard to abate, whether because the technology to do that is not yet available or not yet economically feasible (ETC, 2018). Meanwhile, all processed agricultural commodities industries present a $\widetilde{PD}$ higher than one, due to their strong association with agricultural inputs.

[55] For more on the importance of manufacturing for economic development, see Chapter 1, Section II.

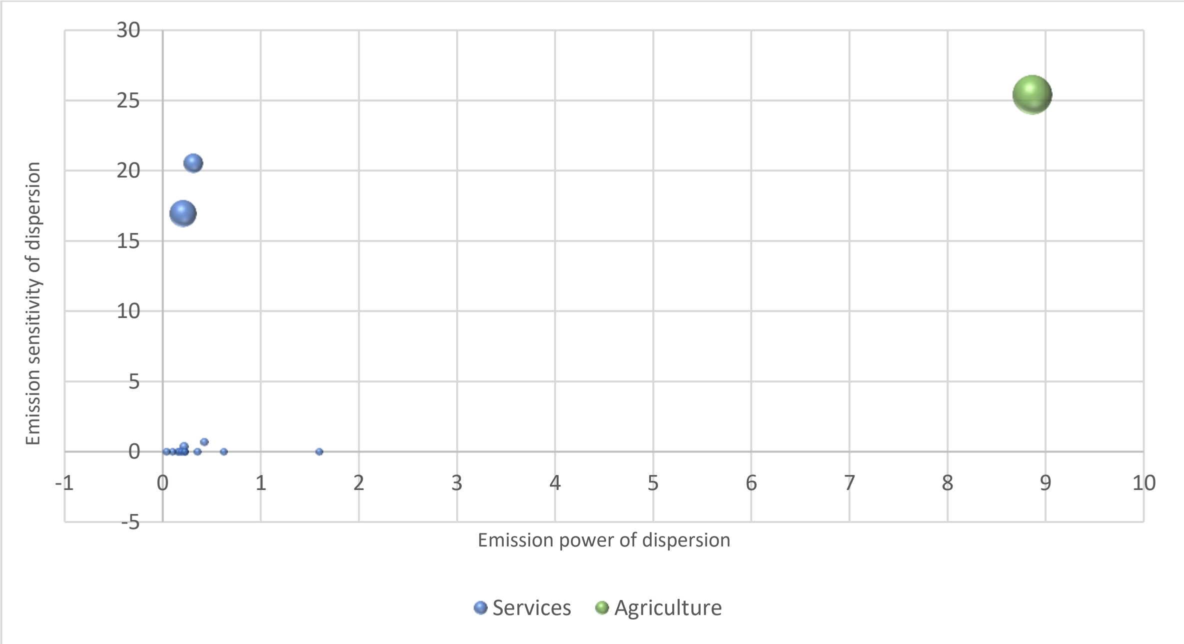
Graph 15 - Manufacturing's emission linkages clusters



Source: author's elaboration

Its already mentioned high emission intensity, self-consumption, and relevance as an input supplier for other industries place agriculture in the transition-preventing cluster. However, given the large amount of emissions that come from consuming inputs from its own production (represented by the size of the bubble), many of the agricultural decarbonization opportunities lie within this sector: for instance, reducing its link with deforestation, better management of manure, recovery of degraded pastures, and no-till farming (Brasil, 2023). Finally, most of the service sectors can be classified as transition enablers, as they have a low material base and flow directly to final demand.

Graph 16 - Service and AGR emission linkages clusters



Source: author`s elaboration.

VI.I.1 Brief comments on the relevance of emission linkages for planning Brazil's transition

Recently, Brazil launched the Ecological Transformation Plan (ETP), aiming for a "*cultural, political, and economic paradigm shift in the social organization of production based on the biome, in favor of sustainable relationships with the territory and nature, generating a better quality of life for its populations*" (BRASIL, 2023a, p.7). This plan is structured around six pillars: (i) sustainable finance; (ii) technological densification; (iii) bioeconomy and agri-food systems; (iv) energy transition; (v) a circular economy; (vi) new green infrastructure and adaptation.

As part of the sustainable finance pillar, the Federal Government has engaged in the elaboration of a sustainable taxonomy, and the issuance of sustainable sovereign bonds, aiming to scale-up the resource mobilization for implementing the Ecological Transformation Plan (ETP). The Brazilian taxonomy is yet to be published, but an action plan for a public consultation was launched in September 2023. The document establishes a set of environmental and sustainable objectives and provides an initial outline of the sectors to be included in the final document.

In this first version, the Brazilian taxonomy will include seven sectors: (i) agriculture, forestry and other land use; (ii) extractive industry; (iii) manufacturing; (iv) power and gas; (v) water, sewage and waste management; (vi) construction; (vii) transport and mailing services. Therefore, the Brazilian taxonomy seeks to identify economic activities within these sectors that can contribute significantly to at least one sustainability objective without causing significant harm to any other objective.

The second pillar of the Brazilian Ecological Transformation Plan draws on the report "*Nova indústria Brasil: programa de neoindustrialização com missões estratégicas*" (New Industry Brazil: a neo-industrialization program with strategic missions). The document identifies six missions to foster a green reindustrialization process: (i) sustainable and digital agro-industrial food chains for food, nutritional, and energy security; (ii) an industrial health complex to reduce vulnerabilities in the Brazil`s Unified Health System (SUS) and expand access to healthcare; (iii) sustainable infrastructure, sanitation, housing, and mobility for productive integration and well-being in cities; (iv) a digital transformation of industry to increase productivity; (v) bioeconomy, decarbonization, energy transition, and security to ensure resources for future generations; (vi) technologies of interest for national sovereignty and defense.

One common limitation of current taxonomies and even transition plans is that this type of instrument usually sees economic activities as isolated entities, i.e. the reasoning of decarbonizing sectors often prevails over the reasoning of decarbonizing production chains. Therefore, there might be situations where certain types of investment comply with the environmental and social criteria of a particular sector, but the unsustainable practices of its input suppliers may compromise the final performance of this sector.

For instance, some of the objectives outlined in the five missions above may hinder decarbonization efforts, particularly if emission flows between sectors are not adequately considered. Specifically, the goals of increasing the share of (i) the agro-industrial sector in agricultural GDP from 23% to 50% (Mission 1) and (ii) biofuels in the transportation energy matrix by 50%, up from the current 21.4% (Mission 5), could pose significant challenges to aligning with decarbonization objectives, given the strong links between upstream sectors (AGR) and deforestation.

To account for inter-industry emission flows, we first identified the economic sectors associated with the six priority areas outlined in the initial version of the Brazilian Taxonomy. Next, we performed a similar analysis using the *Nova Indústria Brasil* document, pinpointing the sectors likely to play a key role in deploying its goals. It is important to note that the resulting list of industries may not be exhaustive; that is, it may not capture all sectors directly involved in the implementation of the Brazilian Ecological Transformation Plan. However, to the best of our judgment, we have incorporated all industries linked to the Plan.

With that disclaimer in mind, Table 17 presents the emission power and sensitivity of dispersion for industries related to the Brazilian Ecological Plan, especially those concerning to the Brazilian taxonomy and the *Nova Indústria Brasil*.

Table 17 - Emission power of dispersion and sensitivity of dispersions for sectors of the Brazilian Ecological Transformation Plan

Group	Industry	$\widetilde{PD}$	$\widetilde{SD}$	Cluster
AC	Manufacture of wood products	1.585	0.086	Emission-dependent industries
	Manufacture of pulp, paper, and paper products	1.141	1.924	Transition-preventing industries
TM	Food and beverages	5.045	1.047	Transition-preventing industries
	Manufacture of textiles*	2.105	0.163	Emission-dependent industries
	Manufacture of footwear and leather goods*	0.676	0.032	Transition-enabling industry
IC	Extraction of oil and gas, including support activities	0.414	5.042	Emission-propagating industry
	Extraction of iron ore, including processing and agglomeration	0.421	0.465	Emission-propagating industry
	Other mining and quarrying	0.513	4.302	Emission-propagating industry
	Oil refining and coking plants	1.124	1.935	Emission-propagating industry
	Manufacture of biofuels	6.884	0.088	Emission-dependent industry
	Cement and other non-metallic mineral products	0.699	10.014	Emission-propagating industry
	Manufacture of steel and its derivatives	0.791	8.098	Emission-propagating industry
	Metallurgy of nonferrous metals	0.642	6.409	Emission-propagating industry
	Metal products - exclusive machinery and equipment	0.757	0.298	Transition-enabling Industry
Services	Construction	0.61834	0.003	Transition-enabling Industry
	Transport, warehousing and mail	0.308512	20.552	Emission-propagating industry
	Electricity generation and distribution of gas, water, sewage, and urban cleaning	0.20293	16.965	Emission-propagating industry

Source: author's elaboration
*Not all goods produced by them can be classified as agro-industrial goods, e.g. clothes using synthetic fabrics

According to the $\widetilde{PD}$ and $\widetilde{SD}$ displayed in Table 17, of the seventeen industries associated with the above-mentioned plans, two fall into the emission-dependent cluster, ten into the emission-propagating cluster, two into the transition-preventing cluster, and only three are classified as transition-enabling. However, this exercise should not be interpreted as an exclusion list for industries that do not fall within the transition-enabling cluster. Exceptions should be made, of course, for industries involved in fossil fuel extraction and refining, which should not be incentivized in a world striving to meet the Paris Agreement targets. Instead, the scores associated with these industries are intended to highlight potential challenges for the Brazilian Transition Plan and pinpoint where decarbonization efforts are most urgently needed—whether within a specific industry, its input suppliers, or both.

As has been mentioned in the previous section, most of the Brazilian extractive sector falls into the cluster of "emission-propagating industries," because of its capacity to propagate emissions from its production process to downstream industries. While the taxonomy's effort to mobilize resources for this sector – subject to the observation of specific sustainability criteria—is valid and may indeed lead to better practices, the emissions from many extractive industries are hard to abate (ETC, 2018). This means that extractive industries are likely to continue propagating significant amounts of emissions to other industries, at least in the short term.

Nevertheless, a taxonomy is a living document that needs to adapt to technological and institutional developments, as well as to the growing need to increase climate ambition. In this sense, it is crucial that updates to the Brazilian taxonomy move the bar higher by including criteria capable of ensuring an increasing decarbonization ambition for emission-propagating industries. As mentioned earlier, for such industries not to obstruct the transition, there must be a within-sector decarbonization process through the adoption of better technologies.

When it comes to mobilizing resources to decarbonize the biofuel and agro-industries in general, the main challenge to transition arises from these industries' strong emission backward linkages with the AGR group, the most emission-intensive group in the Brazilian productive structure. Indeed, as Table 17 shows, almost all agro-industries can be classified as emission dependent, and therefore relies on decarbonization upstream to decarbonize its production.

The Brazilian Framework for Sustainable Sovereign Bonds determines that the biodiesel sector can access the funds from the issuance of sustainable bonds, provided it obtains the Efficient Biofuel Production Certificate according to the terms established by ANP Resolution No. 758/2018. The regulation establishes specific criteria, including "*the attribution of an Energy-Environmental Efficiency Index, which considers the emission intensity of fuels (gCO2eq/MJ) and compliance with parameters such as the non-suppression of native vegetation and the existence of the Rural Environmental Registry (CAR)*" (Brasil, 2023b, p.23). Furthermore, to be eligible for financing with these resources, "*biofuel production must meet the limits set by* *the Climate Bond Initiative (CBI) for greenhouse gas emissions, as well as comply with the DNSH*[56] *criterion to certify production in non-deforested areas*" (Ibid., p.23).

However, verifying the criterion of no relation with deforested areas is quite complex, as much of the deforestation promoted by the expansion of raw materials for biofuel production is indirect (Young, Alvarenga and Sant'Anna, 2023). More specifically, it is the growth in demand for these raw materials that results in increased profitability vis-à-vis other agricultural activities, displacing them to agricultural frontier areas, where land is cheaper (Alvarenga, 2014).

Regarding the services included in the Brazilian taxonomy, two of them (transport, warehousing and mail; and electricity generation and distribution of gas, water, sewage, and urban cleaning) belong to the emission-propagating cluster. As their production tends to be demanded by many industries, their emissions tend to flow to a high number of downstream sectors.

VII. An in-depth exploration of export emissions

As previously seen, exports stand out as having the highest emission intensity among all components of final demand and for experiencing a much faster emission growth rate than other components. Over the period covered by this thesis, Brazil's export weight in total emissions surged from 19.5% to 31.8% when land use emissions were not included, and from 19.8% to 35.6% when they were. Several factors may have contributed to these developments,[57] including technological changes in industries engaged in exported goods and services production, variations in their emission intensity, or shifts in their composition driven by an increasingly regressive specialization within the export basket.[58]

Regarding the latter development, exports seem to have undergone important changes in their composition. Graph 17 shows total exports (at 2010 BRL) by trade partner. The first outstanding element is China's increasing relevance to Brazilian exports. Between 2000 and 2019, exports to China grew by 2,824%, leading the country`s share of total Brazilian exports

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[56] DNSH stands for "Do No Significant Harm," a principle that aims to ensure that actions taken to achieve an environmental objective do not adversely impact other areas or objectives.

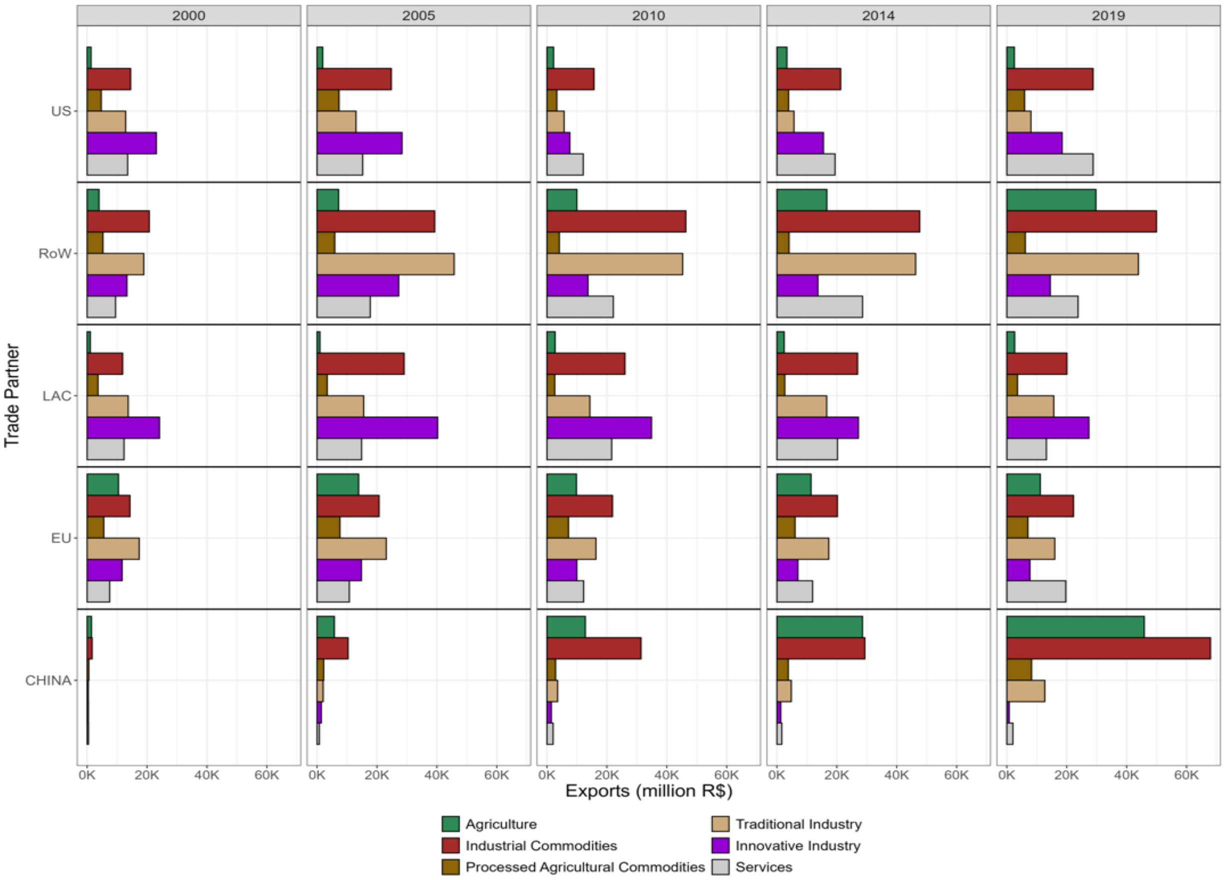
[57] The contribution of each of these elements will become clear in Chapter 4, as we decompose the variations in export emissions.

[58] For more on that, see Chapter 1, subsection IV.2.

to jump from 1.9% to 28.7%. This growth, though, was very unevenly distributed across the different industry groups, predominantly taking place in the IC and AGR groups.

The striking increase in China's share of total Brazilian exports, largely rooted in commodities, would already be enough to push Brazil towards a reprimarization of its export basket. However, Brazilian exports to other partners also shifted towards a higher share of AGR, IC, and AC groups. In the case of the United States (US) and the European Union (EU), not only did total exports from AGR, IC, and AC increase between 2000 and 2019, but exports of TM and IM declined. Consequently, the share of commodities in Brazil's export basket to the US rose from 37.5% to 56.9%, while to the EU, it increased from 52.6% to 62.6% (Table 18). Similarly, the Brazilian export basket to the rest of the world (RoW) experienced a notable expansion in the AGR and IC groups. Although the value of TM and IM exports grew during this period, the share of commodities in Brazilian exports to the RoW rose from 49.9% to 59.8%. For Latin America and the Caribbean (ALC), TM and IM exports demonstrated resilience in absolute terms, though the share of commodities still increased by 6.4 percentage points.

Graph 17 - Brazilian exports by trade partner (in 2010 BRL million)



Source: author's elaboration

Table 18 - Brazilian export basket by trade partner

Industry group	2000					
	ALC	EU	RoW	US	CHINA	Total
AGR	2.1%	17.9%	6.5%	2.4%	32.0%	7.9%
IC	22.9%	25.1%	34.7%	26.5%	37.7%	27.7%
AC	7.1%	9.7%	8.7%	8.6%	12.5%	8.6%
TM	23.2%	26.6%	27.6%	20.7%	8.2%	24.3%
IM	43.6%	19.6%	21.0%	40.9%	9.2%	30.3%
Service	1.2%	1.2%	1.5%	0.9%	0.5%	1.2%
Industry group	2005					
	ALC	EU	RoW	US	CHINA	Total
AGR	1.1%	17.8%	5.9%	2.6%	26.6%	7.9%
IC	33.6%	26.3%	32.0%	33.3%	48.0%	32.4%
AC	3.9%	9.5%	4.7%	9.9%	10.0%	6.8%
TM	16.4%	27.0%	34.7%	16.3%	8.9%	24.0%
IM	43.9%	17.7%	20.9%	36.7%	6.1%	27.6%
Service	1.1%	1.6%	1.8%	1.1%	0.5%	1.4%
Industry group	2010					
	ALC	EU	RoW	US	CHINA	Total
AGR	3.5%	15.0%	8.3%	6.6%	23.8%	10.7%
IC	33.1%	34.1%	39.5%	45.6%	61.6%	41.1%
AC	3.3%	10.9%	3.4%	9.7%	5.3%	5.7%
TM	16.7%	24.1%	36.6%	16.1%	6.4%	23.3%
IM	41.5%	14.3%	10.6%	20.9%	2.6%	17.9%
Service	1.9%	1.6%	1.5%	1.1%	0.4%	1.4%
Industry group	2014					
	ALC	EU	RoW	US	CHINA	Total
AGR	3.4%	18.8%	13.3%	7.4%	42.0%	16.9%
IC	36.7%	32.8%	37.8%	44.0%	44.2%	38.7%
AC	3.6%	9.7%	3.2%	8.4%	5.4%	5.4%
TM	20.6%	26.9%	34.9%	11.5%	6.6%	22.8%
IM	34.3%	10.0%	9.5%	27.6%	1.6%	15.1%
Service	1.4%	1.8%	1.4%	1.1%	0.2%	1.2%
Industry group	2019					
	ALC	EU	RoW	US	CHINA	Total
AGR	3.9%	17.4%	20.8%	4.0%	33.8%	19.4%
IC	29.2%	34.2%	34.8%	43.7%	50.5%	39.6%
AC	5.3%	10.9%	4.3%	9.3%	6.0%	6.5%
TM	21.1%	23.6%	29.0%	11.8%	8.8%	19.1%
IM	38.9%	12.0%	9.9%	29.6%	0.6%	14.2%
Service	1.5%	1.9%	1.3%	1.7%	0.2%	1.2%

Source: author's elaboration based on Secex (2024) data.

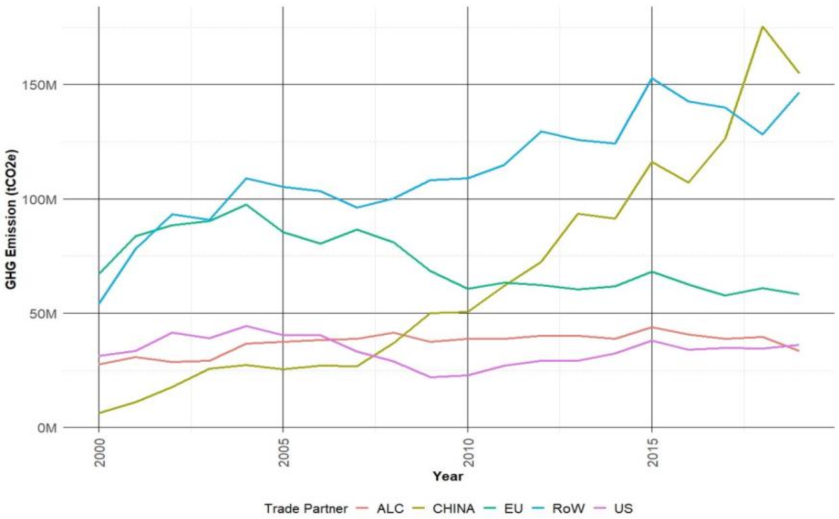
It is relevant to mention that exports from the TM and IM groups exhibited a lower value in 2019 than in 2005 for all trade partners. This may be the result of the increasing competition with Chinese manufacturing for external markets. Hiratuka and Sarti (2017) pointed out that even though Brazil faced an increasing Chinese competition throughout the entire period, after the 2008 economic crisis, the competition intensifies as the deceleration of the US and EU economies made international markets tighter. Additionally, the segments of manufacturing where this competition occurred seem to have changed. Initially, Chinese exports mostly competed with Brazil's in low-technology manufacturing branches. However, more recently they have begun to move towards more technologically sophisticated segments (Paus, 2014).

The changes in the composition of Brazilian exports indicates a potential increasing pressure on Brazil's emissions, as previous results indicated that the industrial groups involved in commodity production are among the most emission-intensive in Brazil's productive structure. Indeed, during the period under review, the Brazilian export basket for all partners moved towards the most emission-intensive industry groups. Indeed, during the period under review, the export basket for all trade partners shifted towards the most emission-intensive industry groups. However, the most concerning changes occurred in exports to the RoW, driven by the rising share of AGR, and to China, due to the growing participation of the IC group.

VII.1. Export emissions, excluding land use change

Graph 18 shows the trajectory of export emissions by trade partners. China was by far the trade partner that presented the highest growth in emissions embodied in its trade relations with Brazil. At least two factors help to explain this trend: the increasing scale of Brazilian exports to China; and the high relevance of AGR and IC groups in the composition of these exports. The same applied to the emissions embodied in exports to the RoW.

