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# Does productive structure matter? Natural resource exploitation and greenhouse gas emissions in Brazil

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**Abstract:**
This paper examines the long-run relationship between natural resource exploitation and greenhouse gas emissions in Brazil from 1990 to 2024, using Autoregressive Distributed Lag models. Natural resource exploitation is measured by domestic extraction, both in aggregate terms and disaggregated into biomass, metal ores, non-metallic minerals and fossil fuels. The study also investigates whether the manufacturing share in GDP moderates this relationship. The results show that total extraction increases emissions, with significant effects for biomass, metal ores and non-metallic minerals. The interaction terms are negative and statistically significant across all material categories, suggesting that a more industrially dense productive structure attenuates the environmental pressure associated with resource exploitation. The findings contribute to the literature by combining physical measures of extraction with a structural moderation approach and highlight the importance of linking natural resource governance to productive and technological upgrading.

**Keywords:** natural resources exploitation, productive structure, environmental degradation.

**Resumo:**
Este artigo analisa a relação de longo prazo entre exploração de recursos naturais e emissões de gases de efeito estufa no Brasil entre 1990 e 2023, por meio de modelos Autorregressivos de Defasagens Distribuídas. A exploração de recursos naturais é mensurada pela extração doméstica, considerada de forma agregada e desagregada em biomassa, minérios metálicos, minerais não metálicos e combustíveis fósseis. O estudo também investiga se a participação da manufatura no PIB modera essa relação. Os resultados indicam que a extração doméstica total eleva as emissões, com efeitos mais expressivos para biomassa, minerais metálicos e minerais não metálicos. Os termos de interação são negativos e estatisticamente significativos em todas as categorias materiais, sugerindo que uma estrutura produtiva industrialmente mais densa atenua a pressão ambiental associada à exploração de recursos. Os resultados contribuem para a literatura ao combinar medidas físicas de extração com uma abordagem de moderação estrutural e ressaltam a importância de articular governança dos recursos naturais com adensamento produtivo e tecnológico.

**Palavras-chave**: exploração de recursos naturais, estrutura produtiva, degradação ambiental.

**Área 8: Economia Ecológica, Mudança Climática e Sustentabilidade**

**JEL Classification:** Q32; Q56; O14.

## 1. Introduction

Since the 2000s, the Brazilian economy has been marked by increasing reliance on the production and export of primary commodities, alongside the declining relative participation of manufactured goods, especially those with higher technological intensity (Nassif and Castilho, 2020). Although this trajectory may have supported short-run economic growth, it has reinforced regressive specialization, with limited long-term effects on productivity, income generation and structural transformation (Bresser-Pereira, 2008). In this sense, the Brazilian trajectory can be interpreted as part of a broader Latin American pattern often described as neo-extractivism, a growth strategy based on the large-scale exploitation and export of natural resources, frequently associated with commodity dependence, socio-environmental conflicts and weak productive diversification (Svampa, 2019).

In Brazil, this issue is particularly relevant because natural resource exploitation is closely connected to land-use change, deforestation, agricultural expansion, mining, fossil fuel extraction and other degrading processes. Thus, the environmental consequences of Brazil's productive specialization cannot be understood only as a matter of economic growth, but also as a result of the material and sectoral composition of the economy.

Recent literature has shown that environmental performance depends not only on the scale of economic activity, but also on the composition and technological characteristics of the productive structure. Studies focusing on industrialization and economic complexity indicate that structural transformation may either increase or reduce environmental pressure, depending on the sectoral composition, technological intensity and energy base of production (Destek, 2021; Avenyo and Tregenna, 2022; Romero and Gramkow, 2021; Guarini and Oreiro, 2023). A more recent branch of this literature has examined structural and technological factors as moderators of environmental impacts. Renewable energy and technological innovation, for example, have been shown to condition the effects of manufacturing, economic growth, trade openness, and natural resource dependence on emissions (Aquilas et al., 2024; Adebayo et al., 2022; Ehigiamusoe et al., 2024; Zhao et al., 2024). However, limited attention has been paid to whether the productive structure itself moderates the environmental effects of physical resource extraction, especially in economies characterized by commodity dependence and deindustrialization.

Against this background, this paper investigates the long-run relationship between natural resource exploitation and environmental degradation in Brazil. Environmental degradation is measured by greenhouse gas emissions, while natural resource exploitation is proxied by domestic extraction, both in aggregate terms and disaggregated into biomass, metal ores, non-metallic minerals and fossil fuels. The central research question is whether natural resource exploitation worsens the long run environmental quality, measured by higher greenhouse gas emissions, and whether this effect depends on the productive structure in which extraction occurs.

Using Autoregressive Distributed Lag models with annual data from 1990 to 2024, the study assesses: (i) whether domestic extraction increases greenhouse gas emissions; (ii) whether this effect differs according to the type of resource extracted; and (iii) whether a higher manufacturing share in GDP mitigates the environmental impact of resource exploitation. The paper is guided by three hypotheses: (i) natural resource exploitation has a positive long-run effect on emissions; (ii) this effect is heterogeneous across resources; and (iii) a more industrially dense productive structure can reduce, although not eliminate, the environmental pressure associated with resource exploitation.

This paper contributes to literature in three main ways. First, it examines the environmental effects of natural resource exploitation using domestic extraction measured in physical terms, rather than relying exclusively on monetary indicators such as natural resource rents or commodity export shares. Second, it disaggregates domestic extraction into biomass, metal ores, non-metallic minerals and fossil fuels, allowing the analysis to identify whether different material categories generate heterogeneous long-run effects on greenhouse gas emissions. Third, it investigates whether the productive structure itself conditions this relationship by introducing the interaction between domestic extraction and the manufacturing share in GDP. In doing so, the paper extends the literature on environmental moderation effects by focusing on a structural mechanism that has received limited attention, particularly in the Brazilian context.

The remainder of the paper is organized as follows. Section 2 reviews literature on natural resource exploitation, productive structure and environmental performance. Section 3 presents econometric strategies. Section 4 discusses empirical results. Section 5 develops the main policy implications in the context of the global low-carbon transition. Section 6 concludes.

## 2. Natural resource exploitation, productive structure and environmental performance

This section reviews literature on the relationship between natural resource exploitation, productive structure and environmental performance. It first discusses the environmental implications of extractive and neo-extractivist development patterns. It then examines how productive structure, particularly the role of manufacturing, can shape environmental outcomes. Finally, it reviews empirical studies that investigate moderating factors in the relationship between natural resource use and environmental pressure, providing the basis for the hypotheses tested in this study.

### 2.1. Natural resource exploitation and neo-extractivism

In this research, natural resource exploitation is understood as the broader economic process through which natural resources are appropriated and incorporated into production and trade. Empirically, this process is proxied by domestic extraction, which measures the physical amount of biomass, metal ores,

non-metallic minerals and fossil fuels removed from the domestic environment. Domestic extraction does not capture all the institutional, territorial and distributive dimensions of resource exploitation, but it provides a consistent measure of its material basis.

Latin American development debate points the concept of neo-extractivism as more than the expansion of individual extractive activities. It describes a growth and accumulation pattern based on the large-scale appropriation of natural resources, generally with limited domestic processing and a strong orientation towards international commodity markets (Brand et al., 2016). Compared with traditional extractivism, the "neo" dimension was initially associated with the more active role played by the state during the commodity boom of the early twenty-first century, including greater public control over resource revenues and their use to finance infrastructure, income transfers and social policies. Nevertheless, the productive and external foundations of the model remained largely dependent on the exploitation and export of natural resources (Gudynas, 2010; Burchardt and Dietz, 2014).

