

Building Weaknesses and Revealing Structural Constraints: Systemic Characterization of Brazilian Regional Resilience¹

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Abstract: We analyze regional resilience to understand how exogenous shocks affect different areas unevenly. Motivated by Brazil's structural disparities and recurring crises, we develop an ex-ante approach using interregional input-output matrices from 2011 and 2019 to simulate shock scenarios. This method identifies vulnerabilities and tracks systemic effects across sectors and regions, deepening the analysis of regional interdependence. Using network metrics and machine learning, we uncover spatial patterns of resilience, revealing strong agglomeration effects and structural heterogeneity among regions with similar resilience degrees. Our results show that resilience remains highest in the Southeast and South, especially in São Paulo, while the North and Northeast continue to show lower levels. This pattern reflects the persistent concentration of productive activity in certain areas. Resilience remains largely static over time, as structural barriers prevent significant changes in this landscape. The findings highlight the importance of public policies that foster productive integration while addressing regional specificities.

Keywords: Regional Resilience ; Input-Output; Network Analysis; Machine Learning

Resumo: A análise da resiliência regional permite compreender como choques exógenos afetam de maneira desigual diferentes áreas. Motivado pelas disparidades estruturais e crises recorrentes no Brasil, desenvolve-se uma abordagem ex ante que utiliza matrizes inter-regionais de insumo-produto de 2011 e 2019 para simular cenários de choque. Esse método identifica vulnerabilidades e acompanha os efeitos sistêmicos entre setores e regiões, aprofundando a análise das interdependências regionais. Por meio de métricas de redes e técnicas de aprendizado de máquina, revelam-se padrões espaciais de resiliência, evidenciando fortes efeitos de aglomeração e heterogeneidade estrutural mesmo entre regiões com graus similares de resiliência. Os resultados indicam que a resiliência regional permanece mais elevada no Sudeste e Sul, especialmente em São Paulo, enquanto Norte e Nordeste continuam apresentando níveis inferiores. Esse padrão reflete a concentração persistente da atividade produtiva em determinadas áreas. Observa-se que a resiliência se mantém essencialmente estática ao longo do tempo, uma vez que barreiras estruturais impedem mudanças significativas nesse panorama. Por fim, ressalta-se a importância de políticas públicas que promovam a integração produtiva, considerando as especificidades regionais.

Palavras-Chave: Resiliência Regional; Insumo-Produto; Redes; Aprendizado de Máquina

JEL Classification: C67, O40, C22, R10, R15

Área temática: Crescimento econômico e desenvolvimento regional

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1 Introduction

Brazil's regions differ widely in their economic, social, and productive structures. These differences help explain why some areas manage to cope better with political, economic, environmental, or health crises, while others remain more vulnerable (Hassink 2010). Understanding how these structural contrasts shape regional responses to adverse events is essential for improving public policy. In this context, regional resilience refers to a region's capacity to absorb, adapt to, and recover from such shocks. Therefore, policymakers must go beyond correcting historical inequalities and also find ways to strengthen each region's ability to respond effectively to crises (Lagravinese 2015).

In Brazil, this challenge is especially relevant given the country's long-standing regional disparities. The industrialization and urbanization process followed a highly concentrated path, reinforcing spatial imbalances and establishing a persistent pattern of uneven development (Haddad 1988; Cano 2007). These disparities are still visible today. In 2021, for example, São Paulo accounted for 30.8 percent of the national GDP, while states like Acre and Amapá each contributed less than 0.3 percent. Although successive policies have aimed to promote decentralization, the economic base remains highly concentrated. As Ruiz and Domingues (2008) point out, regions that have historically been less integrated into national dynamics often struggle to mobilize the resources needed to diversify and grow sustainably.

Recent crises have highlighted how these structural gaps affect regional outcomes. Brazil has experienced several major shocks in the past two decades, each with distinct characteristics including the 2008 global financial crisis (Freitas 2009; Barbosa 2010), the domestic recession of 2014–2015 (Domingues et al. 2014; Monteiro and Feijó 2023), and the COVID-19 pandemic, which disrupted both supply and demand, causing a sharp drop in output, investment, and employment (Paula 2021). These events underscore the need for a deeper understanding of regional resilience.

We address this need by examining how different regions respond to hypothetical economic shocks. The goal is to identify which areas are more resilient and which remain structurally exposed. We focus on how productive interdependencies shape these responses, based on the assumption that regions more strongly integrated into the national economy, particularly those that contribute to the value added of other regions, tend to display greater resilience. To explore this, we develop a novel methodological framework that combines several analytical tools.

First, we use interregional input-output matrices for 2011 and 2019 to simulate shocks through the hypothetical extraction method. This technique models the effects of removing a region or sector from the productive system and quantifies the resulting impact on value added in the remaining areas. While ex post approaches rely on observed data (Dueñas and Campi 2024; Sutton et al. 2025), our ex ante strategy allows for the identification of structural vulnerabilities before shocks occur. The simulation results are then used to construct an interregional network that differs from traditional representations based on direct trade flows (Santana Ribeiro et al. 2023; Han and Goetz 2019). In our network, each link captures the intensity of economic influence that one region exerts on the value added of another, under scenarios that simulate adverse crisis conditions. From this structure, we compute two indicators: Weighted Degree, which reflects the overall intensity of these linkages, and Eigenvector Centrality, which captures a region's broader systemic importance by accounting for its connections to other influential regions. We also include the Leontief Linkage Index, a classical input-output measure that reflects the strength of regional productive integration.