Graph 18 - Brazilian export emissions by trade partner

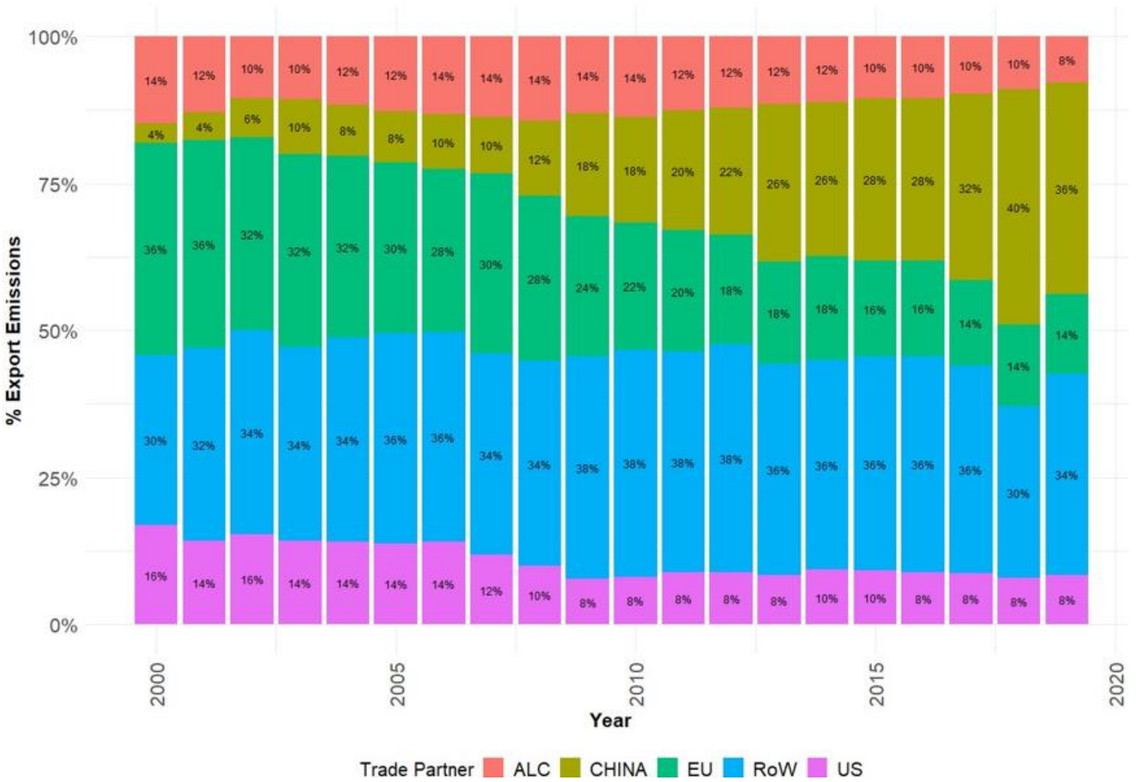


Source: author's elaboration

Meanwhile, emissions embodied in exports to the EU saw a significant decline after 2004, mirroring a corresponding decrease in the value of Brazilian exports to this partner. Between 2005 and 2010, Brazilian exports to the EU fell by 15.3%, primarily driven by a 28.7% reduction in AGR exports. This indicates that both scale and composition effects played a role in the observed decline. A notable reduction in emissions can also be seen in exports to the US, albeit to a lesser extent. In this case, the value of exports dropped even more sharply, with a 52.8% decline. However, this reduction was largely concentrated in IM (-73.8%) and TM (-53.3%) exports, while AGR exports actually grew by 17.2%.

As a consequence of these development, a great shift in the participation of each partner in total Brazilian exports emerged. China's share of Brazilian exports-linked emissions increased throughout the period, rising from approximately 4% to 36% (Graph 19). The shares of all other trading partners have been squeezed out. Most likely, the shifts in each partners' shares in exports-linked emission derived from a combination of factors, such as changes in the scale and composition of exports to these partners and the technology used to produce the exported goods and services, among other factors that will be explored in further detail in the next chapter.

Graph 19 - Brazilian export emissions by trade partner (%)



Source: author's elaboration

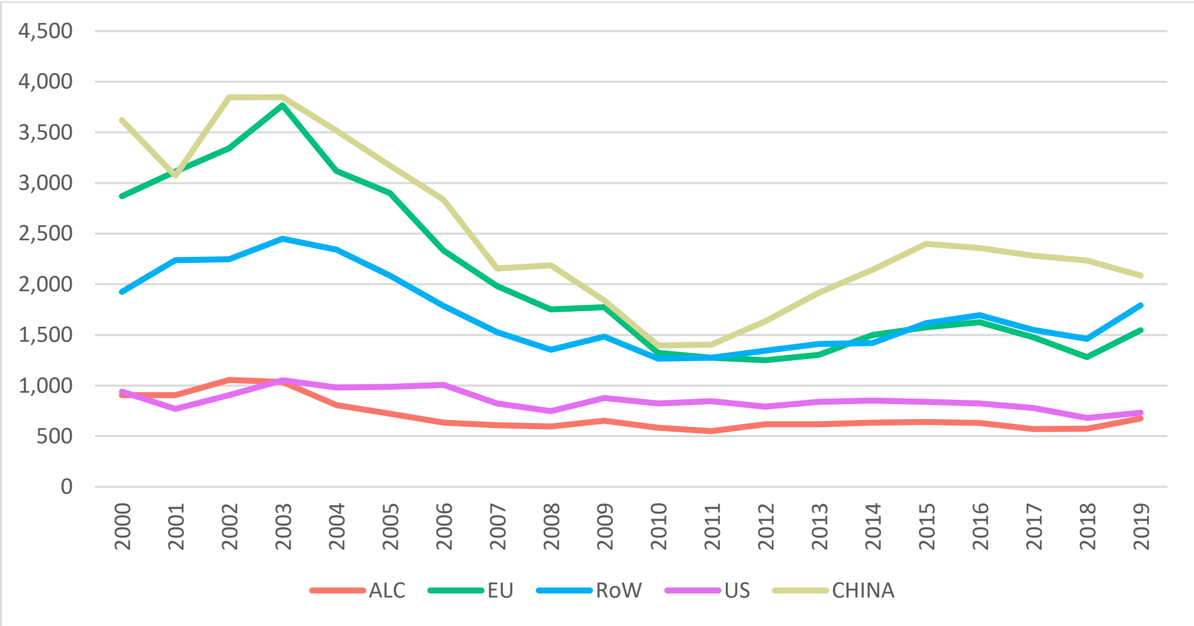
Graph 20 illustrates the emission intensity of exports by trade partner, highlighting China, the EU, and the RoW as having the highest values. This aligns with Brazil's more commodity-intensive export baskets for these partners (Table 18). Nevertheless, it is worth noting that those baskets were the ones presenting the largest emission intensity reduction up until 2008. This trend may be linked to the reduction in AGR's emission intensity especially after 2005, which ended up greatly impacting the emission intensities of the export baskets with China, the RoW, and EU due to the significant weight of the AGR group in these baskets.[59]

Conversely, the emission intensity of exports to the US followed an upward trajectory in the first decade. During this period, the share of AGR, IC, and AC groups in the US import basket from Brazil increased from 37.5% to 61.9%, explaining the rising trend for the emission intensity. As for the LAC, their import basket from Brazil experienced a slight reduction in its emission intensity since 2008. In addition to the previously mentioned reduction in AGR emission intensity, the share of this group in Brazilian exports to the LAC was cut by half.

[59] Table 9 shows that the emission intensity of the AGR group dropped 16.9% between 2000 and 2008.

There seems to be an inflection point in the trajectory of emission intensity, somewhere between 2008 and 2011, depending on the trading partner. This may reflect a multiplicity of factors, such as (i) the increase in thermoelectric plants, which significantly impact emissions embedded in exports from the IC group; (ii) the rising trajectory of deforestation rates after 2012; and (iii) a deepening of the reprimarization process (Passoni, 2019).

Graph 20 - Exports' emission intensity by trade partner



Source: author`s elaboration

VII.2. Export emissions, excluding land use change

As mentioned earlier, land use change (LUC) is the primary source of GHG emissions in Brazil. Chapter 2 allocated LUC emissions based on the contribution of different economic activities to land use transition from forest to other land covers. Since nearly 100% of forest and other primary vegetated area conversions were driven by farming and cropland expansion, almost all emissions from this source were attributed to the AGR sector.

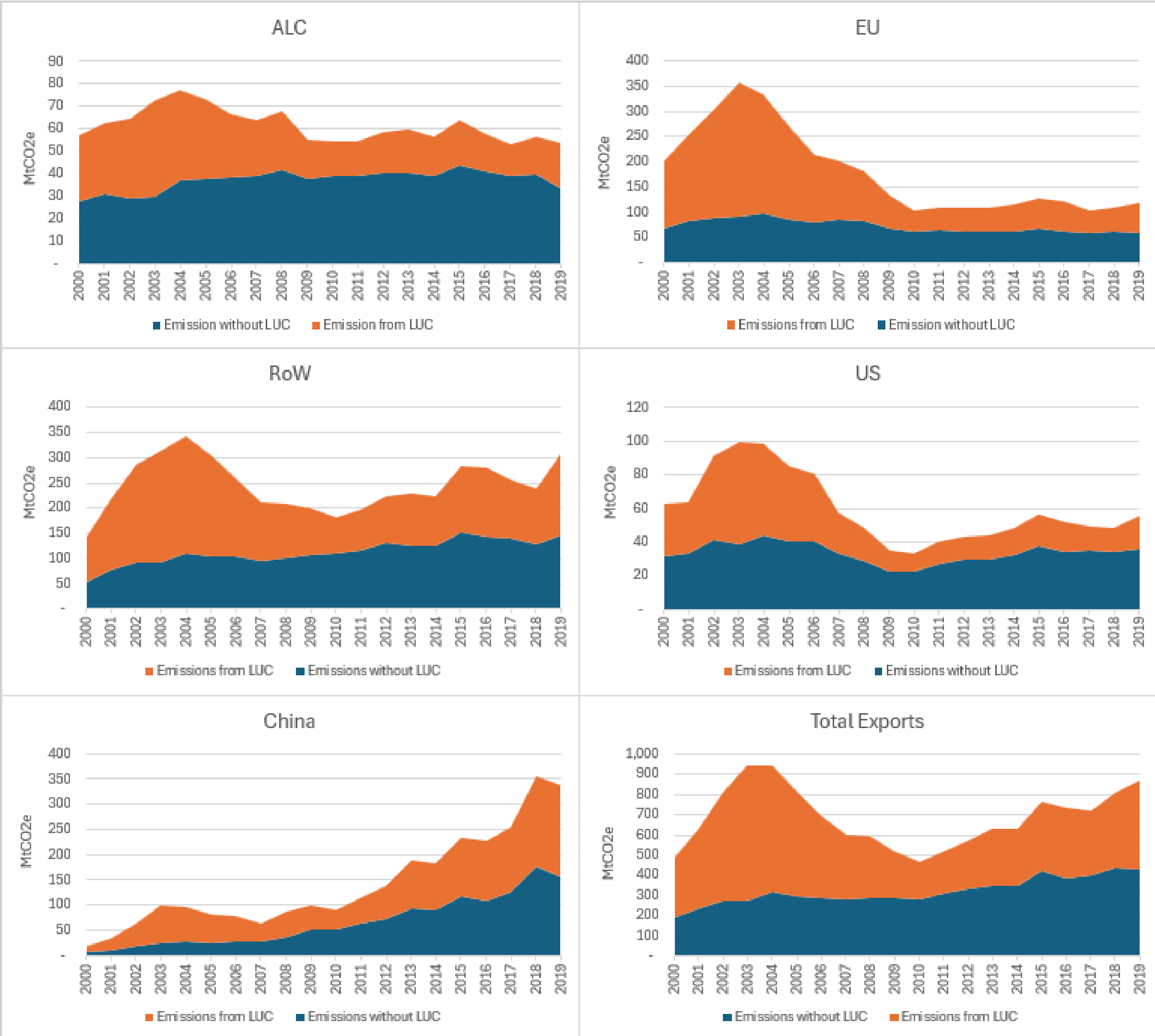
The loss of natural areas is also the main driver of biodiversity loss and is responsible for disrupting many ecosystems, compromising their ability to continue providing essential goods and services. Although understanding the economic, social, and environmental impacts (including feedback effects) of these losses is highly relevant, it goes beyond the scope of this thesis, which focuses on the impact of recent structural changes on Brazilian GHG emissions.

Nevertheless, one of the novelties of this thesis is the estimation of exported GHG emissions by trade partners, with and without land use change. This provides a clear view of the emissions exported to each partner, as well as the extent to which emissions from deforestation are embedded in Brazil's trade relations. These results can inform discussions on shared responsibility for GHG emissions and other environmental issues linked to deforestation.

Graph 21 shows the trajectory of export emissions by trade partner, separating emissions without land use change (blue area) from those specifically from land use change (orange area). Therefore, the combined areas represent the total export emissions for each trade partner. Emissions to all trade partners were significantly impacted by deforestation, in some cases more than doubling what the amount was when LUC emissions were not taken into consideration. Indeed, when emissions from LUC were included, the average emissions embodied in exports increased by 66.2% for LAC, 144.7% for the EU, 117.5% for the RoW, 77.3% for the US, and 118.1% for China.

Except for China, all trade partners experienced the highest deforestation impact in their import baskets from Brazil in 2004, when deforestation rates in the Amazon peaked. However, at that time, Brazilian exports to China were relatively small, particularly in the AGR sector. So, the highest deforestation impact on China's import basket from Brazil occurred in the 2010s, when China was already the main Brazilian partner, and deforestation rates entered a rising path.

Graph 21 - Export emissions without LUC and emissions from LUC, by trade partner



As seen in Section V, the share of exports in total Brazilian emissions increased from 19.8% to 35.6% between 2000 and 2019. This indicates growing responsibility of international trade for Brazilian emissions, under a consumption-based approach.[60] Table 19 isolates the export emissions linked to LUC and distributes them across Brazil's trading partners. Since these emissions resulted from burning biomass during the conversion of natural areas into farms and croplands, the significant growth in the share of exports in LUC emissions indicates that international trade has increased its links with Brazilian deforestation and the various environmental issues that came with it. In fact, the table shows that all trade partners combined were responsible for a staggering 38.8% of the emissions from LUC, which is almost twice the share observed in 2000.

[60] For a definition of consumption-based and production-based approaches, see Chapter 1, subsection III.1.3.

Regarding the share of each trade partner, the EU used to occupy the top position, accounting for 8.9% of total LUC emissions. This percentage peaked in 2003 and then steadily dropped as AGR exports to the EU declined (Graph 15). This reduction also resulted from the rapid expansion of AGR exports to China and the RoW, which caused other partners' share of LUC emissions to decline. Between 2000 and 2019, AGR exports to these two partners increased from BRL 1.8 billion and BRL 4.8 billion to BRL 54.7 billion and BRL 35.5 billion, respectively.

Table 19 - LUC emission by trade partner (%)

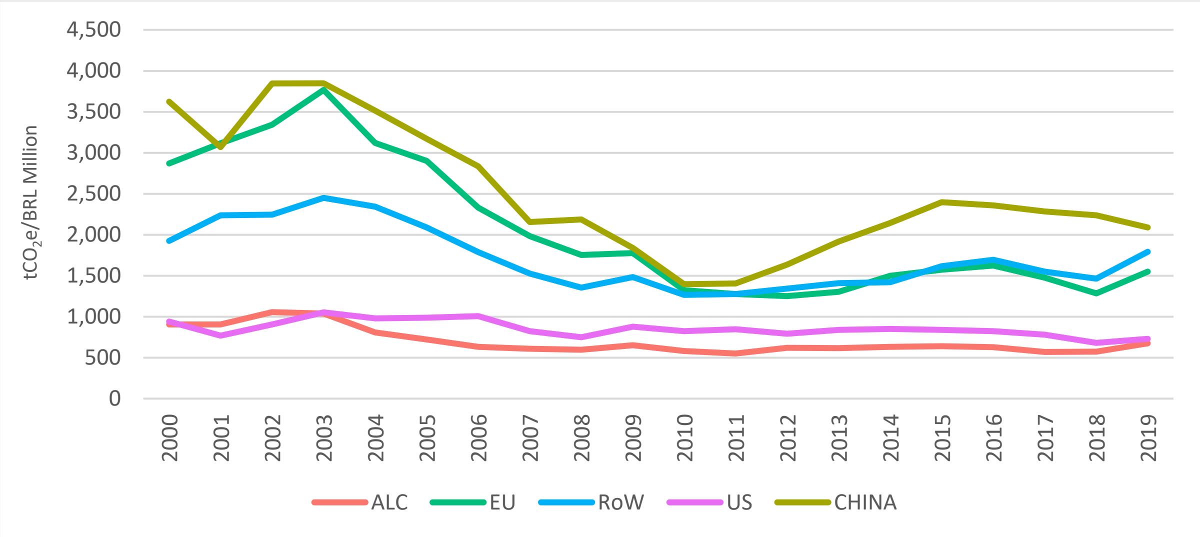
Year	Trade partners' share of total Brazilian emissions from LUC					
	LAC	EU	RoW	US	CHINA	Total
2000	1.9%	8.9%	5.8%	2.1%	0.9%	19.7%
2001	2.0%	10.6%	8.7%	1.9%	1.5%	24.6%
2002	2.1%	12.5%	11.1%	2.9%	2.7%	31.3%
2003	1.9%	12.1%	10.0%	2.7%	3.3%	30.1%
2004	2.0%	11.3%	11.2%	2.6%	3.3%	30.3%
2005	2.1%	10.9%	11.7%	2.6%	3.4%	30.6%
2006	2.2%	10.2%	11.8%	3.1%	3.8%	31.1%
2007	2.3%	10.4%	10.4%	2.2%	3.4%	28.7%
2008	2.5%	9.3%	10.1%	1.8%	4.8%	28.5%
2009	2.4%	8.6%	12.2%	1.7%	6.5%	31.4%
2010	2.3%	6.4%	10.7%	1.5%	5.8%	26.8%
2011	2.2%	6.6%	11.6%	1.9%	7.5%	29.8%
2012	2.3%	6.0%	12.2%	1.7%	8.2%	30.4%
2013	2.2%	5.5%	11.4%	1.6%	10.3%	31.1%
2014	2.2%	6.5%	12.3%	2.0%	11.5%	34.6%
2015	2.1%	6.2%	14.1%	1.9%	12.7%	37.1%
2016	1.9%	6.2%	14.7%	1.9%	12.8%	37.6%
2017	1.7%	5.6%	14.2%	1.7%	15.5%	38.8%
2018	1.9%	5.5%	12.6%	1.6%	20.6%	42.3%
2019	1.7%	5.0%	13.3%	1.6%	15.3%	36.9%

Source: author's elaboration

Incorporating LUC emissions into the analysis significantly raises the emission intensities of exports. This impact is particularly pronounced for trade partners with whom Brazil's export basket is more heavily reliant on primary goods. For the period under review, while the inclusion of LUC emissions results in an average intensity increase of 69.3% for LAC and 73.8% for the US, for partners like China, the EU, and the RoW, the intensity rises by over 150%, 137.2%, and 124.3%, respectively.

In the analyzed period, the share of LUC emissions in total exports' emissions, averaged 52.2%. In the early 2000s, as deforestation rates increased in the Brazilian Amazon, emission intensities for all trade partners increased. However, when more stringent deforestation control policies were implemented, this trend reversed up until 2011. An exception is the US, where emission intensity remained relatively stable from 2003 to 2008, as TM and IM exports to the country sharply declined by 52.1%. It seems that the reduction in emission intensity due to lower deforestation rates was counterbalanced by the reduced share of the two least emission-intensive sectors. Finally, after 2011, the acceleration of deforestation rates, combined with the increasing emission intensity of power generation, led to higher emission intensities for the AGR and IC sectors. Therefore, the emission intensity of the Brazilian export basket with all trade partners increased.

Graph 22 - Export emission intensity by trade partner – with LUC emissions



Source: author's elaboration

CONCLUDING REMARKS

This chapter presented the structural profile of Brazilian GHG emission between 2000 and 2019, seeking to shed light on the distribution of emissions between industrial groups and final demand components, their intensities, and trends. The main intention of this chapter was to demonstrate the behavior of emissions in a period for which the literature indicates, although with some controversy over its intensity and timing, the occurrence of a process of regressive specialization for the Brazilian economy. Among the converging aspects of this debate, there is a certain understanding that this process was more intense for exports and that after the 2008 crisis, there is an intensification of this specific pattern of specialization.

The results in this chapter are divided into two scenarios, with and without emissions from land use change. This source of emissions is too relevant not to be considered, but this very relevance means that its inclusion tends to dominate various trends.

In sectoral terms, the results point to an absolute predominance of industrial groups related to the production of commodities. In a scenario where emissions from land use are disregarded, the AGR group accounted for an average of 52.3% of emissions in the period, followed by the IC group, with 15.7%. Another 0.7% of emissions come from the production of processed agricultural commodities. This means that approximately 69% of national emissions result from the commodity production. When emissions by land use are included, the share of these three industrial groups rises to 84%, with AGR alone contributing 74.8%. In 2003, given the high rates of deforestation in the Brazilian Amazon, the combined share of AGR, IC, and AC peaked at 91.3%. In contrast, the IM and TM groups contributed less than 4% of national emissions, with or without land use change, in all years of the series.

Various factors contribute to the different weights of industrial groups in national emissions, such as scale of production, technology, and emissions intensity. However, there is no doubt about the importance of differences in emissions intensity. Commodity-producing industrial groups are, by far, the most emissions-intensive in Brazil's production structure. The results show that the AGR group, the most polluting sector, is 248.6 times more emissions-intensive than the IM group, the least polluting sector. When emissions from land use are included, this disparity increases to 737.3 times. The difference between the emissions of these two groups allows us to understand why they have such different weights in total emissions. Meanwhile, the emission intensities of the IC and AC groups are 24.8 and 6.1 times higher than those of the IM group.

The trajectory of emissions intensities by industrial group revealed two relevant trends. The first is that only the AGR and IC groups showed significant reductions in intensity. One possible hypothesis is that these industrial groups' closer relationship with exports subjects them to greater scrutiny from the international market, resulting in greater efforts by companies in this sector to comply with international environmental criteria and standards. The second trend pertains to the worsening emission intensities of the TM and IM groups from the late 2000s to the early 2010s. This development is particularly concerning, not only because it diverges from the path toward decarbonization, but also because it may signal a process of adverse selection driven by recent structural changes within these industrial groups. In other words, these changes may not only reflect a regressive specialization for the economy as a whole but could also be favoring firms within these groups that have greater capacity to evade environmental costs as a way to outcompete others. These two hypotheses are crucial for understanding the implications of structural shifts in the country's emissions profile, though they would require firm-level analysis, which falls beyond the scope of this study.

In terms of emissions trajectory, the AGR group showed an increasing trajectory throughout the period. The data from the demand side emission growth accounting revealed that exports were the main driving force behind AGR`s emissions between 2000 and 2019, and in the sub-periods 2000-2004, 2010-2014, and 2014-2019. The only sub-period in which the AGR group's emissions growth was not primarily related to exports was between 2005-2010, possibly reflecting the downturn in international trade in the immediate aftermath of the 2008 crisis. In fact, this was the only period in which total exports made a negative contribution to emissions growth.

Other industrial groups, such as TM, IM, and services, had emissions growth trajectories more related to domestic factors. With regard to the first two groups, the reversal of the emissions growth trajectory occurs at the beginning of the 2010s, while services continue with growing emissions until the middle of the same decade, probably in response to the greater use of fossil sources for electricity generation between 2010 and 2015.

Analysis of emissions by component of final demand revealed an acceleration in emissions from exports, especially between 2000 and 2004 and after 2010. This growth resulted in a substantial increase in the share of exports in total emissions from 19.5% to 31.8% over the period analyzed. This trend was very much influenced by commodity-linked groups. Indeed, the demand-side emission growth accounting revealed that AGR and IC were the main culprit of the increase in exports-linked emissions throughout most of the periods, except for the 2005-2010.

Despite the reduction in AGR and IC emission intensity and the significant role of these groups in the total value of exports, exports were the only final demand component to increase its emission intensity between 2000 and 2019. During this period, the share of AGR, IC, and AC in Brazilian exports rose from 44.2% to 62.5%. This suggests that the impact of changes in the composition of exports on emissions may be outweighing the effects of declining emission intensities in these industry groups.

As expected, the behavior of emissions from the other components of final demand was very much in line with the growth path of domestic absorption. Emissions from household consumption, investment, and government consumption began to decline from 2015 onwards, in response to the economic crisis and the reversal of the fiscal situation.