The literature subsequently broadened the concept beyond the experience of the progressive Latin American governments with which it was originally associated. From this perspective, neo-extractivism represents a persistent development pattern that may operate under different political coalitions and institutional arrangements. Its defining characteristics include the expansion of the extractive frontier, the growing importance of large-scale mining, hydrocarbons and export-oriented agriculture, the formation of enclaves with weak domestic productive linkages and the subordination of territories to the requirements of global commodity chains (Brand et al., 2016; Svampa, 2019). Rather than constituting a temporary response to favourable commodity prices, neo-extractivism can reinforce a structurally dependent form of integration into the world economy, centred on the provision of materials and energy to external markets. Burchardt and Dietz (2014), for example, argue that the available socioeconomic evidence does not support interpreting neo-extractivism as merely a transitory strategy in the region.

Although commodity-based growth can generate foreign exchange, fiscal revenues and short-run improvements in income and employment, the literature highlights substantial economic, social and environmental costs (Svampa, 2019). Economically, extractive specialization may deepen commodity dependence, expose countries to price volatility and discourage productive diversification, thereby limiting the prospects for sustained structural transformation (Warnecke-Berger et al., 2023). Environmentally, the expansion of mining, fossil-fuel production, industrial agriculture and large infrastructure projects is associated with deforestation, land-use change, greenhouse gas emissions, soil degradation, water contamination and biodiversity loss (UNEP, 2019; UNEP & IRP, 2024). These impacts are not restricted to the extraction site, as they are also transmitted through transportation networks, processing activities and the occupation of new territories.

Empirical studies have examined the environmental consequences of extractive specialization and natural-resource dependence in Latin America using different indicators of resource exploitation.

Drawing on material flow analysis for South America between 1990 and 2017, Alonso-Fernández and Regueiro-Ferreira (2022) show that the region's specialization in the extraction and export of natural resources has generated growing physical trade imbalances and transferred an increasing share of the environmental burdens associated with global consumption to South American economies. Their findings suggest that unfavorable terms of trade may reinforce a cumulative dynamic in which countries must continuously expand the physical volume of extracted and exported materials.

Econometric evidence also indicates that dependence on natural resources is associated with greater environmental pressure. Using quantile regressions for Latin American countries, Alvarado et al. (2021) find that natural-resource rents have heterogeneous effects on the ecological footprint across its distribution, indicating that the environmental consequences of resource dependence vary according to countries' structural and environmental conditions. Seri and de Juan Fernández (2023), in turn, estimate ARDL models for 21 Latin American economies and find that the share of commodities in exports, whenever statistically significant, increases per capita $CO_2$ emissions. Their results also show that agricultural land expansion contributes to emissions in several countries, supporting the argument that commodity dependence and extractive specialization constitute important drivers of environmental degradation in the region.

Evidence linking physical resource use to environmental degradation remains limited in Brazil, although recent studies have examined the country's socioeconomic metabolism. Araújo (2022) documents the expansion of domestic material consumption, increasing material intensity and growing physical exchanges with other economies between 1970 and 2019. Using frequency-domain causality analysis, the study also finds that iron ore, biomass and crude oil consumption contribute to economic growth while increasing emissions. Nevertheless, little evidence exists on the long-run effect of domestic extraction—both aggregated and disaggregated by material category—on greenhouse gas emissions, particularly when the conditioning role of productive structure is considered.

### 2.2.Productive structure and environmental performance

The environmental consequences of natural resource exploitation depend not only on the volume of materials extracted, but also on the productive structure through which these resources are processed, transformed and incorporated into economic activity (Antweiler et al. 2001); UNEP (2024)). Structural approaches to the environment commonly distinguish among scale, composition and technique effects. While the scale effect associates economic expansion with greater resource use and pollution, the composition effect reflects changes in the sectoral distribution of production, and the technique effect captures variations in environmental intensity resulting from technological progress, productive efficiency and changes in production methods and energy sources (Grossman and Krueger, 1995).

Consequently, structural change may either increase or reduce environmental pressure, depending on which activities expand and on the technologies through which production is organized.

Manufacturing occupies an ambiguous position in this relationship. On the one hand, industrial production has historically been associated with intensive energy and material use, particularly in sectors such as steel, cement and chemicals (IPCC, 2022). An increasing manufacturing share may therefore raise emissions when industrial expansion is concentrated in pollution-intensive activities and supported by carbon-intensive energy sources. On the other hand, manufacturing can contribute to greater value creation per unit of material used and support the accumulation of technological capabilities required for improvements in resource and energy efficiency. In particular, the production of more sophisticated goods tends to combine higher value added with more advanced technologies and lower emissions intensity (Romero and Gramkow, 2021). Its environmental effect thus depends on the sectoral, technological and energy characteristics of industrialization rather than on the manufacturing share alone.

Structuralist development economics has historically emphasized that economic performance depends on the composition of the productive structure rather than on aggregate growth alone. In the Latin American structuralist tradition, sectoral specialization, technological heterogeneity, productive linkages and the capacity to generate and diffuse technical progress are central determinants of productivity, employment and external vulnerability (Cimoli and Porcile, 2014). As environmental constraints have become an unavoidable dimension of development, this perspective has increasingly been extended to the ecological consequences of structural change. From this standpoint, development requires not only a shift towards more productive and technologically dynamic activities, but also a transformation of the productive structure capable of reducing material, energy and emissions intensity (ECLAC, 1991, 2016). This approach establishes a promising dialogue between Latin American structuralism and ecological economics, since both traditions stress that the qualitative composition of economic activity matters for long-run development and sustainability.

This convergence is particularly relevant for peripheral economies, whose specialization in natural-resource-intensive activities may reproduce not only technological and external asymmetries, but also an ecologically unequal distribution of the material and environmental costs of production and trade (Saes, 2023). Recent contributions have sought to address this problem through the notion of ecological neo-structuralism, which systematically incorporates environmental constraints into the Latin American structuralist framework. Rather than abandoning the traditional concerns with productive specialization, structural heterogeneity, technological gaps and balance-of-payments constraints, this approach expands them by recognizing that economic systems are embedded in finite ecological systems and depend on continuous flows of materials and energy. Accordingly, structural transformation should simultaneously promote technological learning, employment and external sustainability while reducing carbon emissions and material intensity. From this perspective, development requires not simply

economic growth, but a sustainable structural change that simultaneously promotes innovation, employment-generating demand and environmental efficiency (Sánchez et al., 2024).

Taken together, these arguments suggest that the environmental effects of natural resource exploitation are structurally conditioned. A productive structure capable of generating greater value added, technological learning and more efficient material and energy use may weaken the connection between resource extraction and environmental degradation. This does not imply that manufacturing is inherently sustainable, but rather that the magnitude and direction of its environmental effects depend on its sectoral composition, technological content and energy base. The extent to which productive structure improves environmental performance is therefore an empirical question.

### 2.3.Empirical evidence on productive structure and environmental performance

Building on this broader structuralist perspective, a growing empirical literature has investigated whether differences in productive structure help explain countries' environmental performance. These studies have employed indicators such as manufacturing value added, sectoral composition, productive diversification and economic complexity to assess whether environmental outcomes depend on what economies produce and on the technological capabilities embedded in their production structures. More recently, this literature has also examined whether productive, technological and institutional characteristics moderate the environmental effects of economic growth, trade and natural resource dependence.