This chapter has also presented another relevant result for the purposes of this thesis: commodity-producing industrial groups not only have the highest emissions intensities but also the greatest potential to induce or propagate emissions from other sectors, given their high emission linkages. In contrast, the IM group presented a quite modest backward and forward emission linkages compared to the other groups.

To see how different industries performed in terms of their power to pull and dissipate emissions compared to the average of the economy, we normalized the backward and forward emission linkages. Drawing on these normalized indicators, we clustered all 42 industries into four groups according to their capacity to drive decarbonization. We found that all the IM and most of the TM group fall into the category of transition enablers, as their industries neither pull nor propagate large amounts of emissions from and to other industries. Therefore, a pattern of structural change that harms the transition enabler industries could lead to fewer opportunities for transitioning to a low-carbon economy.

Last but not least, given the importance of exports in national emissions, this chapter sought to deepen the analysis of the emissions contained in Brazilian exports. Among the main trends was the high growth in China's share of national emissions. This growth is the result not only of the surging value exported to this country but also of the large share of the AGR and IC groups in its composition. The greater share of AGR and IC in exports to China makes the trade relations with country by far the most emissions-intensive among the Brazilian trading partners.

A rather concerning result is the increase in emission intensities in Brazil's trade relations with all its trading partners starting in 2008. This could be due to various factors, such as a worsening of industry emission intensities or the technologies employed. However, some indications suggest that changes in the composition of Brazilian exports to these countries may be contributing significantly. The main evidence for this is the increase in the share of commodities in exports to all partners starting in the second half of the 2000s. The only exception was in the export to LAC countries, for which the share of commodities in 2019 was roughly the same as in 2005.

Finally, the increasing share of AGR in total exported led to a significant rise in exports participation in emissions from land use change. Indeed, during the period covered by this thesis the responsibility of international trade in Brazil's emission from LUC surged by 19.7% to 36.9%, after peaking at 42.3% in 2018.

CHAPTER 4 - STRUCTURAL DECOMPOSITION ANALYSES OF BRAZILIAN GHG EMISSIONS

I. INTRODUCTION

The previous chapter presented the structural profile of Brazilian GHG emissions based on a series of indicators. The results previously presented revealed some concerning signs, such as the much higher emission intensities and linkages of commodity-related groups. This helps explain why, during periods of accelerated outward growth, which tends to rely more on commodities, national emissions expanded faster, such as during 2000-2005, and after 2011.

The rapid growth in export value alone is enough to pose additional challenges for Brazil in reducing its emissions. However, the country has also undergone a significant shift in the composition of its exports, with a growing share of commodities. This shift was partly driven by Brazil's expanding trade relationship with China and other partners whose imports from Brazil were predominantly commodity-based. Additionally, increasing competition in global markets—especially after the late-2000s financial crisis—further weakened Brazilian manufacturing exports, reinforcing the country's reliance on commodity-base trade pattern. Indeed, the share of commodities in Brazilian exports has risen across all trade partners, except for the Latin America region. These changes certainly contributed to the 39.8% increase in export emission intensity between 2008 and 2019

As may be evident by now, many factors are at play driving the trends presented in Chapter 3. This can range from an increase in deforestation rates, or worsening in technology, to a deepening regressive specialization.

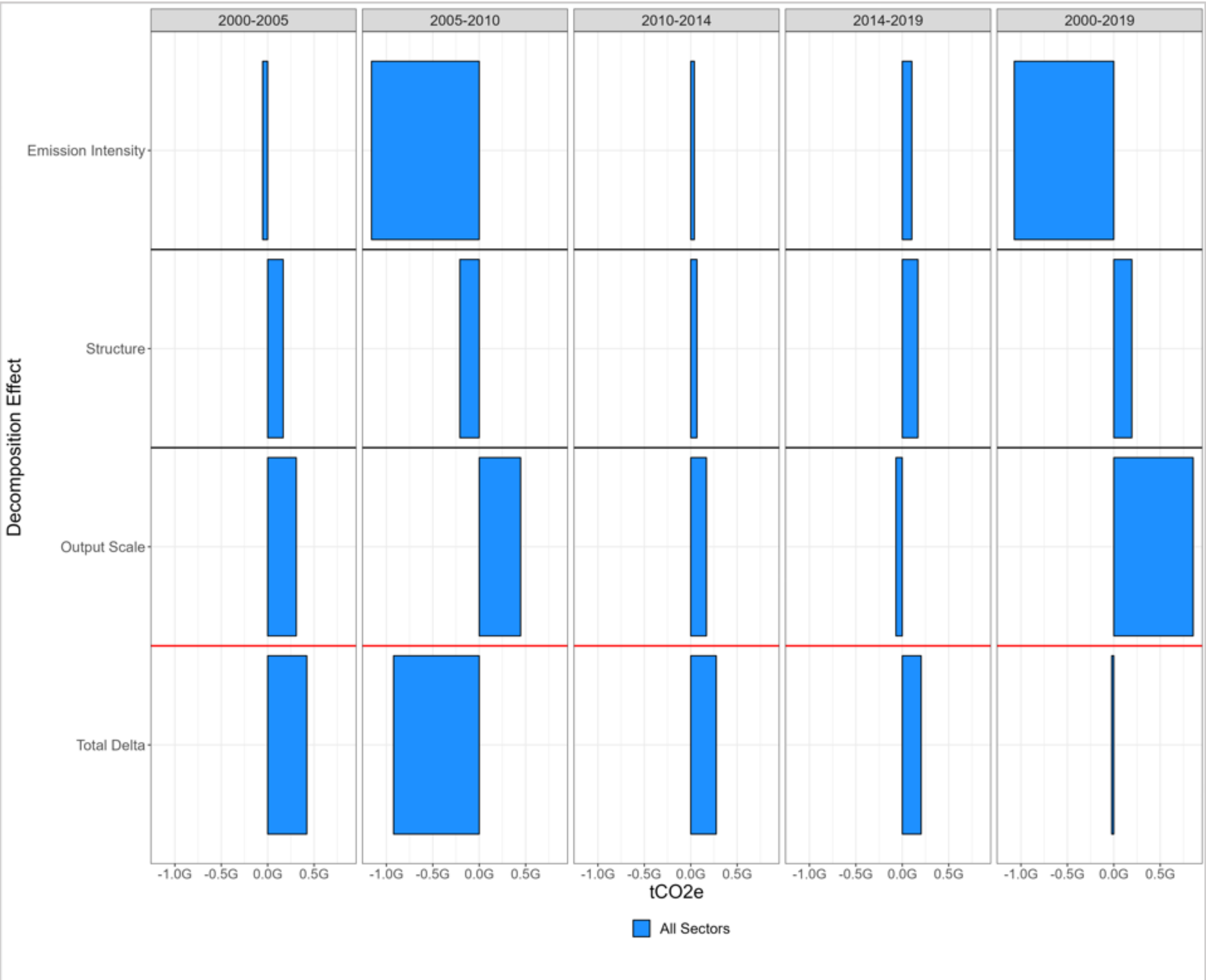
If the previous chapter presented the main trends, i.e., how emissions have increased, in this chapter we will seek to explain why they have increased. This will be done using three structural decompositions. Two of them are carried out for Brazil's total emissions: the first examines contributions from changes in emissions intensity, output scale, and sectoral composition, while the second considers variations in deforestation rates, technology, industrial density, and shifts in final demand structure – including changes in component weights, sectoral composition, scale, and import coefficients. Finally, a third decomposition seeks to clarify the driving factors of exports' emission increase, focusing on the changes in their scale, composition, and the share of each trading partner in Brazilian exports.

II. Decomposition of total emissions into intensity, scale, and structure effects

II.1. Emission changes between 2000 and 2005

In the first period, emissions grew by 421.4 $MtCO_2e$. The primary factor behind this emission increase was the rise in gross output, which accounted for 308.3 $MtCO_2e$. Meanwhile, the structure effect reached its highest value (167.4 $MtCO_2e$) during the period covered by this thesis, indicating that the Brazilian economy underwent substantial shifts in the sectoral composition of output toward industries with higher emission intensity in the first half of the 2000s. The emissions from changes in both output scale and composition were partially offset by a reduction in the industries` emission intensity.

Graph 23 - Structural breakdown of GHG emissions in three terms



Source: author's elaboration.

Breaking down the decomposition by industrial group, we observe that the effects vary significantly across the economy (Graph 24). The magnitude of the effects for the AGR group far outweighs those for other groups. The intensity effect for this group tends to be higher due to the connection between its output and deforestation. As seen in Chapter 2, almost all emissions from forest conversion are allocated to the AGR group. Thus, even small variations in deforestation rates tend to result in large changes in the intensity effect for this group.

The much greater emission intensity of the AGR group also explains why its scale and structure effects were comparatively greater. In general, when we break down the decomposition by industry group, we are left with group-specific decomposition weights. This means that the scale effect of a given industry group will be weighted by its emissions intensity. However, this is not merely an algebraic result. The higher scale effect for a highly emissions-intensive group such as AGR indicates that when an output expansion takes place for this group, it tends to be accompanied by larger amounts of emissions. This is because each additional unit of output from AGR produces significantly more emissions than when produced by other groups. Similarly, its structure effect tends to be higher, as its high emissions intensity amplifies even the smallest changes in its share of total output. Therefore, when the AGR group gains (or loses) relative importance in total output, even if the gain (or loss) is relatively small, the emissions resulting from its structure effect tend to be substantial.

Indeed, taking a closer look at the AGR, we see that this group was the primary source of emissions resulting from shifts in output level and composition, accounting for 82.1% of the total scale effect and 72.2% of the structure effect. With regard to the intensity effect, there was a slight increase in the value for the AGR group. As seen in the previous chapter, the emissions intensity of this group increased slightly over the period, from 8.738 tCO_2 to 8.748 tCO_2 for every million reais produced, which explains the positive intensity effect. The reasons for the changes in the intensity effect will become clearer in the next section as we decompose it into carbonization and deforestation effects.

As IC industries' emission intensity is also high compared to the average, this group`s scale and composition effects also tended to be comparatively greater. In this period, an increase in the IC group`s output scale led to an additional emission of 19.1 $MtCO_2e$, while the structure effect resulted in another 34.5 $MtCO_2e$.

At this point, it is important to clarify that the high positive value shown for IC's structure effect does not necessarily imply that the group increased its share of total output. In a disaggregated decomposition, the structure effect will be positive for industries presenting increasing participation in total output, but negative otherwise. The magnitude of the structure effect of each industry will depend on its weights, meaning that industries with high output and emission intensity will exhibit greater structure effects. The sign of the structure effect that will prevail for each industry group will reflect the sum of the structure effect of each of its industries. Hence, an industry group can exhibit a positive structure effect, either if all its industries increase their share of total output or if some of its industries with sufficiently high emission intensity or scale compared to the group`s average increase their shares. In other words, there might be cases where an industry group is losing (gaining) participation in total output, but its structure effect is positive (negative). This can happen when one or a few of the highly emission-intensive industries in the group increase (decrease) their share of total output and end up dominating the sign of the structure effect. In this sense, the structure effect does not necessarily indicate whether the economic structure is specializing in carbon-intensive industries. What the structure effect does indicate is whether a change in the output composition is conducive to structural decarbonization. [61]

That being said, it is interesting to note that the three industry groups linked to commodity production accounted for 92.6% of all emission growth during this period. Of the total structure effect of 167.4 $MtCO_2e$, more than 92.5% was due to the increase in the share of one or more industries within these groups in total output, while 88.6% of the total scale effect resulted from growth in commodity production.

Table 20 - Structural decomposition of Brazilian emissions by industrial group - in $MtCO_2e$

Period	Effect	AGR	IC	AC	TM	IM	Services	Total
2000-2005	Intensity	2,080,764	-39,386,193	-264,385	638,915	-231,914	-17,082,461	-54,245,274
	Structure	120,919,939	34,433,393	-497,162	1,398,488	469,433	10,663,355	167,387,447
	Scale	253,203,693	19,053,920	784,896	3,417,203	473,292	31,288,759	308,221,761
	Total	376,204,396	14,101,120	23,349	5,454,605	710,810	24,869,653	421,363,934
2005-2010	Intensity	-1,161,895,001	8,549,437	-55,320	2,533,250	1,066,228	-10,505,482	-1,160,306,888
	Structure	-186,095,927	-19,861,674	-651,582	-3,599,640	-259,547	2,140,144	-208,328,225
	Scale	347,480,084	33,488,488	1,289,397	6,448,589	983,397	56,217,009	445,906,964
	Total	-1,000,510,844	22,176,251	582,494	5,382,200	1,790,078	47,851,671	-922,728,150
2010-2014	Intensity	-42,613,110	14,973,786	1,006,641	-10,907,355	-572,318	77,284,603	39,172,247
	Structure	78,328,910	-5,931,771	-1,019,793	-91,292	-771,558	-3,762,242	66,752,254
	Scale	114,500,486	17,597,102	646,461	2,860,453	503,101	32,793,942	168,901,544

[61] As one of the objectives of this thesis is precisely to understand whether recent changes in the Brazilian productive structure have led to a carbonization of the economy, the structure effect seems appropriate for this specific objective. Another extremely important debate focuses on whether these changes in the productive structure, in addition to pointing to a process of regressive specialization, point to a process of specialization in emissions-intensive industries. The results presented in the previous chapter provide strong evidence that this hypothesis is valid. Nevertheless, other indicators will be presented in the final section of this chapter.

	Total	150,216,286	26,639,117	633,309	-8,138,194	-840,775	106,316,303	274,826,045
2014-2019	Intensity	178,480,703	-7,218,195	-550,838	2,653,523	238,853	-70,307,968	103,296,078
	Structure	137,827,461	-11,616,862	1,285,118	1,028,583	-443,758	40,435,076	168,515,617
	Scale	-47,901,990	-6,311,712	-249,500	-925,760	-158,795	-12,808,711	-68,356,469
	Total	268,406,174	-25,146,769	484,779	2,756,346	-363,700	-42,681,604	203,455,226
2000-2019	Intensity	-1,023,946,645	-23,081,165	136,098	-5,081,667	500,848	-20,611,308	-1,072,083,838
	Structure	150,980,384	-2,976,914	-883,420	-1,263,861	-1,005,429	49,476,333	194,327,092
	Scale	667,282,272	63,827,797	2,471,253	11,800,485	1,800,993	107,490,999	854,673,800
	Total	-205,683,989	37,769,719	1,723,931	5,454,957	1,296,412	136,356,024	-23,082,945

Source: author's elaboration

In the meantime, the structure effect of IM is only positive in the first period, turning negative for the rest of the periods. However, according to Table 21, the IM group increased its share of output until 2008. These signs may seem counterintuitive at first, as they show that more emissions are generated when innovative manufacturing, the least intensive industrial group in Brazil's productive structure, increases its share of output, while the loss of this group's share results in emission reductions.

To better understand this apparent contradiction, we must recall that the sign of each industry's structure effect is given by its delta (i.e., the variation in its share of total output). Let us, now, assume that all IM industries are expanding their participation in total output. This would necessarily imply a positive structure effect for this group. However, this does not mean that an increasing share of innovative industries would result in greater emissions for the economy through the structure effect. As we are dealing with relative participation, in order for innovative industries to gain weight in the product, at least one industry in another industrial group must have its participation reduced, for which a negative structure effect would emerge. The net effect of this output recomposition will depend on the emissions intensity of the innovative industries relative to that of the industries whose shares are reduced. As IM is the industrial group with the lowest average intensity, a positive structure effect from its industries tends to be accompanied by a greater negative effect elsewhere.

Therefore, the expected signs for the structure effect of this group are precisely positive between 2000-2005, and negative for the remaining periods, as this group's share of total output began to decrease only after 2008.

Table 21 - Share of industrial groups in gross output value (%)

Year	AGR	IC	AC	TM	IM	Services
2000	4.32%	10.97%	1.64%	11.60%	8.57%	62.89%
2001	4.41%	11.48%	1.52%	11.54%	8.91%	62.13%
2002	4.91%	11.88%	1.58%	11.28%	8.66%	61.68%
2003	5.50%	13.38%	1.72%	11.86%	8.87%	58.66%
2004	5.33%	13.80%	1.79%	12.08%	9.75%	57.24%
2005	4.59%	14.29%	1.61%	11.55%	9.70%	58.26%
2006	4.33%	14.18%	1.52%	11.06%	9.60%	59.31%
2007	4.39%	13.71%	1.48%	10.85%	9.79%	59.78%
2008	4.70%	14.31%	1.39%	10.81%	9.97%	58.82%
2009	4.50%	11.99%	1.27%	10.60%	8.92%	62.72%
2010	4.13%	12.25%	1.37%	10.17%	9.48%	62.61%
2011	4.40%	12.58%	1.26%	10.15%	9.05%	62.56%
2012	4.33%	12.28%	1.22%	10.20%	8.53%	63.44%
2013	4.50%	12.21%	1.18%	10.00%	8.67%	63.43%
2014	4.40%	12.17%	1.19%	9.84%	7.95%	64.46%
2015	4.68%	11.36%	1.19%	9.94%	7.20%	65.62%
2016	5.11%	10.36%	1.21%	10.28%	6.68%	66.35%
2017	4.91%	10.59%	1.22%	10.06%	7.04%	66.18%
2018	4.89%	12.05%	1.32%	9.94%	7.33%	64.47%
2019	4.84%	12.10%	1.27%	9.90%	7.29%	64.60%

Source: author's elaboration

II.2. Emission Changes between 2005 and 2010

During the period 2005-2010, an acceleration of the economy brought the output scale effect up to 445.9 $MtCO_2e$, the highest figure among the periods analyzed. The impact of this output expansion on GHG emissions was alleviated by a shift in output composition towards industries with lower emission intensities. This was the only period in which the structure effect was negative. Even though a shift in output composition was not sufficient to fully compensate for the impacts of the increase in the level of economic activity, the total emissions for this period were strongly negative due to a sizable reduction in the emission intensity that led to a negative value for the intensity effect of 992.7 $MtCO_2e$.

If in the previous period, AGR was the main responsible for the emission increase, in this period, this industry group led a reduction in emissions for the Brazilian economy through its intensity and structure effects. As shown in Table 21, the AGR's share of total output dropped by 0.46 percentage points, resulting in a negative structure effect of 186.1 $MtCO_2e$. Meanwhile, a reduction in AGR's emission intensity contributed an additional emission reduction of

1,000.5 $MtCO_2e$. Together, these effects largely offset the emissions from this group's output growth.

The IC's scale effect resulted in emissions of 33.5 $MtCO_2e$, a figure 75.8% larger than in the previous period. This sharp increase in the IC's scale effect might be related to the growing international demand for industrial commodities spearheaded by China. Contrary to what happened with the AGR group, the IC`s intensity effect was positive, contributing to further increasing this group`s emissions. Even though the negative structure effect offered some relief for this group`s emission, it did not suffice to fully offset the emissions stemming from its larger production level and intensity.

The AC group showed a remarkable increase in its emissions between 2005 and 2010 compared to the previous period. The strong increase was mostly driven by the faster expansion of its output, together with a sharp reduction in its intensity effect. Still, given the relatively low emission intensity and participation in the total output of this group, its emission changes tended to be quite small throughout the entire period.

In the meantime, an emission increase for the TM totaled 5.4 $MtCO_2e$, which is slightly lower than that of the period 2000-2005. It is interesting to note that the drop in the total emission change in the second period happened regardless of the sharp increase in this group`s scale and intensity effect. What made this reduction possible was a significant negative value for the structure effect, which reflected the drop in TM`s participation in the total output from 11.6% to 10.2% in this period. It is worth mentioning that all TM industries in this period scored a negative structure effect, meaning that all of them dropped their share of total output.

Implications for economic development aside, it is hard to tell whether this loss was beneficial to decarbonization. For that, we would need clarity on which sectors were responsible for squeezing TM industries' share of total output, and, depending on their comparative emission intensities, the outcome could be negative or positive. In fact, it does not make much sense to analyze what is happening with the structure effect of a group without considering trends in the overall structure effect for the whole economy. The former says how each group is contributing to overall value, but it is the total structural effect that will offer unequivocal evidence of whether or not the changes in the economic structure are conducive to decarbonization.

The IM group presented a similar pattern to that of the TM group, with a positive scale and intensity effect and a negative structure effect. However, over this period, the IM group has increased its scale effect to a much greater extent compared than in previous period and presented a much lower structure effect. Regarding the first point, the IM group showed the largest scale effect increase in relative terms (107.8%) among all the industry groups. During this period, the IM group performed relatively well, scoring the second-largest output growth, only behind the service sector.[62] Despite its good performance, the IM`s output grew at a rate slightly below that of total output growth, especially after 2008. As a result, this group's participation in total output reduced, explaining its negative structure effect.

Finally, the service sector scored its highest scale effect in this period, reflecting the rapid acceleration in its output between 2005-2010 period. The emissions from service's output expansion were partially compensated for by a decrease in this group's emission intensity, which was responsible for a 10.5 $MtCO_2e$ emission reduction. Its structure effect was positive in the period, indicating that at least one of its sectors increased its share of total output. In fact, 9 of its 14 sectors increased their participation and contributed to the 4.3 percentage point increase in services' share of total output displayed in Table 21.

These developments will become clearer in the two following sections, which will offer an in-depth analysis of the contribution of changes in final demand, deforestation rates, technology and in the trade pattern on the emission levels.

II.3. Emission Changes between 2010 and 2014

The period 2010-2014 was characterized by a cooling of economic growth resulting from the combination of a slowdown in international trade and an hesitant economic policy that failed to reverse the decelerating trend that emerged in this period.[63] The scale effect was significantly affected by the lower economic growth rates.[64] Despite the positive value, the scale effect was 62.1% lower than in the previous period.

Meanwhile, the structure effect turned positive again. The amount of emissions generated by the shift in output composition toward more emission-intensive industries totaled 66.7 $MtCO_2e$, which is equivalent to 24.3% of all emission increases in this period.

[62] While the output of the services sector grew by 31.4% in this period, IM industries' output increased by 19.5%, followed by a 10% rise in that of AGR industries, 7.6% in that of TM industries, 4.8% in that of IC industries, and 4.5% in that of AC industries. Meanwhile, total output growth for the entire economy was 22.2% (Passoni and Freitas, 2022).
[63] For more on the economic slowdown, see Summa and Serrano (2015), Rossi, Dweck and Oliveira (2018) and Carvalho (2018).
[64] The average GDP growth rate dropped from 4.3% per year between 2005 and 2010 to 3.4% per year in the 2010-2014 period.

The positive structure effect was primarily driven by AGR, as all other groups exhibited a negative value for this effect. As shown in Table 21, this group's share of total output increased from 4.1% to 4.4%, which explains its positive sign. However, all other groups saw their shares decrease, except for services which increased its participation in total output by 1.8 percentage points. So, why did the service group score a negative value for the structure effect? As mentioned earlier, it may occur that one or more industries within an industry group dominate the sign due to their much higher emission intensity. This is precisely what happened to the service group in this period. Even though the group expanded its share of total output by 1.8 percentage points, the structure effect reflects the loss of participation by the 'production and distribution of power, gas, water, sewage, and urban cleaning' industry in total output, given its much higher emission intensity than the group's average.

Regarding the structure effect in this period, it is worth noting that, alongside the increase in AGR's share of total output, eight out of the nine industries in the TM group and all six industries in the IM group exhibited a negative structural effect. A negative value at industry level necessarily implies that this industry is experiencing a fall in its share of total output, as the sign for the industry is given by its delta, which reflects the share observed for the industry in its most recent period minus the share it had in the initial period.

As for the intensity effect, this also turned positive in this period, adding an extra 39.2 $MtCO_2e$ to emissions resulting from the scale and structure effects. It is interesting to note that. while the intensity effects of the AGR and TM groups were driving total emissions downward, those of the IC and service groups were pushing total emissions in the opposite direction.

Finally, it is worth mentioning that the industry groups related to commodity production accounted for 64.6% of all emission growth in this period.

II.4. Emission Changes between 2014 and 2019

Finally, the period from 2014 to 2019 is characterized by an acute recession (in 2015 and 2016), followed by a recovery the intensity of which was not sufficient to restore the pre-existing level of economic activity. This decline in activity levels resulted in a negative scale effect across all industry groups that totaled 68.3 $MtCO_2e$. Nevertheless, total emissions in this period grew by 203,5 $MtCO_2e$. In this sense, this period presents a unique situation, as it combined rising emissions with a declining level of economic activity.

The primary contributor to the emission increase in this period was a shift in the composition of output towards emissions-intensive industries, which was responsible for an emission increase of 168.5 $MtCO_2e$. This is the highest value for the period covered by this thesis and is roughly 2.5 times greater than the amount of emission reduction caused by the decline in output level. In other words, even if the intensity effect had been zero, the shift in the output composition would have been enough to drive an emission increase during this period.

Nevertheless, the intensity effect contributed an additional 103.3 $MtCO_2e$ to emissions. The worsening in emissions intensity was essentially concentrated in agriculture, while the service group contributed to counterbalancing it. The reasons for such differences will become clear in the next section when we decompose the intensity effect into carbonization and deforestation effects.

II.5. The general trend of emission changes between 2000 and 2019

The value of each effect for the 2000-2019 period is equal to the sum of the effect's values from the previous periods. In this sense, the decomposition values for the entire period reveal which forces prevailed over the two decades covered by this thesis.

The results show that an increase in the level of activity was the main force behind the growth in emissions, contributing 0.85 $GtCO_2$. The literature review carried out in Chapter 1 revealed that the scale effect tends to predominate among the forces driving emissions to higher levels. However, by disaggregating the analysis by industry group, we found that the groups linked to commodity production were primarily responsible for the scale effect, accounting for 85.8% of all emissions driven by growth in output level.

The decomposition results feature the intensity effect as the main force opposing the emission increase, which is also in line with the findings of the literature review conducted in Chapter 1. In the Brazilian case, the reduction in emission intensities was spearheaded by the AGR, IC, and service groups. Even though the IM group started from the lowest base in terms of emission intensity, it is somewhat concerning that this group not only failed to reduce its emission intensity but also showed the highest intensity effect of all groups.

The evidence found in the literature review to support the idea that deindustrialization could lead to decarbonization under a "*dematerialization through service*" growth path is, at best, contradictory. Most studies did not find unshakable evidence suggesting that countries undergoing a process of deindustrialization would experience a sectoral output change towards cleaner industries. The structure effect in these studies was mostly either very small or even negative.[65]

The Brazilian case is *suis-generis*, as the structure effect during the period under consideration was neither negative nor small. Between 2000 and 2019 the structure effect totaled 194.3 $MtCO_2e$, representing approximately 22.8% of the scale effect. Therefore, over the period covered by this thesis, changes in output composition were indeed a relevant obstacle to Brazilian decarbonization. While the TM and IM groups had their participation in total output reduced from 20.2% to 17.2% in the period, the groups linked to commodity production saw their share of total output increase from 16.9% to 18.2% (Table 21).

It is important to mention that two driving forces were acting against Brazilian decarbonization. The first was the increase in the AGR group's share of total output that occurred in three out of the four analyzed periods (2000-2005, 2010-2014, 2014-2019), as well as over the entire period from 2000 to 2019. As mentioned before, the AGR industries formed the most emission-intensive group; so a shift by the economic structure towards them would inevitably cause more emissions to be released. This force was sometimes intensified by an expanding participation of other commodity-related groups, as seen between 2000 and 2005, when the share of the AGR, IC, and AC groups in total output increased, or between 2014 and 2019, when both the AGR and AC groups gained a greater share.

The second force was the declining share of total output represented by the TM and IM groups. This trend began in 2005, when the combined share of the TM and IM industries started to drop, and these industries have shown a continuous decline ever since. Initially, this decline was due to a decrease in the TM group's share of total output, while the IM group's share showed some resilience. However, the trend became more pronounced after 2008, when the IM industries' share of total output also began a downward trajectory. Given that IM and TM were the two least emission-intensive groups, deindustrialization in the Brazilian context rose as a relevant source of extra-emissions.

However, the possible implications for the decarbonization of the Brazilian economy go beyond short-run impacts on emissions. As will be addressed in the next section, if these

[65] For more on a critical assessment of the dematerialization through services hypothesis see Kander and Henriques (2010), Savona and Ciarli (2019), and Fix (2019).

industries find their share of the economic structure decreasing, this may lead to the loss of key productive capabilities for the transition towards a decarbonized economy.

III. The contribution of changes in demand, technology, trade patterns and deforestation to Brazilian emissions

The previous decomposition sought to explain the variations in emissions as a function of changes in emission intensity and output based on the equation $\boldsymbol{e} = \widehat{\boldsymbol{E}}\boldsymbol{x}$. However, since $\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f}$, variations in the level of emissions can be written as a function of changes in emissions intensity, the Leontief inverse matrix, and final demand, according to the equality $\boldsymbol{e} = \widehat{\boldsymbol{E}}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f}$. From this functional form, it is possible to decompose the level of emissions in order to understand how forces on the demand side interacted with technology, with changes in deforestation rates, with emissions intensity, and with variations in the pattern of international trade to generate emissions.

More specifically, this section will examine the impacts on emissions from (i) changes in environmental and technical efficiencies, (ii) leakages to imports in intermediate and final demand, and (iii) shifts in final demand structure, i.e., its scale, sectoral composition, and the shares held by each of its categories.

III.1 The contribution of environmental and technical efficiencies

As mentioned in Chapter 2, changes in $\widehat{\boldsymbol{E}}$ can be decomposed into (i) a carbonization effect, which measures the impact of variations in industrial emission intensities (excluding the MUT sector) on total emissions; (ii) a deforestation effect, which measures the impact of variations in emission intensities resulting from land use changes on total emissions. Both effects capture the contribution of environmental efficiency gains (losses) to total emissions.

Meanwhile, $\boldsymbol{A}$ can also be decomposed into two effects, one being a technology effect. This effect also measures the impact of changes in efficiency on emissions. However, in this case, it measures how gains (losses) in technical efficiency – i.e., the amount of input required to produce a unit of output – impact emissions.

As seen in the first decomposition, the intensity effect is negative in the first two periods (2000-2005 and 2005-2010) and then turns positive. These values result from the sum of the carbonization and deforestation effects. As shown in Graph 24, the first effect is negative for all periods, and its magnitude does not vary much from one period to another. In contrast, the deforestation effect is always positive, except between 2005 and 2010, and there is significant variation in its value across the analyzed periods.

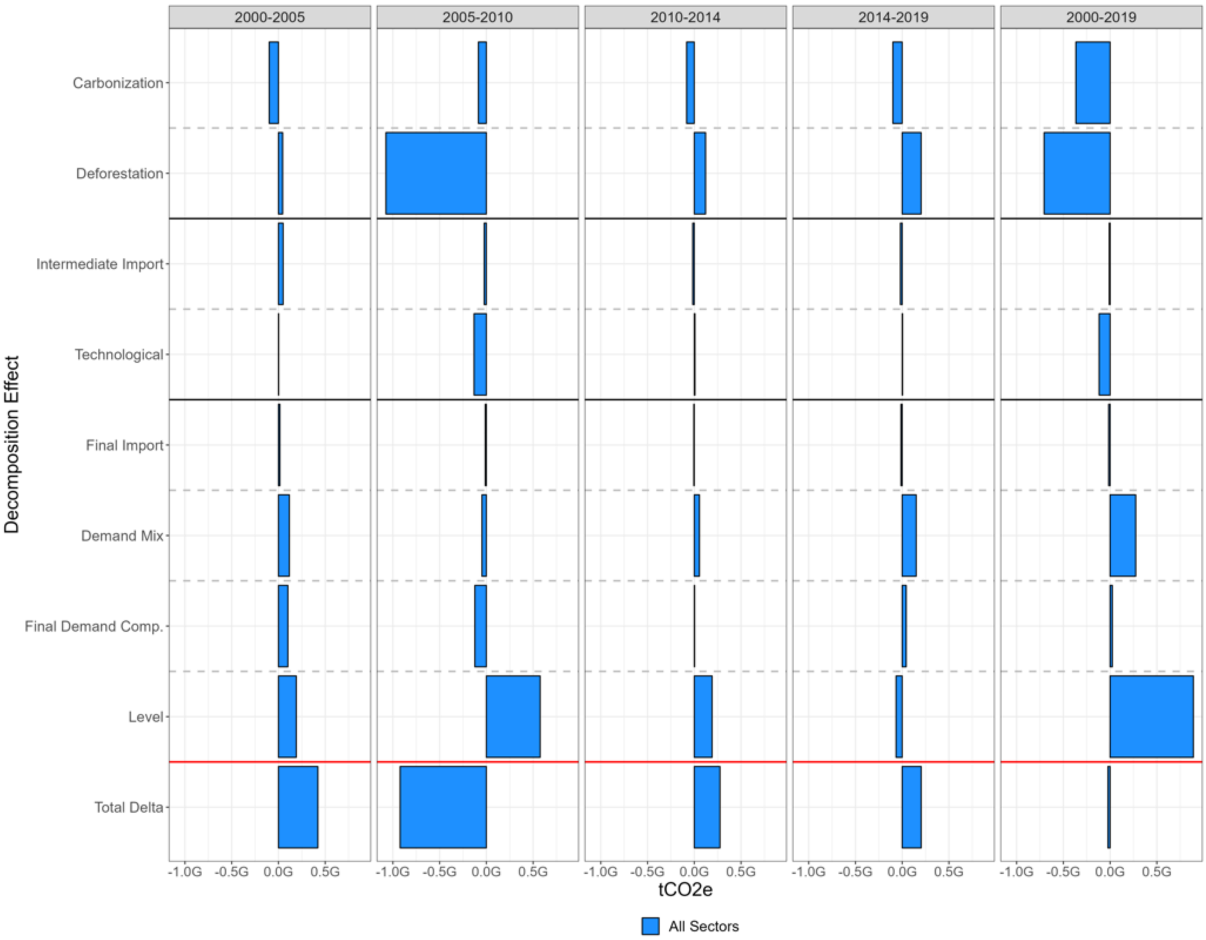
In the first period, the carbonization and deforestation effects move in opposite directions. As shown in Table 22, the carbonization effect was negative, contributing to a reduction in emissions of 99.1 $MtCO_2e$. One factor likely contributing to this reduction was Brazil's adoption of energy efficiency measures in response to a power outage crisis in the early 2000s (Gerard, 2013). During this period, primary energy consumption per unit of GDP fell by 8.9%, and the CO_2 intensity of power production decreased by 2.9% (IEA, 2021). Meanwhile, deforestation rates were still rising in Brazil, explaining the positive value of 44.8 $MtCO_2e$ for the deforestation effect.

In the second period, PPCDAM came into force, rapidly reducing deforestation rates in the Brazilian Amazon. Over this five-year period, deforestation dropped by 63.2%, resulting in a 67.1% decrease in emissions from LUC. The deforestation effect totaled -1,074.7 $MtCO_2e$, by far the largest contribution of any effect in any period to emissions reduction. It was precisely the negative value of this effect that made it possible to reduce total emissions during a period of high economic growth. In fact, the emissions reduction from deforestation control was roughly twice the size of the final demand scale effect. Meanwhile, the carbonization effect was negative at 85.6 $MtCO_2e$, further reinforcing the environmental efficiency gain of the Brazilian economy.

However, from 2010 onwards, the deforestation effect has turned positive again[66], and outweighed the negative carbonization effect. Therefore, in recent periods, it is the resurgence of deforestation rates that has been hindering the capacity of the Brazilian economy to achieve environmental efficiency gains.

[66] For more, see Chapter 3.

Graph 24 - Structural decomposition of GHG emissions in eight terms



Source: author's elaboration

When we break down these effects by industry group, we see that the values are very unevenly distributed across the economic structure. As a large part of LUC emissions are allocated to AGR, this industrial group tends to have quite high deforestation effects compared to the other groups. This also implies that the dividends from controlling deforestation are largely appropriated by this industrial group. For example, between 2005 and 2010, the impact of the deforestation control on AGR's made it possible for this group to drop its total emissions by 1,000.5 MtCO_2e (Table 22). This result illustrates the enormous importance of deforestation control policies in decarbonizing agriculture and counteracting the effects of the above-mentioned shifts in the sectoral composition on country's GHG emissions.

The deforestation effect tends to be relatively small for the other industrial groups, given that land use change is not the main source of emissions for them. Putting in another way, the emission intensities of these other groups are not directly impacted by changes in deforestation rates. However, this does not mean that controlling deforestation is not important for them. As seen in the previous chapter, AGR is positioned upstream in the production process of many industries, which makes them indirectly linked to deforestation. Therefore, not only do these industries have emission from LUC change embedded in their products, but they also may be somewhat exposed to risks associated with the adoption of more stringent policies to ban the imports of goods linked to deforestation.[67]

Table 22 - The contribution of changes in environmental and technical efficiencies to GHG emissions

Period	Effect	AGR	IC	AC	TM	IM	Services	Total
2000-2005	Carbonization	-42,743,735	-38,822,400	-264,388	642,239	-232,705	-17,664,532	-99,085,521
	Deforestation	44,824,499	-563,794	4	-3,324	791	582,071	44,840,247
	Technology	-33,808,830	25,893,059	-336,144	717,240	104,768	10,241,011	2,811,104
	Total Delta*	376,204,396	14,101,120	23,349	5,454,605	710,810	24,869,653	421,363,934
2005-2010	Carbonization	-87,532,957	8,429,501	-55,448	2,535,686	1,067,110	-10,079,598	-85,635,706
	Deforestation	-1,074,362,044	119,936	128	-2,436	-882	-425,884	-1,074,671,182
	Technology	-109,381,754	-12,761,182	-416,925	-1,803,876	-331,094	-7,043,602	-131,738,433
	Total Delta*	-1,000,510,844	22,176,251	582,494	5,382,200	1,790,078	47,851,671	-922,728,150
2010-2014	Carbonization	-163,102,219	14,904,737	1,006,786	-10,908,067	-572,303	76,859,912	-81,811,155
	Deforestation	120,489,109	69,049	-144	712	-14	424,691	120,983,402
	Technology	-6,769,264	4,865,828	-657,174	577,661	-54,699	9,567,518	7,529,870
	Total Delta*	150,216,286	26,639,117	633,309	-8,138,194	-840,775	106,316,303	274,826,045
2014-2019	Carbonization	-25,440,278	-6,786,673	-550,838	2,654,168	238,914	-69,712,213	-99,596,922
	Deforestation	203,920,981	-431,522	0	-644	-61	-595,755	202,893,000
	Technology	-10,566,058	-4,362,378	82,498	622,091	162,126	18,234,936	4,173,214
	Total Delta*	268,406,174	-25,146,769	484,779	2,756,346	-363,700	-42,681,604	203,455,226
2000-2019	Carbonization	-318,819,190	-22,274,834	136,111	-5,075,974	501,015	-20,596,432	-366,129,304
	Deforestation	-705,127,455	-806,330	-13	-5,692	-167	-14,876	-705,954,533
	Technology	-160,525,907	13,635,326	-1,327,745	113,116	-118,899	30,999,862	-117,224,246
	Total Delta*	-205,683,989	37,769,719	1,723,931	5,454,957	1,296,412	136,356,024	-23,082,945

Source: author`s elaboration
*Total delta relates to the total increase in GHG emissions for each industry group, considering all 8 effects of decomposition

The carbonization effect basically measures how the emission intensity of industries is affected by changes in emissions from the agriculture, waste, energy, and industrial processes sectors. During the analyzed period, Brazil faced some episodes of challenges and crises in the power sector, which ended up impacting to some extent the industries` emission intensity. Naturally, the most energy-intensive industrial groups, or those directly related to electricity generation,

[67] One very relevant case is the European Union decision to ban the imports of imported products linked to deforestation. For more, see Regulation (EU) 2023/1115.

were more directly and strongly affected. In fact, the results suggest that the IC and Services sectors had their carbonization effects significantly influenced by these episodes. In the first period, when Brazil responded to the power outage situation by adopting energy efficiency measures, those groups presented a large negative carbonization effect.

In the two subsequent periods, Brazil went through a severe water crisis that forced the country to turn to fossil fuels for power generation. This crisis was primarily driven by an abnormal decline in rainfall in the Paraná River basin, the river basin with the largest installed capacity for electricity production in the country. It began in the late 2000s and worsened up until 2015. (CEMADEN, 2021). Between 2005 and 2010, the share of renewable energy in the Brazilian power matrix dropped by 2 percentage points (IEA, 2021), which helps to explain the positive carbonization effect for the IC group. Contrary to expectations, services had a negative carbonization effect, driven by factors unrelated to the energy sector. Even though the '*Production and distribution of electricity, gas, water and sewage, and urban cleaning*' sector exhibited a carbonization effect of 2.1 $MtCO_2e$, this was outweighed by the large negative carbonization effect from the '*trade*' and '*transportation and mailing*' sectors

As water levels in hydroelectric plant reservoirs dropped (CEMADEN, 2021), the country resorted to an even greater use of thermoelectric energy from fossil fuels. Data from the EIA (2021) reveals an additional decline of 12 percentage points in the share of renewable sources in the country's power matrix between 2010 and 2014. This mainly affected the service and IC groups. The impact on the carbonization effect is very evident for both of them, and for both, the carbonization effect was the main driving force of GHG emissions in this period, accounting for 55.9% and 72.3% of their total emission increase, respectively (Table 22). In the last period, the water crisis eased, steering the carbonization effect for both groups to negative values

It is interesting to note the AGR was the only group to show consistently negative values for the carbonization effect. In chapter 3 we raise two hypotheses for explaining this trend. As mentioned in Chapter 3, the fall in the emissions intensity of AGR may be related to the adoption of better practices to comply with the growing environmental requirements in external market, or to a loss of share of pastureland to soy crops. [68]

Regarding the IM group, its carbonization effect has not shown a clear pattern, alternating between positive and negative values in each period. Nevertheless, it is indeed concerning that

[68] An analysis at the level of firms and rural property is necessary to prove these points. Despite the relevance of the topic, this type of analysis is beyond the scope of this work.

this group ended the period with a higher emission intensity than it began. About 38.6% of this group's total emission increase was due its carbonization effect.

When it comes to the technology effect, no pattern was found for most industrial groups, with the exception of the AGR group and the AC group. In fact, AGR is the only industry group to show a negative sign for the technology effect in all periods, indicating that the techniques employed in this group have become consistently more efficient in the use of inputs over the period analyzed. According to Gasques et al. (2022), agricultural productivity grew by 3.8% per year between 2000 and 2010, and by 3.2% between 2010 and 2020. The productivity of beef and dairy cattle also showed a significant improvement (Brisola and Monteiro, 2020; Oliveira *et al*. 2023). In addition to productivity gains, the very replacement of extensive activities, such as cattle ranching by more productive ones like soybean, may have contributed to reducing AGR's output to input ratio. At the end of the period, the technological effect shows a reduction substantial in AGR emissions of 160.5 MtCO2e between 2000 and 2019.

With regard to the AC group, its technology effect was negative in the first three periods, followed by a small positive effect between 2014 and 2019. Despite the increase in the last period, the technology effect remained negative in the period as a whole, thereby contributing to reducing emissions from this industry group between 2000 and 2019.

The only period in which all industrial groups showed negative technology effects was between 2005 and 2010, resulting in an emissions reduction of 131.7 MtCO_2e. It is worth mentioning that there was a strong exchange rate appreciation in the period, which may have contributed to reducing the cost of imported inputs in relation to the gross value of production in these sectors.[69]

III.2. Impact of demand leakage on emissions

Many studies have drawn attention to the potential harmful impacts of demand leakage associated with the Brazilian deindustrialization process. Some focused on the effects of this leakage on the performance of the manufacturing industry as domestic production is progressively replaced by imports (Bresser-Pereira, 2007; Bresser Pereira and Marconi, 2008; Oreiro and Feijó, 2010). Other emphasized how deindustrialization erodes the Brazil's inter-

[69] Because they are expressed in monetary units, analyses using input-output matrices are subject to interference from changes in relative prices. For more on matrix deflation, see Passoni (2019).

industry fabric, through the weakening and loss of productive linkages (Comin, 2019; Morceiro, 2012; Morceiro and Guilhoto, 2019).

The decomposition results displayed in Graph 24 reveal that final demand leakage and de-densification effect were only positive in the first period. In this particular period, we see an emission increase of 49.7 $MtCO_2e$ and 15.5 $MtCO_2e$ as a greater part of intermediate and final demand was met by domestic production (Table 23). In all subsequent periods, the opposite happened: a portion of Brazilian emissions was shipped out, as the share of domestic production in intermediate and final demand dropped, indicating that domestic production was gradually replaced by imports.

Table 23 disaggregate the de-densification and FD leakage effects by industry groups. Once again, the most emission-intensive group tends to exhibit higher values for both effects, meaning that variations in the domestic content of intermediate and final demand for their production tends to offshore or onshore large amounts of emissions. The AGR group stands out. On average, this group accounts for 61.1% and 81.6% of the total de-densification and FD-leakage effects.

The results also reveal a very striking fact: all industry groups have been subject to emission leakages, as they have all been through a replacement of their products with imported intermediate and final goods and services. Some of the industry groups, such as TM and IM, exhibit negative values for both the de-densification and FD-leakage effects from 2005 on. These results are consistent with the findings provided by Passoni (2019), which indicated a persistent process of final and intermediate demand leakage for both the extractive and manufacturing industries, notably after 2003. The data presented by the author reveals that this process was precisely more intense for the IM and IT groups.

Table 23 - The contribution of demand leakage to GHG emissions changes

Period	Effect	AGR	IC	AC	TM	IM	Services	Total
2000-2005	De-densification	41,005,966	4,405,595	136,975	305,119	116,825	3,727,040	49,697,520
	FD Leakage	16,577,858	-1,802,463	47,902	190,366	52,196	413,484	15,479,342
	Total Delta*	376,204,396	14,101,120	23,349	5,454,605	710,810	24,869,653	421,363,934
2005-2010	De-densification	-14,132,689	-7,377,646	93,461	-355,629	-3,015	-1,687,748	-23,463,266
	FD Leakage	-11,209,902	291,614	-156,603	-219,912	-95,641	-953,509	-12,343,952
	Total Delta*	-1,000,510,844	22,176,251	582,494	5,382,200	1,790,078	47,851,671	-922,728,150
2010-2014	De-densification	-6,178,210	-6,148,377	-257,542	-473,996	-162,671	-3,311,605	-16,532,401
	FD Leakage	-2,952,347	-407,464	110,114	-173,325	-57,266	-1,601,100	-5,081,389

	Total Delta*	150,216,286	26,639,117	633,309	-8,138,194	-840,775	106,316,303	274,826,045
2014-2019	De-densification	-12,176,250	-4,679,960	250,376	-154,279	-142,655	-1,990,786	-18,893,554
	FD Leakage	-9,220,516	-1,732,807	-225,229	-71,100	-137,379	-1,739,199	-13,126,230
	Total Delta*	268,406,174	-25,146,769	484,779	2,756,346	-363,700	-42,681,604	203,455,226
2000-2019	De-densification	8,518,817	-13,800,387	223,269	-678,784	-191,517	-3,263,100	-9,191,702
	FD Leakage	-6,804,907	-3,651,120	-223,815	-273,972	-238,090	-3,880,324	-15,072,228
	Total Delta*	-205,683,989	37,769,719	1,723,931	5,454,957	1,296,412	136,356,024	-23,082,945

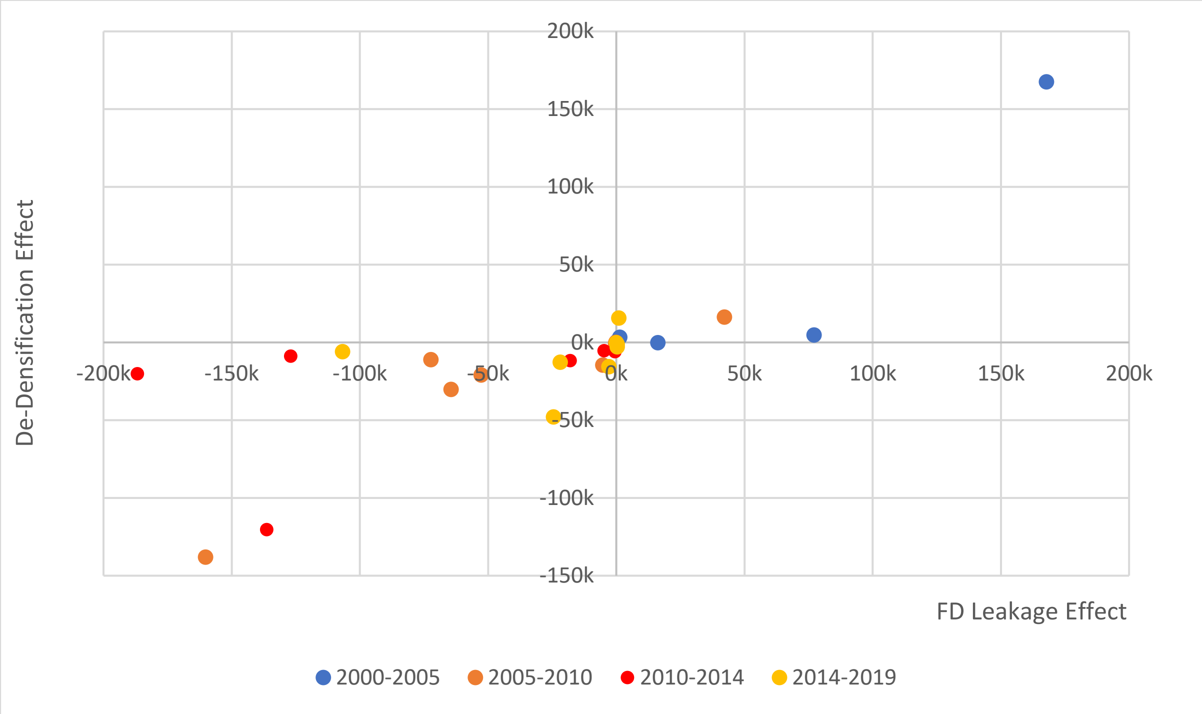
Source: author`s elaboration
*Total delta relates to the total increase in GHG emissions for each industry group, considering all 8 effects of decomposition

To give a clear picture of what happened in the TM and IM industry groups, we plot their industries in Graph 25 and 26. The vertical axis represents the values for de-densification and the horizontal axis shows the values for the leakage effects of final demand. If an industry obtains a negative value for the dedensification effect (FD leakage effect), this means that its production has lost share in intermediate (final) demand for imported goods and services.