Empirical studies using manufacturing or industrial value added as indicators of productive structure have produced mixed results. For several developing and emerging economies, industrial expansion is associated with higher carbon emissions and environmental pressure, particularly when production relies on fossil energy, pollution-intensive activities and limited technological capabilities. Mentel et al. (2022), for example, find that industrialization increases $CO_2$ emissions in Sub-Saharan African countries, although renewable electricity mitigates this effect. Using a broad sample of developing economies, Avenyo and Tregenna (2022) also identify a positive association between manufacturing value added and $CO_2$ emissions, while showing that environmental outcomes vary according to the technological composition of manufacturing. Destek (2021) shows for Turkey that initial industrialization, deindustrialization and reindustrialization generate distinct effects on carbon emissions and the ecological footprint, while Destek et al. (2024) find that these effects also differ between developed and emerging economies. Taken together, this evidence suggests that the environmental consequences of manufacturing depend less on its relative size alone than on the technological, energy and sectoral characteristics of structural transformation.

Moving beyond manufacturing shares alone, a related strand of the literature has examined whether productive sophistication and technologically oriented structural change can improve environmental

performance. Using data for 67 countries, Romero and Gramkow (2021) find that greater economic complexity is associated with lower greenhouse gas emissions per capita and lower emissions intensity, suggesting that the capabilities embedded in more sophisticated production may support cleaner technologies and higher value creation. However, productive sophistication is not intrinsically sustainable, since its environmental effects depend on the technological and sectoral direction of structural change. From a structuralist and new-developmentalist perspective, Guarini and Oreiro (2023) argue that the ecological transition depends not only on cleaner technologies, but also on changes in the composition of production towards activities with lower environmental impacts. Their analysis suggests that reindustrialization and environmental sustainability can be compatible when productive transformation expands green and technologically dynamic activities rather than reproducing carbon- and resource-intensive industrial patterns.

Given the heterogeneous environmental effects of productive transformation, recent studies have increasingly examined whether technological and energy-related conditions moderate the impact of economic activity on environmental performance. Aquilas et al. (2024), for example, find that although manufacturing value added is associated with lower environmental sustainability in African economies, its interaction with renewable energy improves environmental performance. Using an ARDL approach for Malaysia, Ehigiamusoe et al. (2024) similarly show that technological innovation reduces the adverse effects of economic growth and trade openness on carbon emissions. These findings indicate that the environmental consequences of production and trade depend not only on their scale, but also on the energy base and technological capabilities through which economic activity is organized.

This interaction-based literature has also been extended to natural-resource dependence. Adebayo et al. (2022) and Zhao et al. (2024) find that technological innovation and green innovation can weaken the adverse environmental effects of natural resource rents in newly industrialized countries and the BRICS, respectively. However, Ehigiamusoe et al. (2024) obtain the opposite result for Malaysia, where technological innovation does not mitigate the emissions associated with natural resource rents. Taken together, the evidence suggests that technology does not automatically make resource exploitation environmentally sustainable; its moderating effect depends on whether technological capabilities are effectively incorporated into extraction and processing activities and directed towards cleaner production.

Overall, the literature on moderating effects shows that the environmental consequences of economic activity and natural-resource dependence are conditional on the technological, productive and energy characteristics of each economy. This perspective is particularly relevant for Brazil, where extensive natural resource exploitation coexists with commodity dependence, regressive specialization and declining manufacturing participation. Despite growing evidence on the moderating roles of technological innovation, renewable energy and other structural factors, little attention has been paid to whether the productive structure itself conditions the environmental effects of physical resource

extraction. Existing studies generally rely on natural resource rents or commodity dependence and rarely consider domestic extraction in physical terms and disaggregated by material category. This paper addresses this gap by examining whether manufacturing value added moderates the long-run relationship between domestic extraction and greenhouse gas emissions in Brazil.

## 3. Material and Methods

This study investigates the long-run relationship between natural resource exploitation, proxied by domestic extraction, and greenhouse gas emissions in Brazil with annual data from 1990 to 2024. It also investigates whether this effect is conditioned by the country's productive structure, based on the literature regarding the moderating role of structural characteristics in environmental performance.

The empirical strategy is based on Autoregressive Distributed Lag models (ARDL), following Pesaran and Shin (1999) and Pesaran et al. (2001). This approach is suitable because it allows for the estimation of long-run relationships in relatively small time-series samples with variables integrated of order zero or one. It also distinguishes long-run effects from short-run dynamics, which is consistent with the paper's focus on the persistent environmental effects of natural resource exploitation. Another advantage is the ability to choose the most appropriate number of lags for each variable to fit the models.

The model is estimated in its error correction form (ARDL-ECM), which can be specified by Equation (1):

$$\Delta y_t = \alpha_0 + \alpha_1 T + \beta_1 y_{t-1} + \beta_2 x_{t-1} + \sum_{i=0}^{n} \Phi_{1i} \Delta y_{t-i} + \sum_{i=0}^{p} \Phi_{2i} \Delta x_{t-i} + \mathcal{E}_t \qquad (1)$$

where $y_t$ is the dependent variable, $\alpha_0$ is the intercept, $\alpha_1 T$ represents the trend term, $x$ denotes the independent variables, $\beta_i$ are the long-run parameters, $\Phi_i$ are the short-run parameters, and $\varepsilon_i$ is the white-noise error term.

To test cointegration relationship between the dependent and explanatory variables, Pesaran et al. (2001) propose the use of Wald statistic (F-test) to assess the joint significance of the long-run parameters. However, under the null hypothesis of no cointegration, the test statistics follow non-standard asymptotic distributions. To address this, Pesaran et al. (2001) developed a set of critical values (bounds limits), where the regressors are assumed to be either all zero-order integrated — lower bound — or all one-order integrated — upper bound. The analysis involves comparing the computed F-statistics to these bounds. If the F-statistics exceed the upper bound, cointegration is confirmed and the short- and long-run coefficients can be estimated, along with the speed of adjustment toward long-run equilibrium in response to short-run shocks.

In addition, diagnostic tests should be conducted to check for serial autocorrelation (LM test) and to assess parameter stability—using the cumulative sum of residuals (CUSUM) and cumulative sum of squared residuals (CUSUMSQ) tests as proposed by Brown et al. (1975) to ensure the robustness and validity of the estimated models.

Following Equation (1), the research involves estimation of two sets of models, referred to as restricted and expanded models, in ten different specifications according to the natural resource variable considered. The two main specifications are as follows (Equations 2 and 3):

Restricted Models (specifications 1 to 5):

$$\Delta GGE = \alpha_0 + \alpha_1 T + \beta_1 GGE_{t-1} + \beta_2 NRj_{t-1} + \beta_3 GDPpc_{t-1} + \beta_4 Open_{t-1} + \sum_{i=0}^{n} \phi_1 \Delta GGE_{t-i} + \sum_{i=0}^{p} \phi_2 RNj_{t-i} + \sum_{i=0}^{q} \phi_3 \Delta GDPpc_{t-i} + \sum_{i=0}^{r} \phi_4 \Delta Open_{t-i} + \varepsilon_t \quad (2)$$

Expanded Models (specifications 6 to 10):

$$\Delta GGE = \alpha_0 + \alpha_1 T + \beta_1 GGE_{t-1} + \beta_2 NRj_{t-1} + \beta_3 NRj * VAmanuf_{t-1} + \beta_4 GDPpc_{t-1} + \beta_5 Open_{t-1} + \sum_{i=0}^{n} \phi_1 \Delta GGE_{t-i} + \sum_{i=0}^{p} \phi_2 \Delta RNj_{t-i} + \sum_{i=0}^{q} \phi_3 \Delta NRj * VAmanuf_{t-1} + \sum_{i=0}^{r} \phi_4 \Delta GDPpc_{t-i} + \sum_{i=0}^{s} \phi_5 \Delta Open_{t-i} + \varepsilon_t \quad (3)$$

The models use annual data for the Brazilian economy from 1990 to 2024. Although the underlying series are available for a longer period, specifications based on earlier observations showed evidence of parameter instability. The selected period represents the longest common sample for which the models displayed satisfactory stability and diagnostic properties across all specifications. All variables are expressed in natural logarithms to indicate elasticities. Table 1 describes the variables.

The dependent variable greenhouse gas emissions (GGE) is measured as the sum of carbon dioxide, methane and nitrous oxide emissions in $CO_2$ equivalent. The explanatory variable of interest is natural resource exploitation, proxied by domestic extraction, considered both in aggregate terms (RN_total), and disaggregated into biomass (RN_bio), metal ores (RN_met), non-metallic minerals (RN_nmet) and fossil fuels (RN_ff). Data on domestic extraction, measured in metric tonnes, is obtained from the United Nations Environment Programme, International Resource Panel, Global Material Flows Database.

Table 1: Variables Description

| Variable | Definition | Source | Expected sign |
|---|---|---|---|
| GGE | Greenhouse gases emissions (in metric tonnes of $CO_2$ equivalent) | WDI | * |
| $NR_i$ | Natural resource domestic extraction, where $j$ = total, biomass, metal ores, non-metallic minerals and fossil fuels. The data are reported in metric tonnes. | Global Material Flows Database | Positive |
| $RN_i$*VAmanuf | Interaction term between domestic extraction ($j$ = total, biomass, metal ores, non-metallic minerals and fossil fuels) and manufacturing value added as a share of GDP. | WDI | Negative |
| GDPpc | Per capita GDP (in constant 2015 US dollars) | WDI | Positive |
| Open | Trade openness (sum of exports and imports as % of GDP) | WDI | Ambiguous (+/-) |

Source: Own elaboration.

The restricted models provide the baseline estimates of the direct association between natural resource exploitation and greenhouse gas emissions. The expanded models assess whether this association is conditional on the productive structure. In these models, the coefficient of the interaction term indicates whether a greater manufacturing share strengthens or weakens the environmental effect of domestic extraction. If $\beta_1 > 0$ and $\beta_3 < 0$, natural resource exploitation is positively associated with greenhouse gas emissions, but this effect decreases as the manufacturing share increases. In this case, manufacturing value added moderates the emissions effect of domestic extraction, although the overall marginal effect of domestic extraction remains dependent on the magnitude of both coefficients and on the observed level of manufacturing participation.

Each set comprises five specifications, according to the natural resource variable considered. The first uses total domestic extraction (NR_total), while the remaining specifications disaggregate extraction into biomass (NR_bio), metal ores (NR_met), non-metallic minerals (NR_nmet) and fossil fuels (NR_ff). The restricted models therefore correspond to Specifications 1–5, and the expanded models to Specifications 6–10. This disaggregated approach is important because aggregate domestic extraction may conceal substantial differences in the environmental effects of individual material categories. Biomass extraction is closely associated with agriculture, forestry and land-use dynamics; metal ores and non-metallic minerals involve distinct mining, processing and infrastructure requirements; and fossil-fuel extraction is directly connected to carbon-intensive energy systems. Estimating separate models for each category therefore allows the analysis to identify whether the relationship between resource exploitation, productive structure and emissions is driven by particular components of Brazil's material profile rather than by extraction as a homogeneous aggregate.

The central expectation is that the direct coefficient of natural resource exploitation remains positive, while the interaction term is negative. This would indicate that, although resource extraction

increases emissions, a more industrially dense productive structure may reduce the magnitude of this effect. Thus, the expanded models test whether the environmental consequences of resource exploitation depend not only on the amount and type of resources extracted, but also on the broader productive structure in which extraction occurs.

Together, these two sets of models allow the paper to test three empirical questions: whether natural resource exploitation increases greenhouse gas emissions in Brazil; whether this effect differs according to the type of resource extracted; and whether the productive structure, measured by the manufacturing share in GDP, mitigates the long-run environmental impact of domestic extraction.

Other control variables include real GDP per capita and trade openness, both widely recognized as relevant determinants of environmental pressure. Real GDP per capita captures the scale effect associated with economic expansion, since higher levels of production and income tend to increase energy and material use and, consequently, emissions, although technological and structural changes may partially offset this effect at higher development levels (Grossman and Krueger, 1995). Trade openness is included because international integration can affect environmental performance through scale, composition and technique effects. While trade-induced production expansion and specialization in resource- or pollution-intensive activities may increase emissions, access to cleaner technologies and more efficient production methods may operate in the opposite direction. Its expected effect is therefore theoretically ambiguous (Antweiler et al., 2001; Copeland and Taylor, 2004).

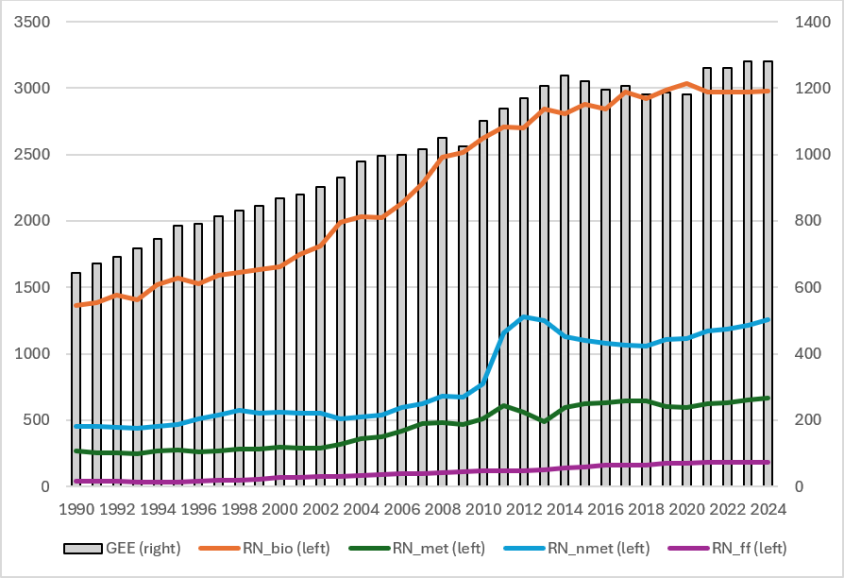
## 4. Results and Discussion

Figure 1 illustrates the performance of the main interest variables from 1990 to 2024. Greenhouse gas emissions averaged approximately 1,008.4 $MtCO_2e$ between 1990 and 2024, ranging from a minimum of 644.0 $MtCO_2e$ in 1990 to a maximum of 1,281.8 $MtCO_2e$ in 2024. Over the period, emissions increased by approximately 99.0%, corresponding to an average annual growth rate of 2.0%. Although the series displays a clear long-run upward trend, this expansion was not continuous: temporary declines occurred in 2009 and between 2015 and 2020, followed by a marked rebound in 2021 and more moderate growth thereafter. Overall, evidence indicates that greenhouse gas emissions nearly doubled over the period analyzed, despite short episodes of contraction associated with weaker economic activity.