Between 2000 and 2005 (in blue), the share of domestic production in intermediate and final demand increased for most TM's industries (Graph25). This scenario changed drastically in subsequent periods. Between 2005–2010 (in orange) and 2010–2014 (in red), all traditional industries lost some of their share of inputs and final goods to imports. Although less extreme, import penetration remained concerning between 2014 and 2019, with 63% of traditional industries losing part of their share in intermediate demand and 88% in final demand (Table 24). Finally, over the two decades covered by this thesis, 88% of TM's industries showed a negative value for the de-densification effect and 100% for the FD leakage effect, revealing that a majority of these industries was affected by the leakage of intermediate and final demand to imports.

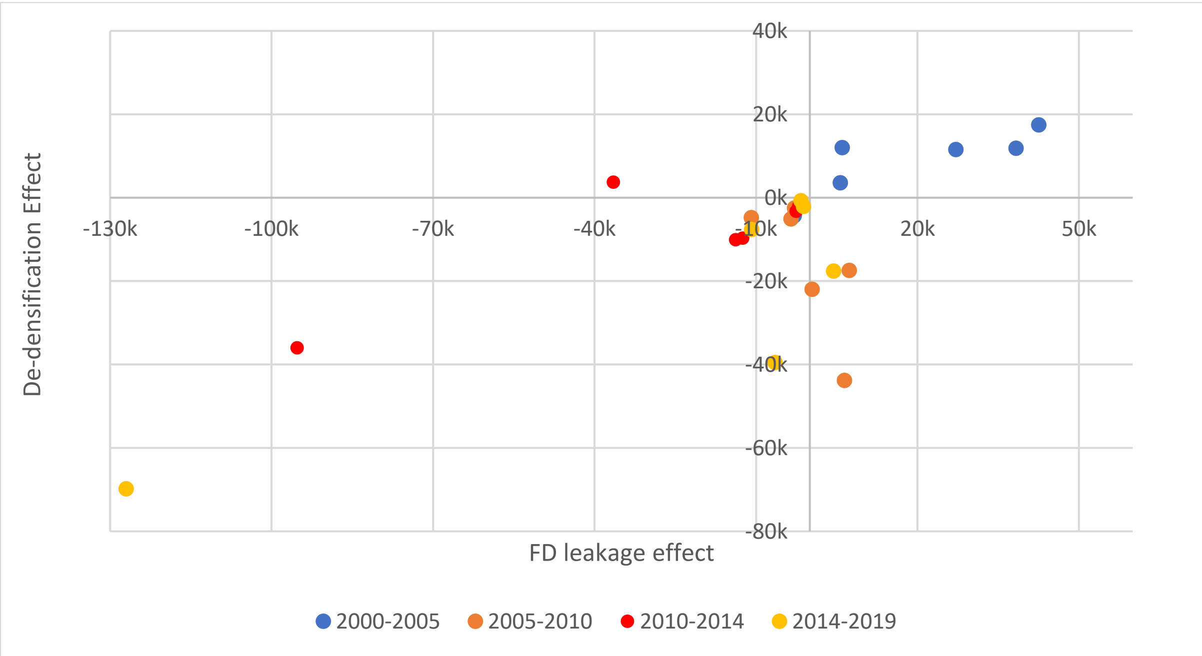
A similar scenario unfolded for the IM group, with most of its industries increasing their emissions during the first period, as their share of intermediate and final demand increased (Graph 25). This scenario was however reversed from 2005 with the majority of IM industries being hit by import penetration. While all IM industries reduced their share of intermediate demand in the 2005-2010 and 2014-2019 periods, 100% of these industries lost some of their share of final demand to imports between 2010 and 2014. By the end of the period, 83% of the industries in this group had seen part of their production of both inputs and final goods replaced by imports (Table 24).

Graph 25 - De-densification and FD leakage effects - traditional manufacturing



Source: author's elaboration

Graph 26 - De-densification and FD leakage effects - innovative manufacturing



Source: author's elaboration

Table 24 - Percentage of TM and IM industries that lost some of their share of intermediate and final demand

Period	TM		IM	
	De-Densification Effect <0	FD Leakage Effect < 0	De-Densification Effect <0	FD Leakage Effect < 0
2000-2005	13%	25%	17%	17%
2005-2010	100%	100%	50%	100%
2010-2014	100%	100%	100%	83%
2014-2019	63%	88%	83%	100%
2000-2019	88%	100%	83%	83%

Source: author's elaboration

The decline in the domestic content of intermediate and final demand for these industries occurred in a context of growing competition from Chinese manufacturers, both in the domestic and the international markets, particularly in Mercosur countries (Castilho et al., 2017; Hiratuka and Sarti, 2017). At first, this competition was more intense in traditional manufacturing segments, including both intermediate and final goods, but later extended to more technologically intensive sectors (Sugimoto and Diegues, 2022). It is noteworthy that the process of import penetration unfolded during an intense period of BRL appreciation, yet the process did not reverse even in the face of exchange rate depreciation during the 2010s. Such developments indicates that demand leakage to imports in this period relates to an increase in price competition but also to Brazil's manufacturing productivity lagging behind its international competitors (Passoni, 2019; Nassif et al, 2020).

The emission increases for the TM and IM groups would have been 17.5% and 33.2% greater between 2000-2019, if it had not been for intermediate and final demand leaking to imports. This means that import penetration was a relevant source of domestic emission reduction for these groups in the period analyzed. However, there are no guarantees that a process of demand leakage will result in net emission reductions. This will depend on the difference between Brazil's emissions and those of its trading partner, particularly for industries where the country has replaced domestic production with imports. This estimation requires the use of Multiregional Input-Output Matrices (MRIO), which is beyond the scope of this work. Nevertheless, even if a reduction in emissions were found, its benefits would be highly controversial.

As seen in Chapter 3, all IM's industries and 75% of TM's industries fall in the category of transition enablers given their capacity to engage in economic growth processes without dragging or propagating larger quantities of emissions from and to other industries. Aside from the repercussions for Brazilian economic development,[70] demand leakages affecting industries in this clusters can have important implications for the transition to a decarbonized economy.

Continued import penetration into the structure of intermediate demand can strain interindustry relations, leading to the loss of critical linkages and productive capacities needed for the transition. As Cornwall (1977) pointed out, the manufacturing industry plays a key role in the diffusion of technical progress through its linkages. In this sense, eroding the interindustry relations between IM industries and other economic sectors could compromise this group's ability to spread emission-saving technical progress across the economic structure, that could support the decarbonization of other transition clusters presented in the previous chapter. In other words, weakening IM linkages could harm potential decarbonization spillovers by limiting this group's capacity to propagate technological progress to other industries.

In addition, weakening or losing these linkages would reduce the capacity of the Brazilian productive structure to respond to the demand generated by decarbonization process (Alvarenga and Young, 2024). Lately, several instruments aiming to steer demand towards low-carbon-and-green sectors are gaining ground internationally, such as sustainable public procurement policies, green taxonomies, public investment prioritization systems, carbon pricing systems, among others (IDB, 2021). In Brazil, some of these initiatives have already been implemented or are underway as part of the Ecological Transformation Plan.

Alvarenga et al. (2022) estimated the impact of a green investment package to put Brazil on a decarbonization path aligned with its Nationally Determined Contributions (NDC). The authors found that this package could lead to the creation of 9.8 million jobs by 2030 and wages 20% higher compared to a status quo scenario. However, these benefits are conditional on the capacity of the Brazilian productive structure meeting the demands created by this green investment package. Leakages in either intermediate or final demand would strip away some of the economic benefits from the transition.

In this sense, productive de-densification for transition enablers could not only lead to scarcer opportunities for decarbonization, but together with final demand leakages could lower the country's capacity to seize the expected social and economic benefits arising from the transition to a decarbonized economy.

[70] For more, see Chapter 1, section IV.

III.3. The Impact of changes in the scale and composition of final demand on emissions

The period covered by this thesis is marked by considerable variations in economic growth rates and shifts in its main driving forces behind this growth, underscoring the relevance of analyzing the impacts of changes in final demand on emissions. In Chapter 3, we saw that there is a great disparity in terms of emission intensities among not only industrial groups but also final demand categories. These aspects are intertwined, as the different intensities of the components of final demand result precisely from the fact that expansion in each of them requires varying amounts of production from each industry. Therefore, not only the magnitude of economic growth but also its composition - that is, which categories of final demand drive growth and which industries these components activate - determine the level of emissions.

To provide a clearer understanding of decomposition effects related to final demand changes, we estimated the contribution of each final demand category to growth, broken down by industry group (see Table 25), and how their shares of total GDP changed over time (Table 26).

The 2000-2005 period was marked by an acceleration of international trade which put exports at the heart of economic growth for this period. During this time, exports contributed with 0.81 points to the 1.08 accumulated growth, increasing their share of total GDP by 5 percentage points. The expansion of the Brazilian exports in this period was primary centered on commodities groups with the AGR, IC and AC amounting to 0.37 points (around 45.7% of total exports growth), closely followed by the TM and IM groups, with 0.36 points. It should be noted that during this period, all five of these groups increased their share of total value added, with the IC and IM groups standing out, gaining 1.8 and 1.6 percentage points, respectively.

Table 25 - Demand-side growth accounting

Industry Group	2000-2005						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.05	0.00	0.00	0.00	0.00	0.03	0.09
IC	0.29	0.00	0.00	0.01	0.01	0.00	0.31
AC	0.03	0.00	0.00	0.01	0.00	-0.02	0.03
TM	0.17	0.00	0.00	0.02	0.00	-0.02	0.16
IM	0.19	0.01	0.00	0.04	0.10	-0.01	0.33
Services	0.08	0.20	0.02	-0.02	-0.11	0.00	0.17
Total	0.81	0.21	0.02	0.06	0.01	-0.02	1.08
Industry Group	2005-2010						Total

	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.01	0.00	0.00	0.01	0.00	0.00	0.03
IC	0.03	0.00	0.00	0.02	0.01	0.00	0.05
AC	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
TM	-0.02	0.00	0.00	0.06	0.00	0.02	0.06
IM	-0.06	0.00	0.00	0.06	0.11	0.02	0.12
Services	0.02	0.27	0.02	0.48	0.26	0.00	1.04
Total	-0.04	0.27	0.02	0.63	0.38	0.04	1.30
Industry Group	2010-2014						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.06	0.00	0.00	0.02	-0.01	0.01	0.08
IC	0.01	0.00	0.00	0.02	0.00	0.01	0.04
AC	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TM	0.01	0.00	0.00	0.07	0.00	-0.04	0.05
IM	-0.01	0.00	0.00	-0.01	-0.04	-0.03	-0.08
Services	0.03	0.19	0.00	0.66	0.13	0.00	1.01
Total	0.11	0.19	0.00	0.77	0.09	-0.05	1.11
Industry Group	2014-2019						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.21	0.00	0.00	0.00	0.01	-0.04	0.18
IC	0.32	0.00	0.00	0.02	-0.01	-0.14	0.19
AC	0.08	0.00	0.00	-0.02	0.00	-0.01	0.04
TM	0.04	0.00	0.00	-0.18	0.00	0.04	-0.10
IM	0.03	-0.01	0.00	-0.19	-0.21	-0.04	-0.42
Services	0.04	0.02	-0.01	0.31	-1.23	0.00	-0.87
Total	0.72	0.01	-0.01	-0.05	-1.45	-0.18	0.97
Industry Group	2000-2019						Total
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory	
AGR	0.08	0.00	0.00	0.02	0.00	0.00	0.10
IC	0.13	0.00	0.00	0.03	0.01	-0.02	0.15
AC	0.01	0.00	0.00	0.00	0.00	0.00	0.01
TM	0.04	0.00	0.00	0.05	0.00	0.00	0.09
IM	0.00	0.00	0.00	0.02	0.06	0.00	0.07
Services	0.05	0.32	0.01	0.67	0.04	0.00	1.09
Total	0.30	0.32	0.01	0.79	0.11	-0.02	1.51

Source: author`s elaboration

Table 26 - Share of each final demand component and Industry Group in total GDP

Year	**Final Demand Components**					
	Exports	Government Consumption	NPISH Consumption	Household Consumption	GFCG	Inventory

2000	10.1%	18.4%	1.7%	53.2%	15.9%	0.7%
2005	15.1%	18.5%	1.6%	49.6%	14.8%	0.4%
2010	10.9%	19.0%	1.6%	49.4%	18.1%	1.1%
2014	10.8%	18.7%	1.4%	51.4%	17.1%	0.5%
2019	13.5%	19.4%	1.4%	52.8%	12.9%	0.0%

Year	**Industry Groups**					
	AGR	IC	AC	TM	IM	Services
2000	2.6%	5.3%	1.2%	11.8%	9.7%	69.3%
2005	3.0%	7.1%	1.3%	12.0%	11.3%	65.2%
2010	2.8%	6.4%	0.9%	10.4%	10.8%	68.7%
2014	3.3%	6.1%	0.8%	9.8%	9.1%	70.9%
2019	4.0%	6.9%	1.0%	9.8%	8.0%	70.3%

Source: author`s elaboration

The results previously presented in this thesis have shown that exports are the most emission-intensive category of final demand, given the higher relevance of commodities in their composition. Therefore, export-led growth tends to impact emissions not only by increasing final demand scale, but also through a shift in its composition and product-mix. It is interesting to note that precisely in this period, the changes in the structure of final demand (Total FD) made the highest contribution to emissions, totaling 407.6 $MtCO_2e$ (Table 27). Of this total, the scale effect accounted for 156.4 $MtCO_2e$, while the composition and product mix effects contributed to emissions of 100.1 $MtCO_2e$ and 116.3 $MtCO_2e$, respectively.

The AGR and IC groups exhibited high values for these effects. The scale and product mix effects are straightforward, driven by the rapid increase in international demand for their production, which ultimately led to a greater share of these groups in total GDP. As for their high composition values the AGR and IC group exhibited, these reflected how the groups contributed to the rise in exports' share of total GDP and how this, in turn, resulted in higher emissions.

The rise in IM`s share of total GDP explains the positive signs for its FD-mix effect. Once again, the positive sign for this group is counterintuitive, as the increasing share of low-carbon industries in total final demand should lead to emission reductions. This does indeed happens because the participation of one industry in final demand can only increase if at least one other industry is having its participation reduced. As the sign of a decomposition effect is given by the delta (the difference in the values of a variable from a year to another), industries with a decreasing share will necessarily present a negative sign. So, the emission reduction from IM industries is being accounted for elsewhere.

Regarding the IM`s negative composition effect, this seems to be related to the contribution of this industry group to the increasing share of exports in total GDP. Again, it does not mean that a faster increase in IM`s exports would lead to an emission increase through the composition effect. Rather, what it means is that in this period IM industries helped exports, the most emission-intensive category of final demand, to increase their share of total GDP. Therefore, the group's composition effect takes a positive sign. This positive sign is offset in two ways: (i) through the negative composition effect for other final demand categories that have lost some of their share of total GDP, (ii) through a negative product mix for industries that have lost some of their share of total value added to IM industries.

Meanwhile, the TM and service groups followed a very similar pattern, with positive values for all three effects. However, the FD mix for services increased, even though this sector's share of total GDP declined. This happened because the share of the two most emission-intensive industries in the service group, "production and distribution of electricity, gas, water, sewage, and urban sanitation" and "transportation, storage, and mailing", grew and ended up dominating the sign.

Table 27 - The impact of changes in final demand on GHG emissions

Period	Effect	AGR	IC	AC	TM	IM	Services	Total
2000-2005	FD Mix	108,249,777	1,323,647	-691,015	603,641	174,113	6,618,455	116,278,616
	FD Composition	85,729,179	11,825,561	645,884	892,176	201,813	1,623,811	100,918,424
	FD Scale	156,369,683	11,841,914	484,132	2,107,148	293,009	19,328,314	190,424,201
	Total FD	350,348,639	24,991,122	439,000	3,602,965	668,936	27,570,580	407,621,242
	Total Delta*	376,204,396	14,101,120	23,349	5,454,605	710,810	24,869,653	421,363,934
2005-2010	FD Mix	-42,755,090	-5,031,830	33,458	-1,019,463	-144,873	1,680,060	-47,237,739
	FD Composition	-108,771,283	-5,081,696	-590,240	-2,129,496	23,784	-6,604,075	-123,153,007
	FD Scale	447,634,875	43,587,554	1,674,664	8,377,326	1,274,690	72,966,027	575,515,136
	Total FD	296,108,502	33,474,027	1,117,882	5,228,367	1,153,600	68,042,012	405,124,390
	Total Delta*	-1,000,510,844	22,176,251	582,494	5,382,200	1,790,078	47,851,671	-922,728,150
2010-2014	FD Mix	73,616,919	-637,988	-354,461	-727,292	-445,589	-16,355,699	55,095,890
	FD Composition	5,787,668	-5,876,066	55,740	336,968	-111,224	3,591,236	3,784,323
	FD Scale	129,324,631	19,869,398	729,990	3,229,145	562,991	37,141,350	190,857,505
	Total FD	208,729,218	13,355,345	431,270	2,838,820	6,178	24,376,887	249,737,719
	Total Delta*	150,216,286	26,639,117	633,309	-8,138,194	-840,775	106,316,303	274,826,045
2014-2019	FD Mix	127,149,739	5,941,890	2,411,687	-2,403,720	-134,744	17,285,959	150,250,811
	FD Composition	40,529,633	-7,050,830	-1,244,079	2,997,007	-197,539	8,172,307	43,206,499
	FD Scale	-45,791,077	-6,044,488	-239,636	-887,177	-152,362	-12,336,852	-65,451,592
	Total FD	121,888,295	-7,153,429	927,972	-293,890	-484,644	13,121,414	128,005,719
	Total Delta*	268,406,174	-25,146,769	484,779	2,756,346	-363,700	-42,681,604	203,455,226

2000-2019	FD Mix	266,261,344	1,595,719	1,399,669	-3,546,835	-551,093	9,228,775	274,387,579
	FD Composition	23,275,197	-6,183,032	-1,132,695	2,096,655	-83,166	6,783,280	24,756,239
	FD Scale	687,538,113	69,254,378	2,649,150	12,826,443	1,978,328	117,098,839	891,345,251
	Total FD	977,074,654	64,667,065	2,916,124	11,376,263	1,344,070	133,110,894	1,190,489,069
	Total Delta*	-205,683,989	37,769,719	1,723,931	5,454,957	1,296,412	136,356,024	-23,082,945

Source: author`s elaboration

By contrast with the first period, the economic growth between 2005-2010 was mostly driven by the increase in domestic absorption. The expansion of household consumption, GFCF, and government consumption brought average growth rates to an average of 4.3%, compared to the 3.2% average growth in the previous period. With higher GDP growth rates, the scale effect across all industry groups surged, totaling 575.5 MtCO2. Nevertheless, the impact of economic growth on GHG emissions was partially offset as inward growth is considerably less emission-intensive in the case of the Brazilian economy. As a result, the final demand composition and product mix effects combined to produce to a 170.4 MtCO2e emission reduction.

Table 26 shows that exports' share of total GDP decreased in this period, thereby lowering the AGR and IC`s participation in total value added, which explains their negative product and composition effects. Nevertheless, this period shows some concerning signs, such as the negative values for the FD Mix effect for IM and TM, which is very likely related to the shrinkage of these groups` participation in total value added. As table 25 shows, both groups dropped their shares between 2005 and 2010, and this trend was not reversed in the subsequent periods.

The period 2010-2014 was characterized by an economic slowdown, which brought the scale effect to much lower levels. As has already been mentioned, this slowdown in the Brazilian economy stems from the cooling of international trade following the 2008 economic crisis, and the weakening of some internal economic growth forces, such as the decrease in government consumption and GFCF. Household consumption went in the opposite direction, increasing its relevance to economic growth.

These changes produced a slightly positive structure effect, since household consumption squeezed the share of two final demand categories with lower emissions intensities (public consumption and GFCF) in GDP. Meanwhile, the product mix resulted in the emission of 55.1 $MtCO_2e$, driven entirely by the AGR group. It's worth noting that, although exports maintained a relatively constant share of GDP (Table 26), their absolute growth was heavily concentrated in the AGR group, which constituted the primary driver of demand for this group's production (Table 25).

The final period was characterized by economic recession, producing a total negative scale effect of 65.5 $MtCO_2e$. This downturn, however, was partially mitigated by an improvement in the external scenario, with exports growing at an average of 3.9% per year. As table 25 illustrates, exports during this period were heavily concentrated in the IC and AGR groups, which largely explains the high composition and product mix effects.

Taking the whole period, we see that changes in the sectoral composition of final demand and the weights of its components were indeed relevant to explain national emissions increase. To put it in numbers, the product mix and composition effects resulted in emissions of approximately 300 MtCO2e, which is equivalent to 33.5% of these emissions attributable strictly to the increase in final demand. This means that economic growth could have been much lower in emissions if it had not been for changes in the final demand structure towards industries with higher emission intensities.

Finally, Table 28 highlights the contribution of each category to the scale and product mix effects, as well as to the increase in emissions from final demand and overall emissions. The data clearly underscore the key role of exports in driving emission increases during the period covered by this thesis, due both to their impacts on the final demand scale and composition. Indeed, exports were the main driving force pushing final demand towards more emission-intensive industries across all periods[71], and led the emissions growth from final demand expansion in two out of the four periods (2000-2005 and 2014-2019). As a result, the overall emission from final demand were largely driven by the Brazilian trade relations, except for the period 2005-2010, while exports were the main contributor to overall emission increase both from 2000 to 2005, and 2015 to 2019. Even in those periods when exports were not the main driver of total emissions growth, its responsibility was high, over one-third.