Total domestic extraction averaged approximately 3.59 billion tonnes between 1990 and 2024, increasing from 2.12 billion tonnes at the beginning of the period to a historical maximum of 5.08 billion tonnes in 2024. This represents cumulative growth of approximately 139.9%, equivalent to an average annual rate of 2.6%. Biomass remained the largest component, although its share of total extraction declined from 64.2% to 58.6%. By contrast, non-metallic minerals increased their share from 21.4% to 24.7%, while metal ores rose from 12.6% to 13.1%. Fossil fuels displayed the fastest proportional

growth but continued to account for a relatively small share of total extraction. Taken together, these trends point to the persistent expansion of a resource-intensive material base, reinforcing the paper's broader argument about the growing importance of natural resource extraction in Brazil's productive structure.

Figure 1 - GGE and Natural Resource Domestic Extraction in Brazil (1990-2024)




Source: Authors' elaboration from WDI and Global Material Flows Database.

Tables 2 and 3 show the main econometric results. The models were estimated with a maximum of four lags. The significant lags for each variable are indicated in the penultimate rows of Tables 2 and 3. The models present satisfactory diagnostic properties. Bounds tests indicate long-run relationships among the variables in all specifications, with F-statistics above the upper critical bounds. According to the LM tests, the models show no evidence of serial autocorrelation. In addition, the CUSUM and CUSUMSQ tests indicate parameter stability[1]. Overall, these results suggest that the ARDL specifications are well adjusted and suitable for interpreting the long-run coefficients.

The validity of the short-run coefficients is also confirmed ($ECM_{t-1}$). It is worth noting that expanded models have a rapid adjustment rate for short-run imbalances, ranging from $ECM_{t-1} = 49.35\%$ (Model 9) to $ECM_{t-1} = 75.84\%$ (Model 10). On the other hand, restricted models take longer after shocks (approximately five years in media) to return to long-run equilibrium ($ECM_{t-1} = 16.11\%$ in Model 3 to $ECM_{t-1} = 23.21\%$ in Model 5).

In line with the expected signs, the restricted models result (Table 2) show that natural resource exploitation has a positive long-run effect on greenhouse gas emissions in Brazil. In the specification (1) using total domestic extraction, a 1% increase in total natural resource extraction is associated with

[1] The CUSUM and CUSUM tests are not presented due to space constraints but can be requested from the authors.

a 0.2278% increase in long-run emissions. When domestic extraction is disaggregated by material category, the strongest effect is found for biomass: a 1% increase in biomass extraction is associated with a 0.3169% increase in emissions. Metallic ores present a positive and statistically significant coefficient, although with lower magnitude (0.2133%). Non-metallic mineral extraction also presents a positive and statistically significant effect, with an estimated elasticity of approximately 0.1327%. By contrast, the coefficient for fossil fuels is not statistically significant. These results reinforce the heterogeneity of resource exploitation effects on environmental degradation and indicate that the aggregate relationship is mainly driven by biomass and mineral extraction.

Table 2. ARDL Long-Run Results Restricted Models – Dependent Variable: Greenhouse Gases Emissions (GGE)

| Models | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| NR_total | 0.2278** | | | | |
| | (0.0148) | | | | |
| NR_bio | | 0.3169** | | | |
| | | (0.0166) | | | |
| NR_met | | | 0.2133** | | |
| | | | (0.0259) | | |
| NR_n-nmet | | | | 0.1327** | |
| | | | | (0.0382) | |
| NR_ff | | | | | -0.1985 |
| | | | | | (0.1610) |
| GDPpc | 0.5032* | 0.4478* | 0.6665* | 0.6298* | 1.5061* |
| | (0.0000) | (0.0000) | (0.0000) | (0.0000) | (0.0001) |
| Open | 0.1829** | 0.1521*** | -0.0955 | 0.1422 | 0.3893* |
| | (0.0170) | (0.0790) | (0.6031) | (0.1165) | (0.0077) |
| LM Autocorrelation | 0.3171 | 0.4248 | 0.9094 | 0.6210 | 1.6396 |
| | (0.8635) | (0.7890) | (0.4820) | (0.6517) | (0.2016) |
| Bounds Tests F-Wald | 12.9954* | 6.2737* | 9.0058* | 12.3068* | 7.1701* |
| $ECM_{t-1}$ | -0.2280* | -0.2204* | -0.1611* | -0.1738* | -0.2321* |
| | (0.0000) | (0.0000) | (0.0000) | (0.0000) | (0.0000) |
| Lags | (1,4,0,0) | (2,4,0,0) | (1,4,4,3) | (1,2,0,0) | (1,2,3,0) |

Source: Authors' elaboration based on the results obtained using EViews 14.
(*) (**) (***) indicate statistical significance at the 1%, 5%, and 10% levels, respectively. P-values are reported in parentheses.

The positive coefficient of total domestic extraction is consistent with the broader socio-metabolic literature, which emphasizes that the mobilization of materials generates greenhouse gas emissions throughout extraction, transportation, processing and use. Global evidence shows that the expansion of material production has become an increasingly important source of emissions, reflecting the close connection between resource use and environmental pressures (Krausmann et al., 2018; Hertwich, 2021; UNEP, 2024). The estimated elasticity of 0.2278% therefore provides country-specific evidence that the expansion of Brazil's material scale has been accompanied by higher greenhouse gas emissions. Unlike much of the existing literature, which relies on natural resource rents, material footprints or

input-output estimates, the present analysis directly relates territorial emissions to the physical extraction of resources.

The disaggregated results show that the positive relationship between domestic extraction and greenhouse gas emissions is driven by biomass, metal ores and non-metallic minerals. Biomass presents the largest estimated elasticity: a 1% increase in biomass extraction is associated with a 0.3169% increase in emissions in the long run. Since the dependent variable excludes emissions from land-use change and forestry, this result should not be interpreted as direct evidence of a deforestation effect. Rather, it is consistent with the emissions associated with Brazil's agriculture- and livestock-based material profile, including methane emissions from livestock, nitrous oxide emissions from soils and fertilizer use, as well as energy use and processing activities connected to agricultural and forestry production.

Metal-ore extraction also presents a positive and statistically significant coefficient, with an estimated elasticity of 0.2133. This result suggests that the expansion of metallic mining is associated with higher emissions through the energy-intensive operations involved in extraction, beneficiation, transport and initial processing. Non-metallic mineral extraction likewise increases emissions, although with a smaller estimated elasticity of 0.1327, a result consistent with the energy and process emissions associated with construction-material chains, particularly cement and concrete production. By contrast, the coefficient for fossil-fuel extraction remains statistically insignificant. This does not imply that fossil fuels are environmentally neutral, but rather that changes in their domestic extraction volumes do not display an independently identifiable long-run relationship with aggregate Brazilian greenhouse gas emissions within the estimated specification.

The control variables also yield relevant results. Real GDP per capita is positive and statistically significant across all specifications, with estimated elasticities ranging from 0.4478 to 1.5061. This indicates that economic expansion in Brazil has been consistently associated with higher greenhouse gas emissions. Trade openness, by contrast, presents less robust results. Its coefficient is positive and statistically significant in Models 1, 2 and 5, with elasticities ranging from 0.1521 to 0.3893, but it is not statistically significant in the metal-ore and non-metallic mineral specifications. These findings suggest that the scale effect associated with economic growth is more systematic than the effect of trade integration, whose environmental consequences appear to depend on the material category considered and on the composition of Brazil's external specialization. The comparatively large coefficients obtained in the fossil-fuel specification should nevertheless be interpreted cautiously, since fossil-fuel extraction itself does not present a statistically significant long-run coefficient.

These results are broadly consistent with the literature on the scale, composition and technique effects of economic growth and trade. The positive coefficient of real GDP per capita suggests that the scale effect of economic expansion outweighed possible gains arising from technological change, greater efficiency or shifts towards less emissions-intensive activities, a result compatible with the

environmental-growth framework developed by Grossman and Krueger (1995). The positive effect of trade openness, in turn, indicates that Brazil's external integration was more closely associated with the expansion of production and with a composition effect favoring resource- and emissions-intensive activities than with a technique effect based on the diffusion of cleaner technologies. This interpretation is consistent with Antweiler et al. (2001) and Copeland and Taylor (2004), who show that the environmental consequences of trade depend on the relative strength of scale, composition and technique effects.

The expanded models (Table 3) constitute the research's main contribution and provide consistent evidence of a moderating effect of the production structure across all material categories. When the interaction between natural resource exploitation and manufacturing value added as a share of GDP is included, the coefficients of domestic extraction are positive and statistically significant in all five specifications. At the same time, the interaction terms between domestic extraction and manufacturing share are negative and significant at the 1% level. This pattern indicates that, although greater extraction is associated with higher greenhouse gas emissions, the magnitude of this effect decreases as manufacturing participation rises. The moderating effect is observed for total domestic extraction, biomass, metal ores, non-metallic minerals and fossil fuels, suggesting that the conditioning role of productive structure is not restricted to a particular material category. These findings therefore indicate that productive structure matters: a higher manufacturing share in GDP appears to attenuate, although not necessarily eliminate, the environmental pressure associated with resource exploitation. The marginal effect of extraction nevertheless remains dependent on the combined magnitude of the direct and interaction coefficients and on the observed level of manufacturing participation.

Table 3. ARDL Long-Run Results Expanded Models – Dependent Variable: Greenhouse Gases Emissions (GGE)

| Models | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|
| NR_total | 0.1955*<br>(0.0000) | | | | |
| NR_bio | | 0.2816*<br>(0.0000) | | | |
| NR_met | | | 0.1637*<br>(0.0000) | | |
| NR_nmet | | | | 0.1256*<br>(0.0000) | |
| NR_ff | | | | | 0.1784*<br>(0.0000) |
| VAmanuf * NR_total | -0.0244*<br>(0.0000) | | | | |
| VAmanuf * NR_bio | | -0.0235*<br>(0.0000) | | | |
| VAmanuf * NR_met | | | -0.0369*<br>(0.0000) | | |
| VAmanuf * NR_nmet | | | | -0.0334* | |

| | | | | | |
|---|---|---|---|---|---|
| | | | | (0.0000) | |
| VAmanuf* NR_ff | | | | | -0.0678* (0.0000) |
| GDPpc | 0.5891* (0.0000) | 0.5047* (0.0000) | 0.6579* (0.0000) | 0.6699* (0.0000) | 0.7048* (0.0000) |
| Open | 0.1751* (0.0000) | 0.2124* (0.0001) | 0.1929* (0.0002) | 0.2073* (0.0000) | 0.1889* (0.0001) |
| LM Autocorrelation | 0.8558 (0.5088) | 2.8360 (0.0649) | 1.0469 (0.4207) | 1.2812 (0.3122) | 2.8988 (0.0644) |
| Bounds Tests F-Wald | 9.0935* | 5.7473* | 7.1871* | 7.0138* | 9.8503* |
| $ECM_{t-1}$ | -0.5985* (0.0000) | -0.6322* (0.0000) | -0.6668* (0.0000) | -0.4935* (0.0000) | -0.7584* (0.0000) |
| Lags | (2,2,0,2,2) | (3,3,1,4,2) | (2,2,4,2,4) | (2,2,0,2,2) | (2,2,3,3,4) |

Source: Authors' elaboration based on the results obtained using EViews 14.
(*) (**) (***) indicate statistical significance at the 1%, 5%, and 10% levels, respectively. P-values are reported in parentheses.

This result is consistent with the emerging literature showing that the environmental effects of economic activities and natural resource dependence are conditional on the structural, technological and energy characteristics of production. Aquilas et al. (2024), for example, find that the environmental effect of manufacturing depends on the energy base supporting industrial activity, while Adebayo et al. (2022) and Zhao et al. (2024) show that technological innovation can weaken the adverse environmental effects associated with natural resource rents. Ehigiamusoe et al. (2024), however, find that this moderating effect is not automatic, since technological innovation did not offset the emissions associated with natural resource rents in Malaysia. The present study adds to this literature by examining a different conditioning mechanism: whether manufacturing participation attenuates the environmental effects of physical domestic extraction. This represents a departure from previous studies, which have generally focused on natural resource rents and technological or energy-related moderators.

These findings should not be interpreted as evidence that industrialization automatically solves environmental degradation. Rather, it indicates that the environmental effect of natural resource exploitation depends on the type of productive structure in which extraction takes place. In a more reprimarized economy, resource extraction tends to be more directly associated with environmental degradation. By contrast, an economy with greater industrial density may be better able to process, transform and organize resource use in ways that reduce the emissions intensity associated with extraction. This interpretation is consistent with the ecological neo-structuralist perspective, which emphasizes that the developmental and environmental consequences of natural resource use depend on the productive capabilities and structural configuration through which resources are mobilized (Sánchez et al., 2024).

The disaggregated specifications reinforce this interpretation by showing that the attenuating role of manufacturing is present across all material categories. Biomass extraction remains positively associated with greenhouse gas emissions, while its interaction with manufacturing participation is

negative and statistically significant. A similar pattern emerges for metal ores, non-metallic minerals and fossil fuels: the extraction coefficients are positive, whereas the interaction terms are negative. Thus, although greater extraction is associated with higher emissions, this relationship becomes weaker as the manufacturing share of GDP increases. The negative interaction is particularly pronounced in the fossil-fuel and metal ore specifications, although comparisons of coefficient magnitudes across material categories should be made cautiously because each series represents a distinct component of domestic extraction.

These results are substantively relevant because different materials enter the productive system through very different technological and sectoral channels. Biomass is closely connected to agriculture, livestock, forestry and land-use dynamics, whereas metal ores and non-metallic minerals are more directly linked to mining, processing, construction and infrastructure chains. Fossil fuels, in turn, are associated with energy-intensive production and transport systems. The persistence of negative interaction coefficients across these categories suggests that the moderating role of productive structure is not confined to a single material flow. Rather, greater industrial density may be associated with stronger processing capabilities, higher value added and more technologically organized forms of resource use, thereby attenuating the connection between territorial extraction and aggregate emissions.

The control variables also present robust results. GDP per capita has a positive and statistically significant long-run association with greenhouse gas emissions across all expanded specifications, with estimated elasticities ranging from 0.5047 to 0.7048. This indicates that economic growth in Brazil has historically been accompanied by higher environmental pressure. Trade openness is likewise positive and statistically significant in all models, with coefficients ranging from 0.1751 to 0.2124, suggesting that Brazil's external integration has not contributed to reducing emissions and is consistent with a trade pattern associated with resource- and emissions-intensive activities. Taken together, these results indicate that greenhouse gas emissions in Brazil are shaped not only by the scale of economic activity, but also by the country's productive and trade structure.