[71] The negative values for the demand mix effect of exports between 2005 and 2010 occur because exports moved counter to the trend of decreasing participation of carbon-intensive industries in final demand during this period. Similarly, the negative value for the scale effect of exports indicates that, while total final demand was declining, exports continued on an upward trajectory.

Table 28 – Scale and demand mix effect by final demand component growth (%)

Period	Termo	Exports	Government Consumption	NPISH consumption	Households Consumption	GFCF	Inventory Changes
2000-2005	Demand Mix	26.2%	0.2%	0.0%	32.3%	4.4%	36.9%
	Scale	93.1%	2.3%	0.1%	4.5%	0.4%	-0.4%
	Total FD	74.0%	1.7%	0.1%	12.4%	1.6%	10.2%
	Total Delta*	69.8%	2.3%	0.2%	14.3%	4.7%	8.7%
2005-2010	Demand Mix	-130.2%	-2.8%	-0.1%	169.2%	64.7%	-0.8%
	Scale	-8.6%	5.1%	0.3%	73.9%	21.9%	7.4%
	Total	5.6%	6.0%	0.3%	62.8%	17.0%	8.3%
	Total Delta*	34.7%	1.5%	0.2%	61.7%	3.6%	-1.7%
2010-2014	Demand Mix	147.4%	-2.3%	0.0%	-41.1%	-27.3%	23.3%
	Scale	23.6%	3.7%	0.0%	78.1%	4.8%	-10.2%
	Total	50.9%	2.4%	0.0%	51.8%	-2.3%	-2.8%
	Total Delta*	44.2%	5.2%	0.0%	51.9%	0.6%	-1.9%
2014-2019	Demand Mix	40.9%	-0.4%	0.0%	12.5%	14.0%	33.0%
	Scale	-553.0%	-0.5%	0.5%	17.8%	252.2%	382.9%
	Total	144.1%	-0.4%	0.0%	11.6%	-27.4%	-27.9%
	Total Delta*	114.4%	-3.4%	0.0%	22.7%	-15.3%	-18.4%
2000-2019	Demand Mix	85.5%	-0.1%	0.0%	-16.9%	-7.1%	6.0%
	Scale	43.8%	4.0%	0.2%	54.1%	5.9%	-8.0%
	Total	53.4%	3.1%	0.1%	37.7%	2.9%	2.8%
	Total Delta*	-1421%	-12%	2%	1385%	187%	-40%

Source: author`s elaboration

IV. Structural decomposition of the emissions from exports

The great influence of exports on Brazilian`s emission growth is a result of many factors at play, ranging from changes in industries` technology and emission intensity, to variations in the scale and composition of total exported. In this section we are going to shed light on the contribution of each of these factors, putting a special emphasis on the changes in total exported and its sectoral composition by trade partner. In doing so, we will provide important evidence on two key aspects. How is reprimarization of export basket impacting the country`s emissions. Are these impacts arising from a relation with a specific trade partner, rather than a generalized trend?

To answer these questions, the structural decomposition developed in Chapter two put forward two terms of great interest. The export basket effect, which measures how shifts in the sectoral composition of exports impact emissions. However, when we disaggregate the export vector by trading partner the delta for the sectoral composition becomes specific to each partner. This means that this effect will measure whether or not the trade relation with this specific partner is moving toward emission-intensive industries.

Hence, it may occur that a trade partner, with whom Brazil has a significantly above-average emission-intensive export basket, drastically increases its share of Brazilian exports without necessarily altering the sectoral composition of its imports from Brazil. If that is the case two things would occur: first, a null composition effect with this partner, and second, an increase in the weight of emission-intensive industries in the country's total export basket.

The impact of the latter development on emissions would be felt through the trading partner effect. When this effect is positive, it indicates that Brazil is increasing the share of emission-intensive industries in its exports by simply strengthening trade relations with partners whose export baskets are heavily concentrated in high emission sector.

In this sense, while the basket effect measures a within-partner shift towards more emission-intensive industries, the trade partner effect accounts for an across-partner shift towards emission-intensive industries. Both effects are fundamental to understanding the repercussions of AGR and IC's increasing share of Brazilian exports on the country's emissions from producing goods and services for export.

IV.1 Aggregated decomposition of emissions from the Brazilian exports

Graph 27 illustrates the results for the aggregate decomposition of export-linked emissions. During the first period, the acceleration of international trade emerged as the primary driver of emission growth. This surge in international demand for Brazilian goods and services drove the scale effect to a peak of 294.3 MtCO2e.

The trade partner effect was the second largest contributor to emission growth, accounting for 26.7 MtCO2e. The positive sign for this effect indicates that Brazil shifted its trade relations toward countries with whom its export basket is more carbon-intensive. Meanwhile, the export mix effect was relatively small (3.6 MtCO2e). The explanation for this mismatch lies in two developments.

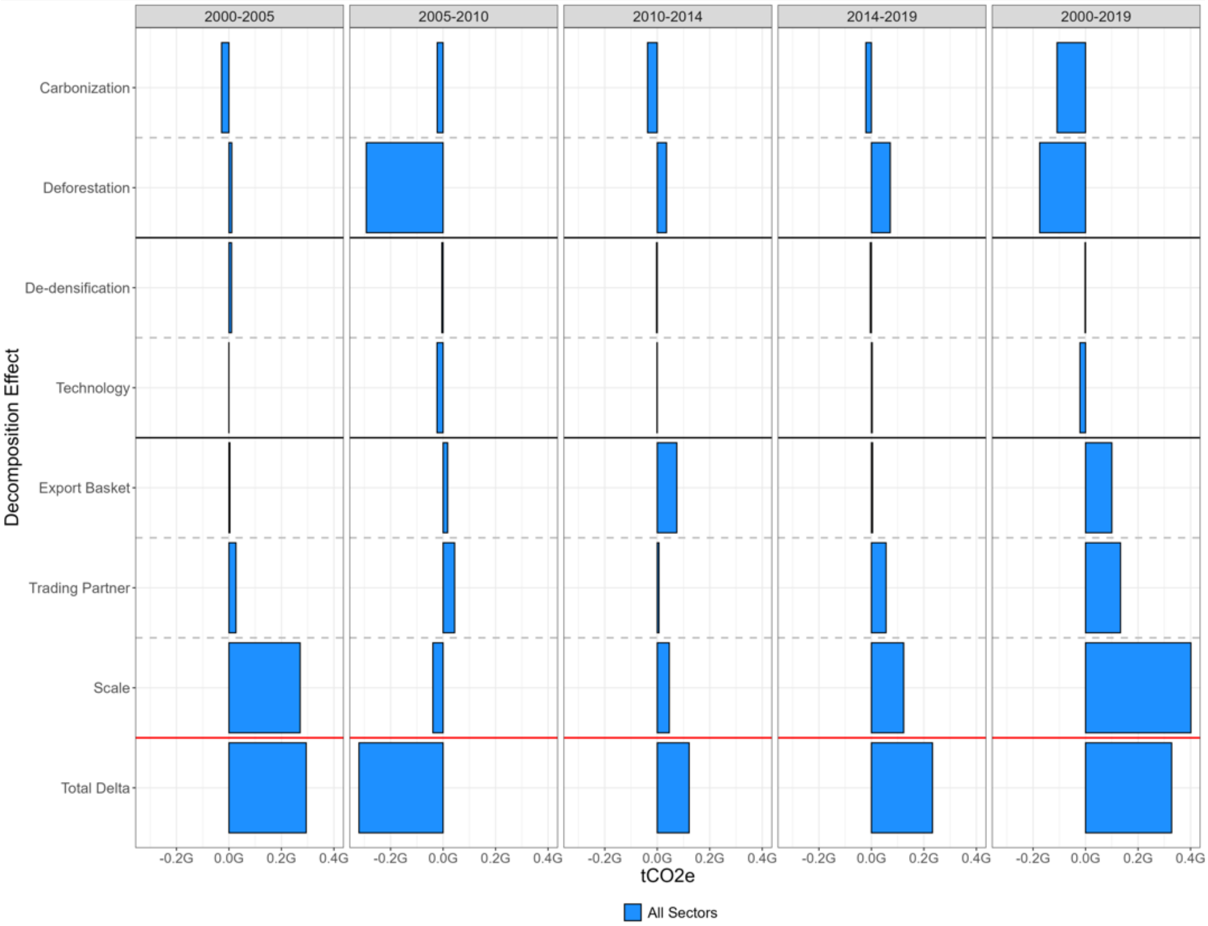
As shown in Table 29, Brazilian exports increasingly shifted toward China and the rest of the world (RoW), two trading partners with whom Brazil's exports have higher than average emission intensity. While the export basket with China is more than twice as carbon-intensive as Brazil's overall export basket, the one with the RoW has a slightly higher-than-average emission intensity. So, the outcome of these changes should be a substantial impact on emissions through the basket effect.

However, as China held a relatively small share (around 4% on average) of Brazilian exports in the early 2000s, its capacity to influence the total export composition was limited. In contrast, the RoW had a large enough share of Brazilian exports to significantly impact Brazil's overall export basket. Still, as the RoW gained ground, a trading partner with even higher emission intensity—namely, the EU—saw its share shrink. Thus, the emission increase expected from the RoW's growing share was partially compensated by the EU's decline in importance within total Brazilian exports.

Yet, this mismatch cannot be fully understood without a closer look at some shifts in the sectoral composition of Brazilian exports by trade partner, which will be addressed in the subsection IV.2.2.

The carbonization and deforestation effects follow a similar rationale to what was previously discussed, so we will not dedicate much time to explaining their values in this section. However, these effects will be examined in greater detail in the next subsection, where the decomposition is broken down by trading partner. This will allow for an analysis of how the emissions of export baskets for different partners have responded to changes in environmental efficiencies during the period under review, notably those arising from changes in the deforestation rates.

Graph 27 – Structural Decomposition of emissions from exports



Source: author's elaboration

Table 29 - Brazilian exports and export basket intensity – by trading partner

Share of trade partners in total Brazilian Exports						Total Brazilian Exports (2010 BRL Millions)
Year	LAC	EU	RoW	US	CHINA	
2000	22%	25%	26%	24%	2%	280,601
2005	22%	21%	32%	19%	6%	451,676
2010	22%	19%	34%	10%	15%	422,176
2014	19%	16%	34%	12%	18%	465,720
2019	14%	14%	30%	13%	29%	564,907
Emission Intensity of the Brazilian Export Basket by trading Partner						
Year	LAC	EU	RoW	US	CHINA	Total
2000	905	2,869	1,924	939	3,622	1,731
2005	721	2,900	2,087	988	3,172	1,801
2010	582	1,324	1,266	822	1,396	1,102
2014	633	1,498	1,419	852	2,144	1,345
2019	675	1,548	1,793	731	2,087	1,543

Source: author's elaboration

International trade was heavily impacted by the 2008 global economic crisis, with global imports dropping by 6.7% within two years of the crisis outbreak. [72] As a result, Brazilian exports decreased by 6.5%, explaining the negative scale effect during this period. In the meantime, a sharp increase in the environmental and technical efficiencies emerged, further reducing exports' emissions. The carbonization, deforestation and technology effects combined delivered an emission reduction of 338.4 MtCO_2e (Table 30).

The retraction in international trade was very unevenly distributed across trade partners, making their shares of total Brazilian exports vary significantly. The value of Brazilian exports to LAC declined by 7.3%, to the EU by 15.3%, to RoW by 0.3%, and to the US by 52.9%. Exports to China, however, went in an opposite direction, rising by 49.1%, leading to a 9-percentage-point increase in this partner's share of Brazilian exports. The sizable growth of China`s share helps to explain the positive trading partner effect. Other factor that contributed to this value was the increase in the RoW' share at expenses of other partners with who Brazil had a cleaner trade relation.

In this period, trading partner effect led to an emission of 43.8 MtCO2e. Two elements, however, helped to constrain the growth in trading partner effects. The first one was the decline in the participation of EU in Brazil's total exports. The other was the convergence of the emission intensity of the export basket to China toward the average exports' intensity.

In this period, the export basket effect also increased amounted to 17.5 MtCO_2, a figure 4.8 times higher than in the previous period. Also here, the drop in the emission intensity of the exported goods and services to China work preventing an even greater increase in export-basket effect.

Table 30 - Structural Decomposition Analysis of emissions from exports – Aggregated results

Effect	2000-2005	2005-2010	2010-2014	2014-2019	2000-2019
Carbonization	-27,942,249	-22,380,384	-37,060,965	-21,217,505	-108,601,104
Deforestation	10,763,494	-292,750,684	35,178,022	71,841,508	-174,967,659
Technology	-323,993	-23,266,300	-917,138	3,178,647	-21,328,784
De-densification	10,036,932	-4,794,822	-2,844,259	-4,284,296	-1,886,446
Export Basket	3,672,758	17,500,024	74,601,819	4,450,953	100,225,555
Trading Partner	26,792,353	43,982,421	6,634,194	55,819,773	133,228,742
Scale	271,297,612	-38,856,963	45,927,681	123,018,603	401,386,933

[72] Data from World Trade Organization (2022)

Total Delta	294,296,906	-320,566,709	121,519,355	232,807,684	328,057,237

Source: author's elaboration

In the third period, international trade recovered, reaching an accumulated growth rate for global imports of 19.6%. Brazil, however, showed a more modest resumption of its exports, around 10.3%. The scale effect was positive but much lower than in the first period. Meanwhile, the export basket effect stood out as the main driver of emission growth, adding an additional 74.6 MtCO2e. In this particular period, AGR's share in total exports jumped from 10.7% to 16.9%, increasing across most trading partners (except for LAC) and squeezing out all other industry groups from Brazilian exports. This was majorly driven by a profound sectoral recomposition of exports to China, as AGR's share in its basket increasing from 23.8% to 42.8%.

China continued to gain share in Brazil's emissions. Nevertheless, the trading partner effect reached its lowest value (6.6 MtCO2e). This low value can be explained by the fact that the impact of China's growing share on emissions was offset by the increasing share of the US. Both countries experienced a similar increase in their share of Brazilian exports and showed comparable divergence from the average emission intensity of Brazilian exports. As a result, by the end of the period, their effects essentially balanced each other out.

It is noteworthy that environmental efficiency (the combined effect of carbonization and deforestation) improved during this period, resulting in an emission reduction of 1.9 MtCO2e. However, the average emission intensity of the Brazilian export basket increased by 22.1%. This indicates that impact of growing share of emission-intensive industry groups in Brazilian exports prevailed over the impact of reduction in industries emission intensity. In other words, the reprimarization of Brazilian exports during this period hindered the country from fully reaping the environmental benefits of within-industry improvements in emission efficiency.

Finally, in the last period, the scale effect significantly increased, reaching 123.0 MtCO2e, driven by a 21.3% growth in Brazilian exports. Exports to China grew much faster than those to other partners, causing China's share of total Brazilian exports to surge. Despite the 11-percentage-point increase in China's share, the export basket effect did not follow suit, as the AGR' share of total exports to China bounced back to lower levels. Still, the total export basket effect was positive, and together with the trading partner effect, it led to an emission increase of 60.3 MtCO2e. An additional 53.8 MtCO2e was produced by efficiency losses during this period.

The values for the 2000–2019 period reveal which trends prevailed during the timeframe covered in this thesis. Typically, scale effects tend to be positive, which is not inherently problematic. Countries need to export to meet their foreign currency obligations. The problem for Brazil, however, lies in the shift in its export pattern toward more emissions-intensive industries.

Over the two decades analyzed, Brazil's balance of payments became increasingly reliant on the country's willingness to accept higher levels of national emissions. The export basket effect contributed 100.2 MtCO2e, while an additional 133.3 MtCO2e came from the trading partner effect. Both effects point to a carbonization of the Brazilian export basket – either through increased dependence on emission-intensive industries within the export baskets of individual trading partners (within-partner carbonization) or through the strengthening of trade relations with partners with whom Brazil's exports are more emission-intensive (across-partner carbonization). Despite fluctuations in these effects across different periods, together they accounted for an alarming 71.1% of all emission increases from exports between 2000 and 2019.

This result strongly suggests that the Brazilian reprimarization process is driving greater trade specialization in emission-intensive industries. However, this trend could also be driven by one or a few highly emission-intensive industries, without necessarily implying that emission-intensive industries as a whole are gaining ground in Brazilian exports. In this case, while the results accurately reflect the carbonization of Brazil's export basket, they may misrepresent whether high-emitting industries are increasing their overall share in Brazilian exports. This issue will be explored in the final section.

The impact of this carbonization of Brazil's export basket would have been even greater if not for the improvements in environmental efficiency observed during the period, which contributed to a reduction of 233.4 MtCO2e. Technical efficiency gains also played a role, albeit to a lesser extent, in reducing emissions, as did the de-densification effect, which was negative in all periods except the first. This suggests that export production likely became more dependent on imported inputs, thereby reducing emissions associated with intermediate demand.

IV.2 Structural Decomposition of Export Emission by trade partner

IV.2.1. Impact of environmental and technical efficiencies changes on emissions

Graph 28 illustrates the SDA results disaggregated by trading partners. As we can see, the environmental and technical efficiencies have largely varied across periods and partners. Table 31 displays the numerical results for the carbonization, deforestation and technology effects.

In the first period, the results showed that the carbonization effect was negative for all partners, while the deforestation effect was positive across the board. As discussed in Section 3.1, the overall negative carbonization effect for the Brazilian economy during this period was largely driven by the AGR and IC groups. Consequently, the countries that benefited the most from the emission reductions associated with this negative carbonization effect were those with higher shares of Brazilian exports from these two industry groups—namely, RoW and the EU. The carbonization effects for these partners totaled -8.8 MtCO2e and -7.1 MtCO2e, respectively, as a significant portion of their imports from Brazil consisted of goods produced by these sectors.

The EU and RoW also stood out for their large deforestation effects, as these regions were the primary destinations for AGR exports in the early 2000s. Together, these two partners accounted for 74.5% (8.0 MtCO2e) of the emissions increase from land-use change (LUC), representing the majority of the total deforestation effect.

The US and LAC also exhibited relatively high carbonization effects of -5.6 MtCO2e and -4.8 MtCO2e. However, in this case, this was mainly due to the relevance of the IC group in their imports from Brazil. As for the deforestation effect for both partners is positive, as emissions from LUC were still rising in this period due to the ascending deforestation trajectory.

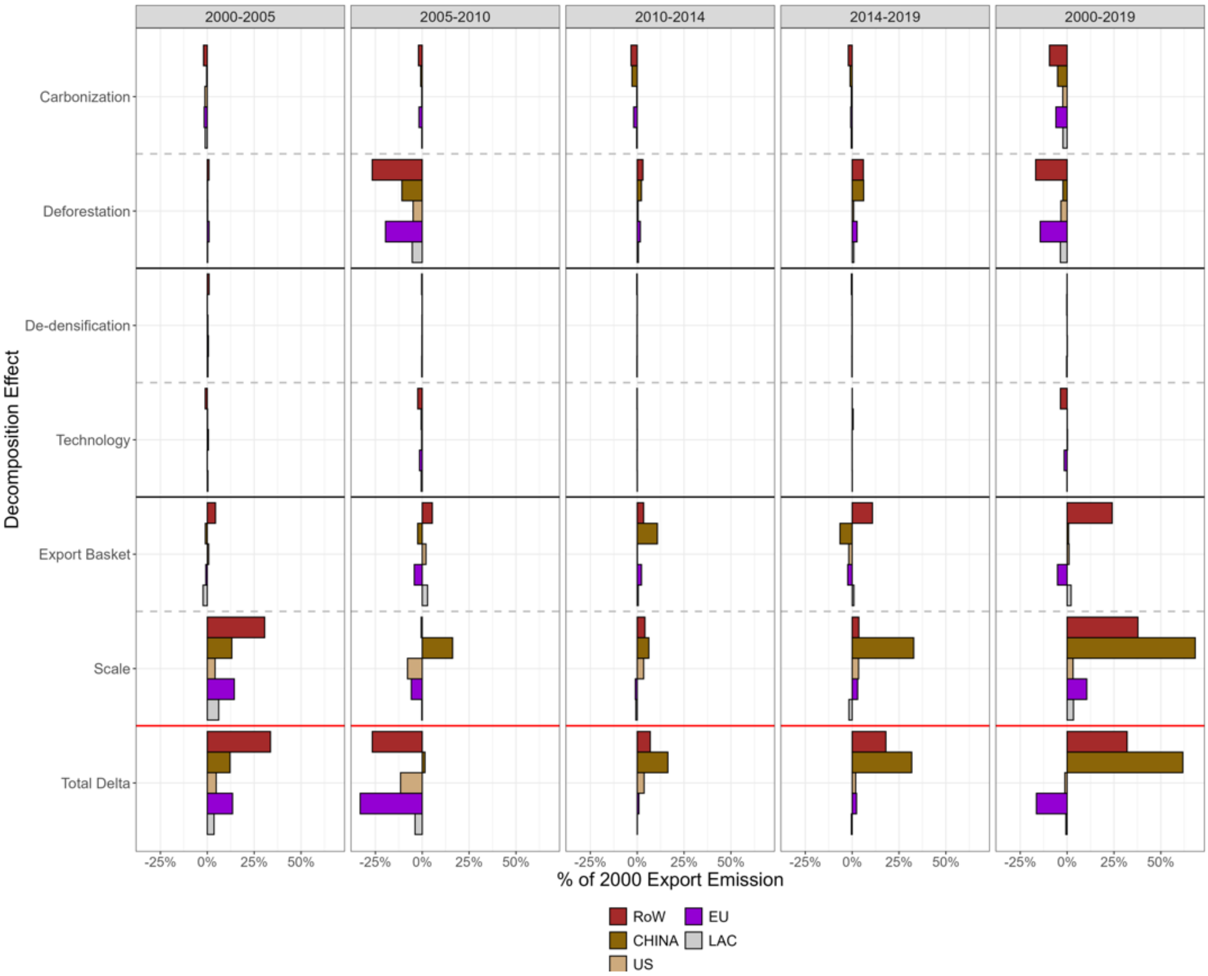
When it comes to China, neither its carbonization, nor deforestation effects were high. Even the Brazilian exports to China was already very centered on the AGR and IC groups, this relevance of this country as a destination for the Brazilian export groups was still modest during this period.[73]

As shown earlier in this chapter, the technology effect was largely negative for the AGR group and positive for the IC between 2000 and 2005. Therefore, a positive technology effect prevailed for partners whose imports from Brazil had a greater presence of industrial

[73] Based on data from MDIC (2024), we estimated the Chinese share of AGR and IC. The results revealed that in 2000, China was the destination for 8.0% and 2.7% of the Brazilian exports from the AGR and IC groups respectively. In 2005, these shares rose to 19.5% and 8.5%.

commodities compared to AGR products, as was the case with LAC, the US and China. The share of IC in the EU and RoW import baskets from Brazil was also substantial; however, the share of AGR was high enough in these cases to drive the technology effect to negative values.[74] In light of the above, it is important to note that China was the only partner for which the total efficiency gain resulted in positive emissions.

Graph 28 – Structural decomposition of export emissions by trade partner



Source: author's elaboration

[74] The share of each industry group in the Brazilian exports by trade partner is displayed in Table 18.