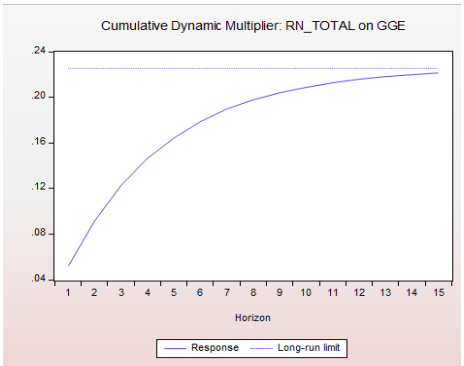
In addition, the dynamic multipliers show how a change in an explanatory variable affects the dependent variable over time, rather than only in the period in which the change occurs. They describe the adjustment trajectory until the long-run effect is fully realized. In this regard, Figures 2 and 3 illustrate the convergence paths of greenhouse gas emissions following shocks to the natural resource exploitation variables over a 15-year horizon. We report the results for the extraction categories that presented statistically significant coefficients in the restricted models: total domestic extraction (NR_total), biomass (NR_bio), metal ores (NR_met), and non-metallic mineral (NR_nmet). Figure 2 presents the multipliers from the restricted models, while Figure 3 displays the separate trajectories associated with the extraction variables and their interactions with the manufacturing share of GDP.

Figure 2 shows that shocks to total domestic extraction, biomass extraction, metallic and non-metallic mineral extraction generate persistent positive effects on greenhouse gas emissions. In

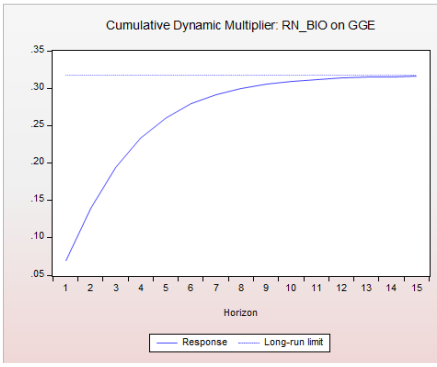
restricted models 1 to 4, the cumulative responses increase and converge towards positive long-run levels, although the magnitude and speed of adjustment differ across material categories. This visual pattern reinforces the baseline results reported in Table 2, according to which the expansion of these forms of domestic extraction increases environmental pressure in Brazil.

Figure 2 - Cumulative Dynamic Multipliers for Domestic Extraction (Restricted Models)

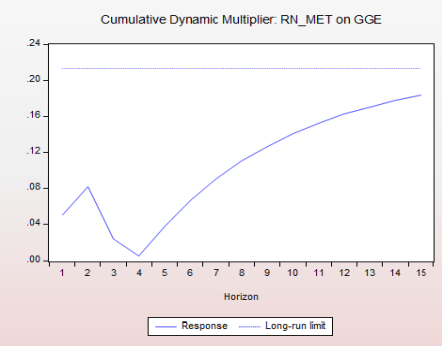
(a) Model 1



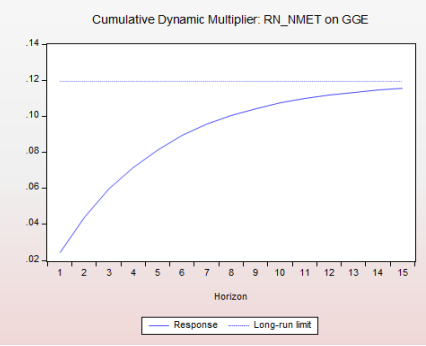

(b) Model 2




(c) Model 3




(d) Model 4



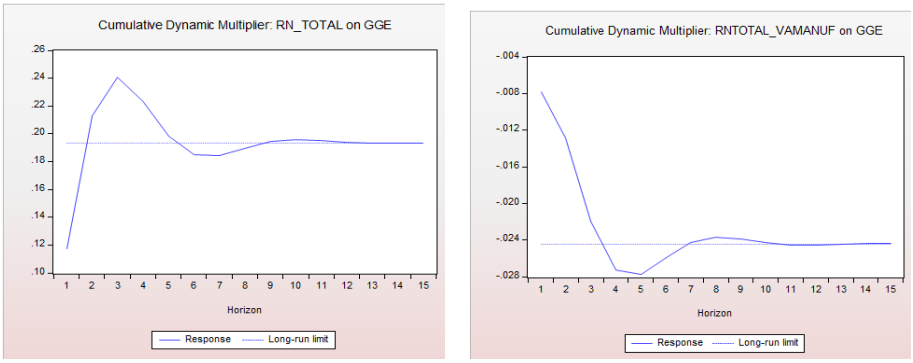

Source: Outputs Eviews 14.

Figure 3 provides a visual representation of the moderating role of productive structure. For each material category, the multiplier associated with domestic extraction remains positive, whereas the multiplier associated with its interaction with the manufacturing share is negative. The opposing directions of these trajectories make the moderating mechanism particularly clear: a higher manufacturing share counteracts part of the positive emissions effect associated with resource extraction. The interaction multipliers decline below zero and subsequently converge towards negative long-run levels, indicating that the attenuating effect persists over time rather than being limited to the initial periods following the shock. Thus, Figure 3 visually reinforces the econometric result that manufacturing participation attenuates, although it does not necessarily eliminate the environmental pressure associated with domestic extraction.

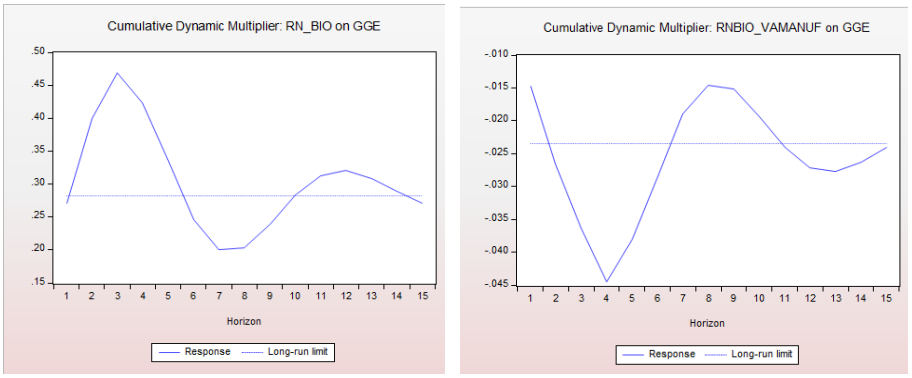
Overall, the evidence supports the three hypotheses of the study. First, natural resource exploitation increases greenhouse gas emissions in the long run. Second, this effect differs according to the type of resource extracted, with biomass and non-metallic minerals showing particularly relevant results. Third, a more industrially dense productive structure appears to attenuate, although not eliminate, the environmental impact of resource exploitation. These findings suggest that the Brazilian environmental problem cannot be reduced to the amount of resources extracted; it also depends on how the economy is structurally organized around this extraction.