Table 31 – Impact of changes in environmental and technical efficiency changes on export emissions

Period	Effect	LAC	EU	RoW	US	CHINA	Total
2000-2005	Carbonization	-4,840,393	-7,102,311	-8,807,546	-5,626,845	-1,565,153	-27,942,249
	Deforestation	852,686	4,156,137	3,860,750	1,010,966	882,956	10,763,494
	Technology	1,341,718	-226,988	-4,789,970	2,579,891	771,355	-323,993
	Total Efficiency gain	-2,645,990	-3,173,162	-9,736,766	-2,035,988	89,158	-17,502,748
	Total Delta*	15,626,678	58,583,973	146,557,344	20,719,996	52,808,916	294,296,906
2005-2010	Carbonization	-1,148,623	-7,508,562	-8,849,114	-1,248,821	-3,625,264	-22,380,384
	Deforestation	-23,153,957	-85,208,188	-116,082,832	-21,199,407	-47,106,299	-292,750,684
	Technology	-2,354,210	-6,416,560	-10,498,530	-1,550,365	-2,446,635	-23,266,300
	Total Efficiency gain	-26,656,790	-99,133,310	-135,430,477	-23,998,594	-53,178,198	-338,397,368
	Total Delta*	-16,722,925	-143,908,610	-115,912,731	-50,288,949	6,266,506	-320,566,709
2010-2014	Carbonization	-1,378,069	-8,183,751	-14,327,505	-1,094,852	-12,076,788	-37,060,965
	Deforestation	2,644,526	7,309,693	13,253,967	2,090,988	9,878,849	35,178,022
	Technology	173,812	-230,375	-496,373	-141,530	-222,672	-917,138
	Total Efficiency gain	1,440,269	-1,104,433	-1,569,911	854,606	-2,420,612	-2,800,081
	Total Delta*	18,180	4,000,145	30,323,771	16,006,332	71,170,927	121,519,355
2014-2019	Carbonization	-2,172,577	-3,227,604	-8,904,246	-2,070,645	-4,842,433	-21,217,505
	Deforestation	3,978,754	11,389,227	26,072,725	3,681,194	26,719,608	71,841,508
	Technology	350,540	158,893	256,278	70,959	2,341,977	3,178,647
	Total Efficiency gain	2,156,717	8,320,516	17,424,757	1,681,508	24,219,152	53,802,651
	Total Delta*	-1,908,437	10,100,568	78,246,238	8,250,616	138,118,699	232,807,684
2000-2019	Carbonization	-9,539,663	-26,022,229	-40,888,410	-10,041,164	-22,109,639	-108,601,104
	Deforestation	-15,677,991	-62,353,131	-72,895,390	-14,416,260	-9,624,887	-174,967,659
	Technology	-488,140	-6,715,030	-15,528,596	958,955	444,026	-21,328,784
	Total Efficiency gain	-25,705,794	-95,090,390	-129,312,396	-23,498,468	-31,290,500	-304,897,547
	Total Delta*	-2,986,504	-71,223,924	139,214,621	-5,312,005	268,365,048	328,057,237

Source: author's elaboration

In the second period, carbonization, deforestation, and technology effects all scored negative values, leading to significant emission reductions embedded in Brazilian exports. These reductions spanned all trade partners, lowering the emission intensity of their import baskets with Brazil. The major driving force in this case was the steep decline in deforestation rates that made emerge large environmental efficiency gains. These gains combined with those stemming from the negative carbonization effect drove reductions of export emissions of 320.6 $MtCO_2e$ Interestingly, the environmental efficiency gains sufficed to drive reductions in the emissions embedded in export to for all partners, apart from China. The reason for this lies in the consistent growth in exports to China, as will be explained in the next subsection.

In the 2010–2014 period, the deforestation effect turned positive again, as LUC emissions reentered an ascending path. However, environmental efficiency gains still persisted for this period, as the overall negative carbonization effect outweighed the positive deforestation effect. Meanwhile, the technology effect was slightly negative.

These efficiency gains were unevenly distributed across Brazil's trading partners. Major importers of the AGR group, including the EU, RoW, and China, experienced significant positive deforestation effects. They also recorded substantial negative carbonization effects, as the AGR group reached its most pronounced negative value for this effect in period (- 163,1 $MtCO_2e$). In all three cases, the negative carbonization effect was sufficient to offset the emissions increase from LUC.

However, in the last period, this situation reversed, with the deforestation effect significantly surpassing the carbonization effect for all trade partners. The decline in environmental and technical efficiency resulted in a 23.1% increase in total export emissions during this period. For LAC, the efficiency loss was the primary driver of rising export emissions, as the value of exports to this partner decreased between 2014 and 2019. Meanwhile, efficiency losses contributed to an 82.4% increase in total emissions embedded in exports to the EU, 22.2% to RoW, 20.3% to the US, and 17.5% to China.

Over the entire period, efficiency gains led to a reduction of 304.9 MtCO2e in emissions from exports. In other words, total emissions embedded in Brazilian exports would have been 92.9% higher if no efficiency gain had not been achieved. Notably, the majority of these gains were concentrated in the 2005–2010 period, driven by the steep reduction in deforestation rates under the influence of PPCDAM.

IV.2.2. Impact of changes in export scale and composition on emissions

In this section, in particular, we are interested in understanding how changes in the scale and composition of exports to each trading partner drove emissions throughout the different periods. Table 32 presents the disaggregated scale and composition effects by trading partner. The results reveal that, in the first period, the growing exports to the RoW and EU stood out as the main drivers of GHG emissions. These two partners combined were responsible for 65.8% of the total scale effect. Meanwhile, the EU and US were the only partners to experience a carbonization of their import baskets with Brazil.

Interestingly, China did not score a positive export basket effect. As seen in Chapter 3, Brazil's exports to China are fundamentally based on commodities. Nevertheless, in this particular period, the share of high emission-intensive industries in Brazilian exports to this country dropped, as AGR's share of total exports to China was squeezed out by the increase in the share of the IC group.[75] As the latter industry group has a significantly lower emission intensity, the export basket effect for China was negative.

Table 32 – Structural decomposition of export emissions by trade partner

Period	Effect	LAC	EU	RoW	US	CHINA	Total
2000-2005	Export Basket	-9,717,315	-3,526,241	19,030,815	3,249,648	-4,468,852	4,568,053
	Scale	26,468,138	62,643,842	133,068,746	18,093,450	56,920,493	297,194,669
	Subtotal	16,750,823	59,117,601	152,099,561	21,343,097	52,451,641	301,762,723
	Total Delta*	15,626,678	58,583,973	146,557,344	20,719,996	52,808,916	294,296,906
2005-2010	Export Basket	12,355,091	-18,460,781	23,435,927	8,587,901	-10,635,479	15,282,659
	Scale	-1,136,627	-25,377,462	-2,412,472	-34,163,015	70,432,400	7,342,823
	Subtotal	11,218,463	-43,838,243	21,023,455	-25,575,113	59,796,921	22,625,482
	Total Delta*	-16,722,925	-143,908,610	-115,912,731	-50,288,949	6,266,506	-320,566,709
2010-2014	Export Basket	2,413,103	9,970,017	14,992,511	494,870	46,807,198	74,677,700
	Scale	-3,105,692	-4,385,253	17,976,541	15,018,287	26,982,111	52,485,995
	Subtotal	-692,589	5,584,764	32,969,053	15,513,158	73,789,309	127,163,695
	Total Delta*	18,180	4,000,145	30,323,771	16,006,332	71,170,927	121,519,355
2014-2019	Export Basket	4,148,154	-10,303,290	47,122,766	-7,863,297	-28,213,824	4,890,510
	Scale	-7,519,813	12,745,462	15,568,271	14,901,170	142,703,729	178,398,820
	Subtotal	-3,371,658	2,442,172	62,691,037	7,037,874	114,489,905	183,289,330
	Total Delta*	-1,908,437	10,100,568	78,246,238	8,250,616	138,118,699	232,807,684
2000-2019	Export Basket	9,199,033	-22,320,295	104,582,019	4,469,123	3,489,042	99,418,923
	Scale	14,706,007	45,626,588	164,201,086	13,849,893	297,038,733	535,422,307
	Subtotal	23,905,039	23,306,293	268,783,106	18,319,015	300,527,776	634,841,230
	Total Delta*	-2,986,504	-71,223,924	139,214,621	-5,312,005	268,365,048	328,057,237

Source: author's elaboration

It seems that in the second period, the international crisis had an impact on the level of Brazil's exports with all partners except China. Brazilian exports were most affected with the EU and the US, which fell by 15.2% and 52.8% (Table 32). Given the significant drop in the level of exports with these partners, their scale reached a large negative value. There is, however, a difference between the decline in Brazilian exports to these partners. For the EU, this decline was accompanied by a change in the composition of its exports that favored the reduction of emissions, namely a steeper decline in exports of the AGR group. As for the US, on the other

[75] During the first period, the AGR's share of total exports to China dropped from 32.0% to 26.6%, while the IC group had their share increased from 37.7% to 48.0%. For more, see Table 19.

hand, this decline was accompanied by an increase in the value exported by the AGR group. This explains why these partners present opposite signs for their export basket effect.

The trade relationship with the LAC region also appeared to shift towards more emission-intensive industries. Notably, the export basket effect with this partner remained negative during the two subsequent periods. The increasing positive trend in the export basket effect suggests that one or more highly emission-intensive industries are gaining ground in Brazilian exports to this partner.

When it comes to China, the negative basket effect indicates that, although Brazil's exports to this country departure from highly emission-intensive profile, some improvements were evident during the first decade. However, this does not imply that Brazil's export basket with China is escaping reprimarization. What actually occurred is that Chinese demand for products from the IC group grew much faster than for those from the AGR group, causing the participation of the latter group in the exports to China to decline[76].

Table 33 – Brazilian Exports Basket by trade partner – BRL Million (at 2010 prices)

Period	2000					Total
	ALC	EU	RoW	US	CHINA	
AGR	1,304	12,648	4,807	1,586	1,769	22,114
IC	14,413	17,702	25,757	17,815	2,086	77,772
AC	4,467	6,837	6,485	5,776	693	24,258
TM	14,611	18,760	20,459	13,914	451	68,196
IM	27,505	13,870	15,564	27,465	507	84,911
SG	769	838	1,120	595	28	3,351
Total	63,069	70,654	74,192	67,150	5,535	280,601
Period	2005					Total
	ALC	EU	RoW	US	CHINA	
AGR	1,159	16,597	8,605	2,278	6,919	35,558
IC	33,986	24,480	46,427	28,758	12,468	146,118
AC	3,932	8,868	6,878	8,517	2,592	30,787
TM	16,593	25,140	50,388	14,062	2,309	108,493
IM	44,375	16,445	30,356	31,689	1,580	124,446
SG	1,141	1,513	2,556	933	131	6,273
Total	101,186	93,043	145,210	86,237	26,000	451,676
Period	2010					Total
	ALC	EU	RoW	US	CHINA	
AGR	3,276	11,839	12,019	2,673	15,401	45,207

[76] The export basket by trade partner is illustrated in Table 19.

IC	31,084	26,874	56,950	18,555	39,897	173,360
AC	3,099	8,579	4,937	3,923	3,425	23,964
TM	15,659	18,999	52,818	6,565	4,152	98,193
IM	38,886	11,308	15,320	8,499	1,652	75,665
SG	1,766	1,231	2,114	439	237	5,786
Total	93,771	78,831	144,158	40,653	64,764	422,176
Period	2014					Total
	ALC	EU	RoW	US	CHINA	
AGR	3,070	14,331	20,957	4,205	35,915	78,477
IC	32,838	24,967	59,523	25,063	37,814	180,204
AC	3,217	7,408	4,968	4,778	4,636	25,008
TM	18,445	20,511	54,847	6,561	5,690	106,054
IM	30,762	7,659	14,896	15,720	1,380	70,416
SG	1,240	1,359	2,158	627	178	5,562
Total	89,572	76,233	157,350	56,953	85,612	465,720
Period	2019					Total
	ALC	EU	RoW	US	CHINA	
AGR	3,124	13,328	35,466	3,020	54,729	109,667
IC	23,305	26,198	59,353	33,158	81,787	223,800
AC	4,226	8,335	7,294	7,028	9,769	36,653
TM	16,858	18,049	49,511	8,995	14,313	107,725
IM	31,054	9,157	16,909	22,457	891	80,469
SG	1,226	1,491	2,251	1,256	369	6,593
Total	79,793	76,558	170,784	75,914	161,858	564,907

Source: author's elaboration based on data from Passoni and Freitas (2022) and MDIC (2024)

Between 2010 and 2014, the value exported bounced back to higher levels, as exports to the RoW and the US partially recovered from the fall in the previous period, and Chinese demand for Brazilian goods continued to rise. This recovery, however, did not happen for the exports to the LAC and EU regions, explaining why these partners exhibited a negative scale effect.

During this period, the growth of exports to China showed a unique pattern, largely concentrated in the AGR group. In fact, exports of unprocessed agricultural commodities accounted for around 52.3% of the growth in value exported to this trading partner between 2011-2014 (Table 32). This concentrated pattern in the most intensive industrial group in the Brazilian production structure has led to the emergence of a large export basket effect. Another particularity of the period lies in the fact that export baskets with all partners, without exception, moved in the direction of more carbon-intensive sectors. In addition to China, other partners showed a very high export basket effect, as in the case of the EU and RoW.

In the last period, Brazilian exports have been on an upward trend with all partners, with the exception of countries in the Latin American and Caribbean region. The growth of the scale effect in this period was at least mitigated by a considerably smaller, but still positive, export basket effect. Of particular note is the large value of the export basket effect for the RoW, the highest recorded in all periods and among all partners. This effect was partially offset by the improvement in exports to China, the US and the EU in environmental terms.

Finally, when the whole period is analyzed, some characteristics stand out. The first point concerns the fact that shifts in the Brazilian export basket with RoW consistently pointed toward carbonization across all periods. The cumulative impact of these changes on emissions totaled 104.6 MtCO2e, way above the impact from shifts in the basket with other partners.

With regard to LAC, this partner had the second-largest export basket effect, i.e., Brazil's exports to this trading partner have undergone the second-largest emission increase due to changes in its sectoral composition. Furthermore, the export basket effect has remained consistently positive since the second period. These developments may be the result of increasing competition with Chinese manufacturing industry for LAC markets, especially after 2008, as highlighted in studies such as Castilho et al. (2017) and Hiratuka and Sarti (2017). This development may have pushed Brazil toward a higher degree of trade specialization in emission-intensive-commodity-based industries in the region.

The results also indicate that China’s main contribution to the carbonization of Brazilian exports has not stemmed from shifts in its import composition with Brazil. The trade relationship with this partner already started from a very high emission-intensive basis, and except for the period 2010–2014, the recomposition of Brazil’s export basket to this country has not undergone significant carbonization. Nevertheless, given that China has drastically increased its share of Brazilian exports on a much higher emission-intensive basis, its growing demand for commodities likely pressured Brazilian exports toward greater specialization in emission-intensive industries.

V. Towards a specialization in carbon-intensive industries

In chapter 1, the literature review indicated the existence of a process of regressive specialization for Brazil, albeit with certain controversies regarding its timing and intensity. At this point, this thesis aims to assess whether this pattern of regressive specialization also coincides with a pattern of specialization in emissions.

The structural decompositions carried out in the previous sections revealed two extremely important facts about the process of structural change in the Brazilian economy between 2000 and 2019. The first is that changes in the sectoral composition of output led the country to a higher level of emissions. The second concerns the fact that changes in the country's export basket also resulted in a significant increase in emissions. On this point, the evidence presented in this thesis leaves little room for doubt that changes in the structure of production and trade during this period created obstacles to the decarbonization process.

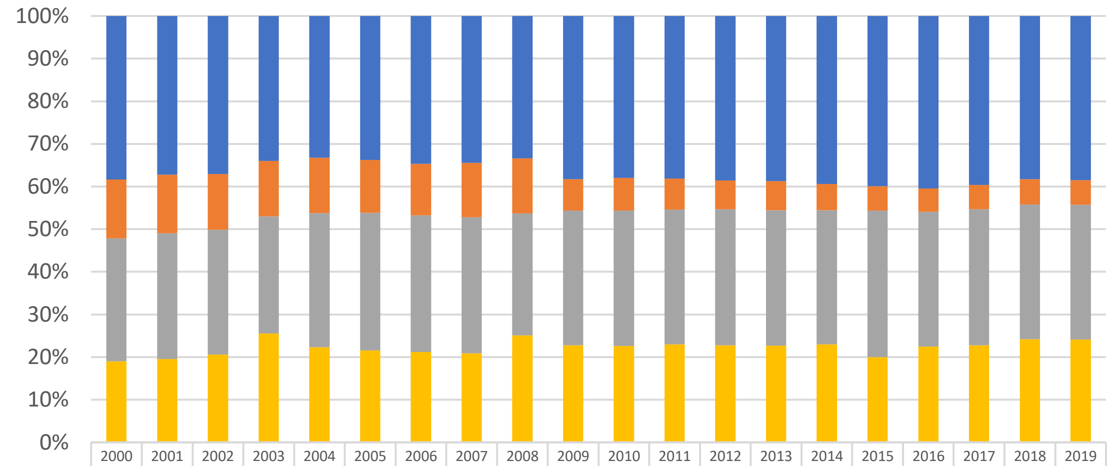
However, the decomposition terms may not offer a clear view of whether there was a greater specialization of production and trade in emissions-intensive industries during the period. As mentioned above, given the significant disparity in emission intensities among industries, it may happen that a highly emissions-intensive industry ends up dominating the decomposition sign of an entire industrial group even in the face of a marginal increase in its share of total output or exports. But while this happen, other low-emission industries may also be gaining ground in the economy. Another possibility is that very emissions-intensive industries are taking over the share of industries with marginally lower emissions intensities.

To assess whether Brazil's production structure is specializing in emissions-intensive industries, we grouped industries into quartile of emissions intensity and estimated their shares of total gross output (Graph 29). The data show that the 50% least emitting industries lost 7.8 percentage points in the composition of the Brazilian output between 2000 and 2019. However, all of this loss of share occurred in the second quartile. Indeed, the share of the first quartile marginally increased in this period. As shown in Table 34, the first quartile is entirely made up of sectors from the services group, including basic public services and/or public utility services. Not only do these industries exhibit negligible emission intensities, but their shares of total output also tend to be more resilient, as their size in the total economy may be strongly influenced by demographic factors, fiscal regimes, and regulations.

When it comes to the second quartile, relative stability can be observed for its share of total output up until 2008. It is symptomatic that this quartile was the only one to reduce its share, as it includes 80% of the industries in the IM group, 37.5% of the TM industries, all of which ended the period with a lower share of output than they had at the beginning.

Meanwhile, both the third and fourth quartiles increased their share of total output, with the fourth quartile showing the most significant growth, gaining 5.1 percentage points. It is worth noting that the quartile that saw the largest increase in its share of output during the period was the one predominantly composed of industries involved in the exploration and processing of renewable and non-renewable natural resources.

Graph 29 - Participação no valor bruto da produção por quartil de intensidade de emissão



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1st Quartile	38.3%	37.2%	37.1%	34.0%	33.3%	33.7%	34.7%	34.4%	33.4%	38.3%	38.0%	38.1%	38.6%	38.7%	39.4%	39.9%	40.4%	39.6%	38.3%	38.5%
2nd Quartile	13.8%	13.8%	13.0%	12.9%	13.0%	12.4%	12.1%	12.8%	12.9%	7.4%	7.7%	7.3%	6.7%	6.8%	6.2%	5.7%	5.5%	5.7%	5.9%	5.8%
3rd Quartile	28.8%	29.5%	29.3%	27.5%	31.4%	32.3%	32.0%	31.9%	28.6%	31.6%	31.7%	31.6%	31.9%	31.8%	31.5%	34.4%	31.6%	31.9%	31.6%	31.6%
4th Quartile	19.0%	19.6%	20.6%	25.5%	22.3%	21.6%	21.2%	20.9%	25.1%	22.8%	22.6%	23.0%	22.8%	22.7%	23.0%	20.0%	22.5%	22.7%	24.2%	24.1%

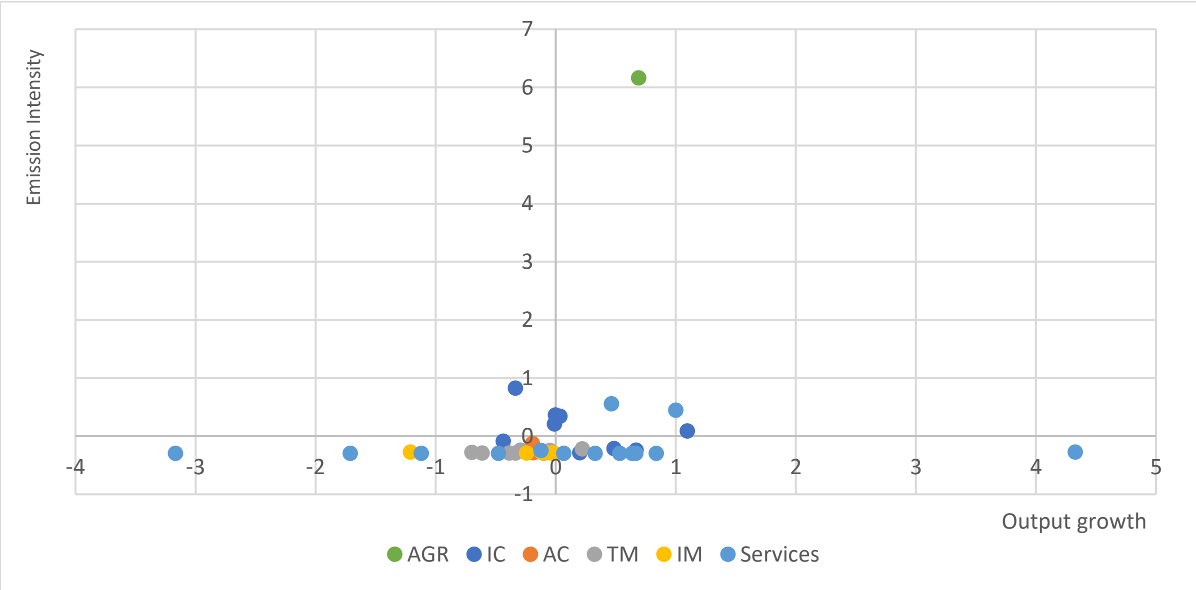
Table 34 - Number of Industries from Each Group in the Four Emission Intensity Quartiles

Industry Group	1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
AGR	0	0	0	1
IC	0	1	3	6
AC	0	2	0	1
TM	0	3	5	0
IM	0	5	1	0
Service	10	0	2	2

Graph 30 illustrates how industries performed in terms of growth between 2000 and 2019, based on their emission intensities. The results reveal a concerning pattern in the evolution of the Brazilian economy. Among the 26 industries that lost share in total output, 23 had emission intensities below the national average. Particularly notable is that 100% of the industries in the IM group and 87.5% of those in the TM group fall into this category. This suggests that the structural transformations of the Brazilian economy – specifically, the ongoing process of deindustrialization and regressive specialization – had negative implications for the country's emission levels.

Of the remaining 16 industries that gained share, 11 had emission intensities below the national average. Most of these are in the services sector (7), including basic public or utility services, followed by 3 in the IC group and 1 in the TM group. Of the 5 industries with above-average emission intensities, 4 are linked to commodity production (one from the AGR group and three from the IC group), while two belong to the services sector.

Graph 30 – Output growth and emission intensities by industry – in standard deviation units (2000-2019)

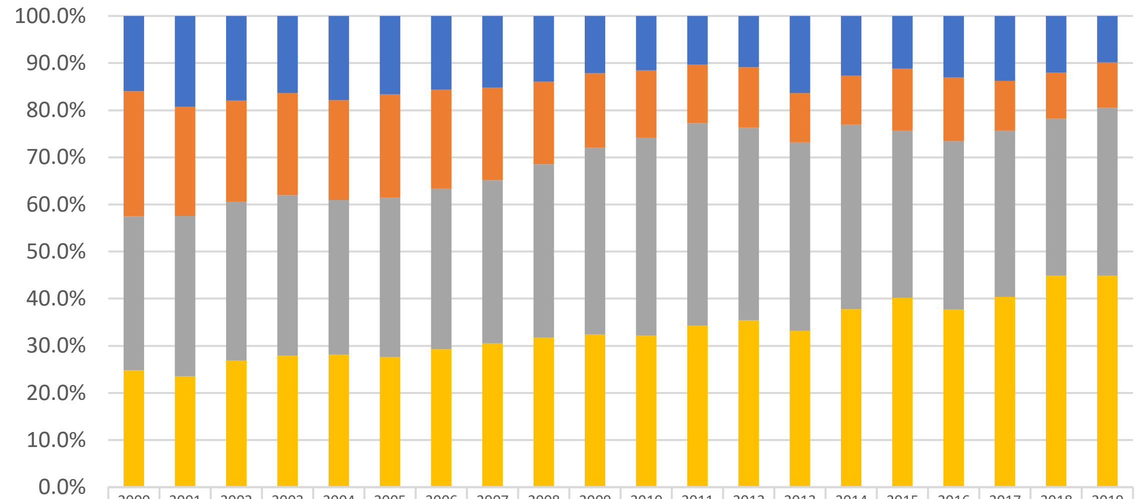


Source: author's elaboration

Graph 31 illustrates the share of industries in Brazil's exports by emissions intensity quartile. To minimize the impact of non-tradables on the emissions intensity range defining each quartile, we excluded the services group from the analysis, reducing the total number of industries from 42 to 28. The results highlight a significant loss of 23.1 percentage points in the combined share of the two least emitting quartiles in Brazil's export composition between 2000 and 2019, which helps explain the high export basket (100.2 MtCO2e) and trading partner (133.2 MtCO2e) effects discussed in Section IV. While the first quartile lost 6 percentage points, particularly after 2008, the second was under a continuous declining path, that led to a 17-percentage point loss by 2019. Notably, these two quartiles comprise 62.5% of the industries in the TM group and 100% of those in the IM group.

Similar to the trend observed in total gross production, the quartile comprising the most emissions-intensive industries saw the largest increase in Brazil's export share. However, in the case of exports, the growth was even more pronounced, with the share of the highest-emitting industries rising by 20.1 percentage points between 2000 and 2019.

Graph 31 – Brazilian export basket by emission intensity quartiles



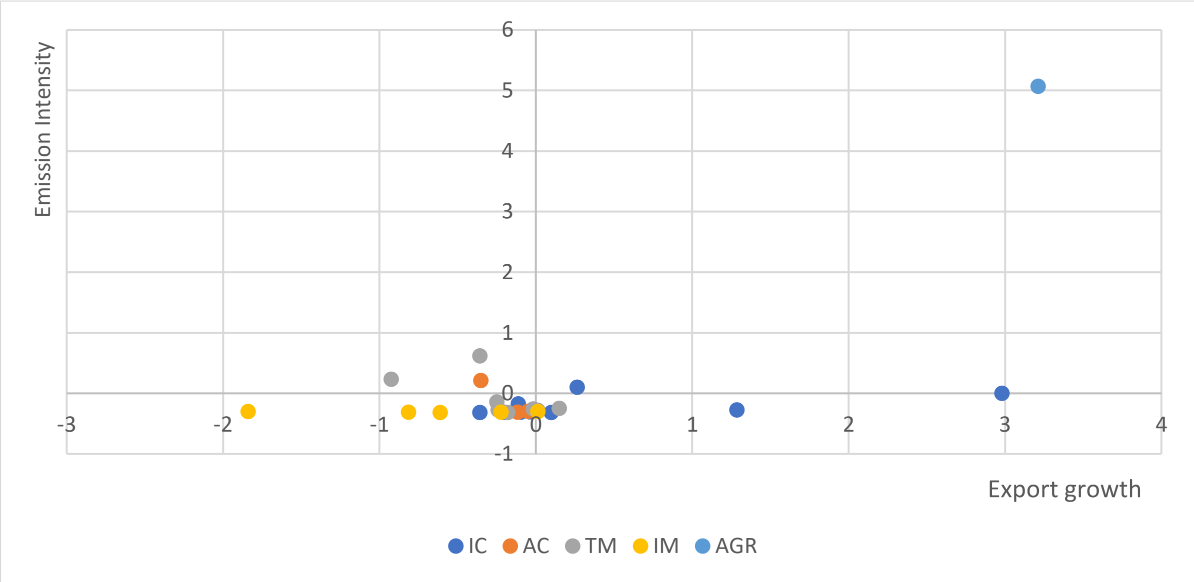
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1st quartile	15.9%	19.3%	17.9%	16.4%	17.9%	16.6%	15.6%	15.2%	13.9%	12.2%	11.5%	10.3%	10.8%	16.4%	12.6%	11.2%	13.1%	13.8%	12.0%	9.9%
2nd quartile	26.59%	23.15%	21.52%	21.61%	21.16%	21.99%	21.04%	19.59%	17.52%	15.77%	14.35%	12.43%	12.88%	10.46%	10.50%	13.13%	13.46%	10.58%	9.81%	9.62%
3rd quartile	32.7%	34.0%	33.7%	34.0%	32.9%	33.8%	34.1%	34.6%	36.9%	39.7%	42.0%	43.0%	40.9%	40.0%	39.1%	35.5%	35.7%	35.2%	33.3%	35.7%
4th quartile	24.8%	23.5%	26.9%	28.0%	28.1%	27.6%	29.3%	30.6%	31.7%	32.4%	32.2%	34.3%	35.4%	33.1%	37.8%	40.2%	37.7%	40.4%	44.9%	44.9%

Source: author’s elaboration

Finally, Graph 32 illustrates the performance of industries based on their emission intensities. The horizontal axis represents the extent to which each industry's exports grew between 2000 and 2019. Both axes are measured in standard deviation units. Thus, the values in the graph indicate which industries increased their value exported above (below) the average and how much more (less) emissions-intensive these industries are compared to the national average.

Of the 28 industries analyzed, 20 experienced below-average growth and saw their share in the export basket decline, 17 of which had emission intensities below the national average. Notably, 80% of the industries in the IM group and 62.5% of those in the TM group fall into this category. Meanwhile, five of the eight industries that increased their share in the country’s export are commodity producers (one from the AGR group and four from the IC group), three of which have emission intensities above the national average.

Graph 32- Exports' growth and emission intensities by industry – in standard deviation units (2000-2019)



Source: author's elaboration

The data presented in this section provide context for the findings of the previous sections, which indicated that changes in the sectoral composition of output and exports (whether through the export basket or trading partner effect) were relevant driving forces of emissions increase. What the data in this section reveal is that the structure, export basket, and trading partner effects do not reflect isolated cases of a higher-emission sector gaining ground in the Brazilian output or exports. Instead, they point to a broader reshaping of the economy and export basket, where emissions-intensive industries gain prominence at the expense of a widespread decline in the share of sectors with below-average emissions. In this sense, the structural changes in the Brazilian economy during the period suggest a clear pattern of specialization in emissions, both for production and exports, although this pattern is far more pronounced for the latter.

VI. CONCLUDING REMARKS

This chapter analyzed the impact of the structural changes in the Brazilian emissions using three structural decomposition analysis, each of them aiming to shed light on different aspects concerning these changes.

As pointed out by the literature, both regressive specialization and deindustrialization exert influence in the composition of economic aggregates. With this in mind, we conducted an initial SDA to examine how the changes in the Brazilian gross output have impacted the country's

GHG emission levels. In this specific decomposition we broke down the change in the emission level between different periods into three effects: This decomposition breaks down the change in emissions between periods into three effects: (i) the intensity effect, which captures the impact of changes in industries' emission intensity on total emissions; (ii) the structure effect, which reflects the influence of shifts in the sectoral composition of output on emissions; and (iii) the scale effect, which quantifies the impact of overall output growth on emissions.

The results revealed that output growth was the primary driver of emissions during the period covered by this thesis. This effect was particularly significant in driving emissions between 2000 and 2010 but diminished in relevance due to the economic downturn of the Brazilian economy during the 2010s. A notable characteristic of the Brazilian case was the large predominance of commodity-producing groups in the scale effect. This predominance stemmed from both their higher emission intensities and the fact that, during specific periods, their output growth outpaced that of other sectors. Combined, the AGR and IC groups accounted for 85.5% of the total emissions associated with output growth between 2000 and 2019.

The findings also highlighted the significant role of the structure effect in explaining changes in emissions. Over the entire period, the structure effect contributed 194.3 $MtCO_2e$. This substantial figure reflects a sustained shift in the sectoral composition of output toward industries with higher emission intensities. In fact, the structure effect was negative only between 2005 and 2010. In all other periods analyzed, changes in the sectoral composition of output accounted for at least 24.3% of emissions growth, with the effect being particularly pronounced during the 2014-2019 period. During this time, as economic growth ceased, the structure effect became the primary driver of emissions, accounting for 82.8% of the total increase in emissions.

Meanwhile, the intensity effect was considered relevant in mitigating the increase in emissions, leading to a reduction in emissions of 1,072 $MtCO_2e$. However, improvements in the emissions intensity of industries were largely concentrated in the 2010s. Beyond that period, the intensity effect turned positive and reinforced the upward trends in emissions driven by the structure or scale effect, or both.

The second SDA results provided new evidence for understanding the emission changes in the period covered by this thesis. The eight terms of the decomposition were grouped into major components: (i) changes in environmental and technical efficiencies, (ii) variations in demand leakages, and (iii) changes in final demand structure.

The changes in environmental and technical efficiencies comprise the carbonization, deforestation, and technology effects. The results showed that efficiency gains were an important driver of emission reduction in the 2000s, first due to a largely negative carbonization effect, and later due to the sharp decline in deforestation rates. In the 2010s, as deforestation began to rise again, the total efficiency gains vanished. However, the balance between the gains of the first decade and the losses in the second pointed to a significant emission reduction of 1,189.3 MtCO2e.

Throughout the entire period, the AGR group was the key determinant of efficiency gains, defining the sign of the deforestation, carbonization, and technology effects. The high relevance of this group in the deforestation effect relates to the fact that the vast majority of emissions from LUC are allocated to this group. However, for the latter effects, agriculture underwent significant productivity gains and shifts in its composition, from extensive cattle ranching to mechanized crop production. Both developments help explain why the carbonization and technology effects were largely negative for this group throughout the period.

Meanwhile, the de-densification and FD leakage effects revealed a sustained process of demand leakage starting from the second period. From 2005 onward, all industrial groups experienced leakages in both intermediate and/or final demand across every period. These leakages contributed to a reduction of 24.3 MtCO2e between 2000 and 2019. However, it is not possible to determine whether this represents a net gain in emission reductions without knowing where the demand leaked to and under what environmental conditions these goods and services are now being produced.

What the results do reveal is that these leakages are likely to pose significant challenges for Brazil's decarbonization process, particularly since industries in the TM and IM groups were severely impacted. It is important to note that 100% of the industries in the IM group and 75% of those in the TM group were classified as transition enablers, given their low capacity to induce or propagate emissions to other industries. Additionally, the growing penetration of imports within the IM group could result in the loss of critical productive capabilities for the transition towards a low carbon economy, and weaken production linkages, impairing these industries' ability to diffuse emission-saving technological progress to other sectors.

Changes in the structure of final demand were found to be the primary driver of emissions growth in all periods analyzed. The role of final demand in increasing emissions varied according to both the level and engines of economic growth. In three out of the four periods analyzed the Brazilian economy exhibited concerning signs regarding the environmental quality of economic growth. Even though the scale effect was positive, as expected, the impact of economic growth on emissions were aggravated as it increased its reliance on emission-intensive industries. Over the entire period, while growth in final demand resulted in an emission of 891.3 $MtCO_2e$, the composition and FD-mix effects contributed to another 299.1 $MtCO_2e$.

These two latter effects are intertwined: as final demand shifts toward categories with a higher concentration of emissions-intensive industries, the share of these industries in total final demand increases. This is precisely why the composition and FD-mix effects were more pronounced during periods of outward-oriented economic growth, such as 2000-2005 and 2014-2019. Despite variations in the intensity and driving forces of economic growth during this period, some regularities persisted over time. For instance, exports played a key role in explaining both the scale and demand mix effects, as it accounted for 43.8% and 85.5% of the total value for these effects between 2000 and 2019. This clearly place exports as the main driving force pushing final demand toward more emissions-intensive industries. As a corollary, industry groups linked to commodity production were at the forefront of emission increases stemming from final demand scale, composition, and mix effects.

The significant contribution of exports to emissions growth was not solely due to their increased share of Brazil's GDP, which rose from 10.1% to 13.5% during the period covered by this thesis. It also reflects a profound shift in the export mix toward more emissions-intensive industries.

The third decomposition revealed that changes in the export basket were responsible for 71.1% of the increase in export-related emissions between 2000 and 2019. This figure resulted from both an inter-partner and intra-partner carbonization trend: the former concerns the strengthening of trade relations with partners with whom Brazil maintains a highly emissions-intensive export basket, while the latter stems from the growing prominence of emissions-intensive industries in export baskets with specific trading partners.

During the analyzed period, Brazil export basket with all trade partners but the EU has gone through a rising share of emission intensive industries. Surprisingly, Brazil's exports to China did not undergo a significant shift toward high-emission industries, as the exports to this country were already heavily concentrated in commodities in the early 2000s. However, this does not mean that China had a smaller influence on Brazil's emissions linked to exports. Instead, given that exports to China were consistently more emissions-intensive than the average for Brazilian exports, its surging participation in total Brazilian exports inevitably pushed the overall export basket toward more emissions-intensive industries.

Finally, this chapter presented the evolution of industries' share in total gross output and exports by emissions intensity quartiles. The findings highlighted a process of productive and trade specialization in emissions-intensive industries. The output composition showed a growing participation of the two most emissions-intensive quartiles, with the third and fourth quartiles' shares rising by 2.7 and 5.1 percentage points, respectively. A similar trend occurred in exports, though it was far more pronounced. The fourth quartile's share of total exports surged by 20.1 percentage points, while the third quartile increased its share by 3 points. For both exports and output, the quartiles that lost share were predominantly those containing most of the industries in the IM and TM groups.

FINAL REMARKS

A fruitful debate concerning Brazil's economic and trade structure emerged in the mid-2000s, drawing attention to an ongoing pattern of structural change that could potentially undermine the country's development trajectory. Part of the specialized literature pointed to a process of premature deindustrialization beginning as early as the 1990s, triggered by an abrupt shift in economic policy. This shift combined trade and financial liberalization reforms with high interest rates and an overvalued exchange rate, which ended up dismantling the protective apparatus of Brazil's manufacturing sector, leading to its persistent underperformance and subsequent contraction. Additionally, the literature highlighted that the same economic policy missteps contributed to a regressive specialization in both the productive and trade structures—commonly referred to as the *reprimarization* of the export basket.

The debate, however, was not without controversy, particularly regarding the triggering mechanisms, timing, and intensity of the deindustrialization and reprimarization processes. Despite these divergences, some points of convergence can be identified. Notably, there seems to be broad agreement that exports underwent a considerably more pronounced regressive specialization than the overall productive structure. Moreover, it is widely recognized that the Brazilian economy has faced increasing challenges related to import penetration, particularly within the manufacturing sector.

One of the missing parts of this debate is the analysis of the environmental repercussions of the changes that hit Brazil's productive and export structure, as a higher relevance of commodities in the aggregates may be linked to the depletion of natural resources, degradation of ecosystems' ability to keep providing goods and services and larger amounts of GHG emissions.

This thesis provided a comprehensive investigation into the coevolution of Brazil's productive and trade structure and the country's GHG emissions, shedding light on the environmental implications of structural changes emerging for the Brazilian economy between 2000 and 2019. The hypothesis held by this thesis is that changes in the Brazilian structure worked against the country decarbonization by increasing its specialization in emission-intensive industries.

To investigate the validity of this hypothesis, this thesis presented in its first chapter an extensive literature review on the nexus between economic development, structural change, and the environment. Hands down, the Environmental Kuznets Curve (EKC) hypothesis represents the most widely spread effort within the debate on these topics, having inspired a vast body of research over the past three decades. A particularly relevant theme within the EKC framework concerns the alleged tendency for environmental degradation to decline through the dematerialization process of economic growth, as manufacturing makes room for a higher participation of services in the economic structure. Among the various criticisms leveled at the EKC, one of special interest is the following: its validity may not hold when the analysis is adjusted for trade.

Chapter 1 also explored the discussion on recent structural changes in Brazil, focusing on the deindustrialization and reprimarization of the country's export profile. Additionally, it highlighted some concerning trends in environmental indicators during the analyzed period, including the extraction and intensity of natural resource use in the Brazilian economy, as well as those related to the volume and intensity of emissions and energy efficiency between 1990 and 2019. The trajectory of environmental indicators raised serious concerns about the environmental repercussions of recent structural changes in the Brazilian economy.

To investigate these repercussions, this thesis focuses on one specific indicator: GHG emissions. Based on this indicator, the study is structured around four key research questions: (i) What is the Brazilian structural emission profile? (ii) What are the main driving forces behind emission growth during the analyzed period? (iii) Are changes in the Brazilian productive structure and trade patterns hindering the country's decarbonization? (iv) How has the share of emission-intensive industries in total output and exports evolved?

The analysis to answer these questions, we built gross emission vectors and applied environmentally extended input output techniques, including three structural decomposition analysis, all of them covering the period 2000-2019. The first SDA focused on investigating the impact of shifts in the output structure on emissions, while the second and third decompositions follow a similar strategy but dedicated to understanding the impacts of changes in the structure of final demand and exports on total emissions.

Chapter three presented the Brazilian emission structural profile. The results in this chapter revealed that commodity linked groups, especially AGR and IC, had by far the highest emission intensity of the Brazilian structure, and that these sectors performance were tightly connected to exports. Therefore, AGR and IC emissions increased faster in periods of fast acceleration of international trade.

Despite their higher emission intensities, these two groups were the only ones to reduce emissions during the analyzed period, which may be linked to the increasing scrutiny of international markets regarding the environmental conditions under which these goods were produced.

Meanwhile, the growth in export emissions during the period far outpaced the economy's average, leading to a sharp increase in their share of total emissions—from 19.5% to 31.8% when land-use change emissions are excluded, and from 19.8% to 35.1% when included. Throughout the analyzed period, export emissions intensity increased, indicating that the rise in their share of the country's total emissions was not solely due to the expansion of export value.

When analyzing export emissions by trading partner, the results revealed a sharp increase in emissions associated with exports to China. This trend was driven by the consistent growth in Chinese demand for commodities throughout most of the analyzed period, making China's imports from Brazil the most emissions-intensive among all trading partners. Still, it is important to mention that post-2008, export emissions intensities increased across all trading partners.

The context of high international demand for commodities has also led to increasing pressure on deforestation rates. This is evidenced by the substantial rise in the share of exports in emissions from land-use change, which jumped from 19.7% to 36.9% between 2000 and 2019, peaking at 42.3% in 2018. This indicates that Brazil's trade relations are increasingly responsible for a broader set of environmental impacts resulting from the loss or degradation of forested areas, which is not dealt with in this thesis, such as biodiversity loss, soil degradation deterioration of microclimate and rainfall regimes, among others.

This chapter also proposed four clusters to categorize Brazilian industries regarding their ability to support decarbonization, based on normalized emission backward and forward linkages indicators. The analysis revealed that all IM industries and most TM industries can be classified as *transition enablers*, as they induce or propagate less emissions to other sectors compared to the economy's average. Therefore, steering economic growth towards these industries could help Brazil progressively decouple its economic development from emissions. In contrast, industries associated with commodity production, which are at the forefront of Brazil's regressive specialization process – either induce significant emissions in upstream sectors, propagate large amounts of emissions to downstream sectors, or both.

Finally, the fourth chapter presented the results of the structural decomposition analyses conducted in this thesis. All three SDAs revealed that growth in the level of economic activity was the most prominent force driving emissions upward. Indeed, the output and final demand scale effects were the primary contributor to emissions increases between 2000 and 2019, as well as across all analyzed periods, except for 2014-2019, which was marked by an economic downturn in the Brazilian economy. The scale effect also predominated in export-related emissions for the entire 2000-2019 period and specifically during the 2000-2005 and 2014-2019 subperiods.

The positive scale effect is not a problem *per se* but rather an expected outcome of economic growth; whenever an economic aggregate increases, the scale effect will inherently be positive. The real issue facing the Brazilian economy during this period lies in factors that should have offset emissions from economic growth but instead exacerbated them.

Indeed, the results show that, while environmental efficiency gains helped reduce total emissions between 2000 and 2019, these gains were largely concentrated in the 2000s – particularly during 2005-2010, when deforestation rates in Brazil sharply declined. However, these efficiency gains ceased in the 2010s, with emission intensity starting to contribute positively to emissions growth. As for technical efficiency, no clear trend emerged, as it alternated between positive and negative values. Nonetheless, over the entire period, the technology effect yielded a substantial negative value, indicating that technical efficiency gains ultimately prevailed.

The most concerning aspect, however, is that the growth patterns of output, final demand, and exports worked against decarbonization. During the period covered by this thesis, changes in the sectoral composition of output, final demand, and exports significantly increased emissions.

Between 2000 and 2019, the output's structure effect contributed to 194.3 $MtCO_2e$, demonstrating that shifts in the sectoral composition of output drove emissions higher. A similar situation applies in three of the four subperiods analyzed (2000-2005, 2010-2014, and 2014-2019), with output composition changes driving emissions upward. Although the significance of this effect varied across periods, depending on the characteristics of economic growth, it accounted for at least 24.8% of total emissions growth. In the final subperiod, changes in output composition were responsible for a staggering 82.8% of the total emissions increase.

The second decomposition revealed that final demand forces steered towards more emission-intensive sectors. Combined, the composition and FD-mix effects contributed to 299.1 $MtCO_2e$. The findings in this decomposition pointed to exports as primary culprit of pushing final demand towards emission-intensive industries, since exports outperformed other final demand component, and their composition is more reliant on high emission-intensive industries than the average of the economy – as indicated by its considerably higher emission intensity. In fact, exports played a key role in explaining both the scale and demand mix effects across most of the periods analyzed and accounted for 43.8% and 85.5% of the total value for these effects between 2000 and 2019.

The de-densification and FD-leakage effects revealed a generalized trend of import penetration in both intermediate and final demand across all industry groups and periods. As a growing share of emission demand was met through international trade, import penetration led to a reduction in national emissions. However, as highlighted in the literature on Brazilian deindustrialization, import penetration can harm the interindustry fabric by weakening linkages across industries and potentially leading to the loss of key productive capabilities.

Thus, beyond its short-term emissions-reducing impact, the continued import penetration raises concerns about Brazil's decarbonization prospects. This process has hit the IM and TM groups particularly hard, affecting most of their industries after the second half of the 2000s. While final demand leakage to imports diminishes the potential decarbonization benefits that could be retained within the Brazilian economy, the de-densification of inter-industry relations compromises the country's productive capacity to respond to policy efforts aimed at steering demand toward low-carbon industries. Moreover, by weakening the IM group's linkages, this process could reduce its ability to propagate decarbonization throughout the Brazilian economy via the diffusion of emissions-saving technological progress.

As per the third decomposition, it revealed that changes in the export basket accounted for a striking 71.1% of the increase in export-related emissions between 2000 and 2019. This was driven either by the strengthening of trade relations with partners to whom Brazil exports a highly emissions-intensive basket or by the growing prominence of emissions-intensive industries within the export baskets of specific trading partners.

It is important to note that Brazilian exports to all partners, except the EU, have shifted toward more emissions-intensive industries, particularly in exports to the RoW and LAC countries. The export basket effect with China was relatively small, as Brazilian exports to this partner were already heavily reliant on emissions-intensive industries in 2000. Nonetheless, the rapid expansion of exports to China, rooted in a highly commodity-based pattern, has undoubtedly contributed to increasing the embedded emissions in Brazil's export basket.

Finally, this thesis demonstrated that the share of emission-intensive industries has increased in both Brazil's productive structure and exports. Industries in the two most emission-intensive quartiles expanded their share of total output by 7.8 percentage points, with the largest growth (5.1 percentage points) occurring in the fourth quartile. Regarding Brazilian exports, the share of the two most intensive quartiles rose by 23.1 percentage points, with 20.1 percentage points of this increase concentrated in the most emission-intensive quartile. In both cases, these expansions came at the expense of a decline in the shares of quartiles predominantly composed of IM and TM industries.

Given this, it is evident that the structural changes during the analyzed period have created significant obstacles to Brazil's decarbonization. Beyond the regressive specialization often cited in the literature, this thesis demonstrated that the Brazilian economy experienced an *emissive specialization* – i.e., a shift toward greater reliance on high-emission industries. In other words, the evolution of the Brazilian economy between 2000 and 2019 featured a structural carbonization process, that is a situation in which sectoral composition changes further amplified the emissions stemming from economic growth. Therefore, looking forward, the decarbonization of the Brazilian Economy is very unlikely to take off if the deindustrialization and reprimarization processes are not halted.

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