Figure 3 - Cumulative Dynamic Multipliers for Domestic Extraction and Its Interaction with Manufacturing Share (Expanded Models)

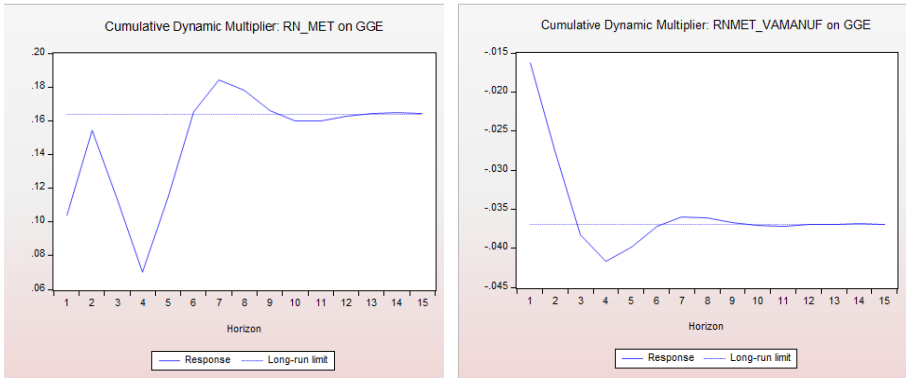
(a) Model 6 (RN_total)



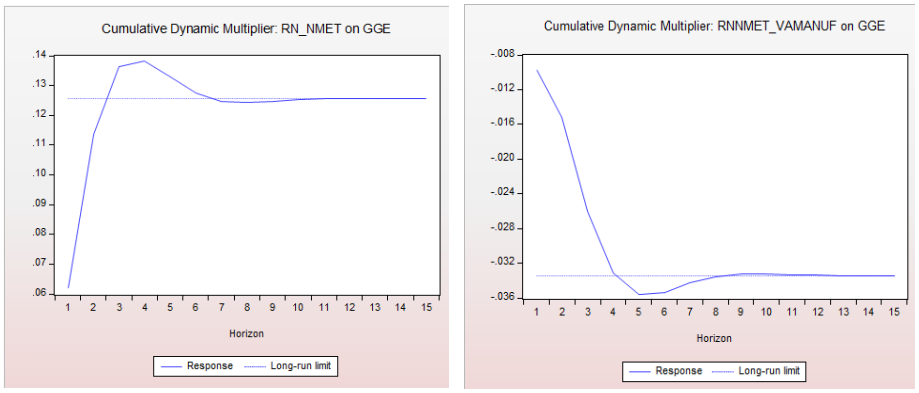

(b) Model 7 (Biomass)




(c) Model 8 (Metal ores)




(d) Model 9 (Non-metallic minerals)




Source: Outputs Eviews 14.

Notes: left-hand panels: Domestic extraction shock; Right-hand panels: Interaction-term shock

These results extend the existing literature on environmental moderation effects. Previous studies have mainly examined whether technological innovation, renewable energy or institutional characteristics alter the environmental consequences of natural resource rents. The present analysis identifies a related but distinct structural mechanism: manufacturing participation appears to attenuate the relationship between physical domestic extraction and greenhouse gas emissions, and this pattern is observed not only for aggregate extraction but also across different material categories. The findings therefore suggest that the environmental implications of resource exploitation depend on both the scale and composition of extraction and on the productive structure into which these material flows are incorporated.

## 5. Policy implications

The policy relevance of these findings becomes particularly evident in the context of the global low-carbon transition. The rapid deployment of electric vehicles, battery storage, renewable energy systems and electricity networks is expected to generate a substantial increase in demand for critical minerals and other material resources. Under the International Energy Agency's net-zero scenario,

mineral demand from clean energy technologies may almost triple by 2030 and quadruple by 2040, with particularly strong growth in lithium, graphite, nickel, copper and other battery-related materials (IEA, 2024). Given its extensive mineral reserves, biomass resources and renewable-energy potential, Latin America is likely to become an increasingly important supplier of the material inputs required by global decarbonization.

This renewed demand, however, may reproduce a new cycle of extractivism under a green rationale. The climate imperative can legitimize the expansion of mining, large-scale renewable-energy projects and other resource-intensive activities without necessarily transforming the region's subordinate position in global value chains. The literature has described this process as green extractivism or decarbonization by dispossession, emphasizing how the material costs of low-carbon transitions may be displaced towards territories in the Global South (Andreucci et al., 2023). From this perspective, mineral- and energy-producing regions risk becoming "green sacrifice zones": territories whose ecological integrity, water resources and local livelihoods are subordinated to the decarbonization objectives of distant consumers and industries (Canelas and Carvalho, 2023; Tornel, 2024).

The results of this study suggest that such an outcome is not structurally predetermined. The positive relationship between domestic extraction and greenhouse gas emissions confirms that a new expansion of material extraction may intensify environmental pressures. At the same time, the negative interaction coefficients indicate that these pressures are weaker in a more industrially dense productive structure. The central policy implication is therefore not simply that Brazil and Latin America should extract fewer or more transition minerals, but that the environmental and developmental outcomes of this new material cycle will depend on how extraction is embedded in the productive system.

A strategy based primarily on the export of unprocessed or minimally processed materials would tend to reproduce the traditional separation between the territories that bear the environmental costs of extraction and the economies that concentrate technological capabilities, manufacturing and value creation. By contrast, the development of domestic processing, manufacturing, engineering and innovation capabilities may increase the value generated per unit of material extracted and create better conditions for organizing resource use through more efficient technologies, stronger regulation and greater integration between extraction and downstream activities.

This requires a green industrial policy connecting resource management to the development of downstream activities such as mineral processing, batteries, renewable-energy equipment, recycling and material-efficient technologies. However, productive upgrading must be accompanied by stringent environmental regulation, territorial planning, traceability, participation by affected communities and policies aimed at reducing absolute material pressures. Industrial densification can attenuate the environmental effects of extraction, but it cannot substitute for ecological limits or guarantee sustainability on its own.

## 6. Conclusion

This paper examined the long-run relationship between natural resource exploitation and greenhouse gas emissions in Brazil using data from 1990 to 2024, considering both aggregate domestic extraction and its main material components. It also investigated whether the environmental effects of extraction are conditioned by the country's productive structure, measured by the manufacturing share in GDP.

The restricted models indicate that the expansion of total domestic extraction is associated with higher greenhouse gas emissions. The disaggregated results show that this relationship is heterogeneous, with biomass, metal ores and non-metallic minerals presenting significant positive coefficients, while fossil fuels do not display statistically significant effects in the baseline specifications. GDP per capita and trade openness are also positively associated with emissions, suggesting that both economic expansion and Brazil's pattern of external integration have reinforced environmental pressures.

The expanded models provide the paper's main contribution. The interaction terms between domestic extraction and manufacturing participation are negative and statistically significant across all material categories. These findings suggest that a more industrially dense productive structure attenuates the positive relationship between resource extraction and emissions. This does not imply that industrialization is inherently sustainable or that it eliminates the environmental costs of extraction. Rather, it indicates that the effects of resource exploitation depend on how material flows are processed, transformed and incorporated into the broader productive system.

These results support the three hypotheses proposed in the Introduction. The first hypothesis is confirmed by the positive and statistically significant long-run coefficient of total domestic extraction, indicating that natural resource exploitation increases greenhouse gas emissions. The second hypothesis is also supported, since the estimated effects differ across material categories, with particularly relevant results for biomass. Finally, the negative and statistically significant interaction terms support the third hypothesis, suggesting that a more industrially dense productive structure attenuates, although does not eliminate, the environmental pressure associated with resource extraction.

The significance of these findings is particularly evident in the context of the global low-carbon transition, which is likely to generate renewed demand for minerals, biomass and energy resources from Brazil and Latin America. A strategy centered on exporting unprocessed materials may reproduce commodity dependence and green extractivism. By contrast, policies that combine environmental governance with the development of processing, manufacturing, engineering, recycling and technological capabilities may increase the value generated per unit of material extracted and improve the conditions under which resources are mobilized. Productive upgrading, however, must remain subject to ecological limits, territorial planning and effective social and environmental regulation.

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