Next, we apply machine learning techniques to interpret resilience patterns. Specifically, we use the K-means algorithm to group regions with similar responses to simulated shocks. We then apply logistic regression with permutation importance to assess whether and how strongly the indicators influence cluster membership (Altmann et al. 2010; Silveira et al. 2023). This method allows us to characterize resilience in a novel, data-driven, and interpretable way (Molnar 2020). Here, interpretability means identifying which structural features such as Eigenvector Centrality, Weighted Degree, and the Leontief Linkage Index most influence regional classification. These metrics play a key role in explaining resilience patterns and guiding targeted policy actions.

This empirical strategy directly reflects our conceptualization of regional resilience. Although partially aligned with the ecological perspective, which defines resilience as the ability to absorb shocks without major structural changes (Martin 2012; Webber et al. 2018), our approach focuses specifically on resistance rather than recovery. In Brazil, recent studies examine resilience through various lenses (Tupy et al. 2021; Cezaro Eberhardt and Fochezatto 2024), showing that structural diversity leads to unequal outcomes in times of crisis. It is worth noting that our approach differs not only from these but also from other existing approaches. We adopt an ex-ante perspective and simulate scenarios in which the economy faces shocks. This leads to a second fundamental contribution: we conduct a systemic analysis of regional and sectoral interdependencies based on production rather than employment. Indicators built on labor data, including the traditional resistance and recovery indices proposed by (Martin et al. 2016), fail to capture these structural linkages. Empirical econometric analyses, which rely on these indicators, also overlook the role of interdependencies.

In contrast, our approach models how interdependencies influence the timing and intensity of shock transmission, underscoring their role in regional resilience. It also allows the identification of cascading effects, where a slowdown in one sector or region affects demand and supply elsewhere, potentially altering aggregate economic dynamics at broader scales. This framing also contributes to ongoing debates about the role of specialization and diversification. While specialization can drive economic growth in the short run, it tends to increase vulnerability to external shocks (Essletzbichler and Rigby 2007; Fusillo et al. 2022). Diversified regions, on the other hand, are often better positioned to adapt and recover (Davies and Tonts 2010; Martin and Sunley 2015).

Our results show that resilience in Brazil is closely tied to structural factors. Regions with more diversified economies and stronger interconnections tend to withstand shocks more effectively. In contrast, regions with weaker ties to the national economy face greater constraints. The concentration of productive activity in a few states also increases systemic risk, since localized disruptions can trigger widespread effects. Comparing 2011 and 2019, we find only gradual improvements in resilience, suggesting that structural changes take time and are driven mainly by internal dynamics.

The remainder of the paper is structured as follows. Section 2 presents the dataset. Section 3 details the empirical strategy. Section 4 discusses the main results. Section 5 concludes.

2 Database

The methodology of this study relies on the Brazilian interregional input-output matrices for the years 2011 and 2019, developed by the Regional and Urban Economics Nucleus of the

University of São Paulo (NEREUS) according to the Interregional Input-Output Adjustment System (IIOAS) ¹ method, as described by (Haddad et al. 2017). The matrices cover the 27 federative Units and present a sectoral disaggregation into 68 economic activities. This high level of disaggregation allows for precise identification of the sectors responsible for specific effects, thereby avoiding analytical distortions. However, it hinders the presentation of results, especially given the need to justify specific sectoral choices. Therefore, although the analysis is conducted using the 68 sectors, the results are presented in an aggregated form.

Accordingly, the results are presented based on the sections of the National Classification of Economic Activities (CNAE 2.0), totaling 20 sectors. To mitigate precision losses, the manufacturing industry is further disaggregated according to technological intensity, following the classification of the Organisation for Economic Co-operation and Development (OECD), increasing to 23 the number of sectors considered in the final presentation of the results.

3 Empirical Strategy

The methodology integrates complementary techniques to measure and characterize the impacts of shocks on regional economies. Initially, an interregional input-output matrix is used to simulate counterfactual scenarios by removing regions or sectors from the productive structure and evaluating the effects on the value added of the other federative Units. This ex-ante analysis allows for the estimation of impacts in advance, distinguishing itself from traditional measurement approaches based on the observation of shocks that have already occurred (ex-post). Subsequently, network analysis is applied to identify patterns of productive interdependence between regions and sectors. Finally, a two-step machine learning approach is adopted: the *K*-means algorithm groups the federative Units based on indicators of interdependence and simulated impacts, and logistic regression with permutation importance validates the groupings, highlighting the most relevant variables for characterizing regional resilience.

3.1 Interregional input-output model and hypothetical extraction

According to Miller and Blair (2009), the interregional input-output model can be represented by the following relationship between total output x , the technical coefficients matrix $A \in \mathbb{R}^{n \times n}$, where $n = r \times s$ with r regions and s sectors, and the final demand f :

$$x = Ax + f \tag{1}$$

Rearranging, we have:

$$x = (I - A)^{-1} f = Lf \tag{2}$$

where I is the identity matrix and $(I - A)^{-1}$ is the Leontief inverse matrix, which captures the direct and indirect effects on production.

To measure the systemic effects of regional shocks, the hypothetical extraction method is adopted, as proposed by (Dietzenbacher et al. 1993). The central idea consists of simulating the removal of a specific region or sector from the economy and observing how this exclusion alters production levels in the remaining regions, enabling the estimation of interdependence and its influence on regional resilience.

1. Some applications of the IIOAS method include studies for Colombia (Haddad et al. 2016), Greece (Haddad et al. 2018), and Mexico (Haddad et al. 2020a).

For convenience, it is assumed that region 1 is removed from a system composed of n regions and s sectors. Based on the partitioning of the interregional input-output matrix, total output² can be expressed as:

$$x = \begin{bmatrix} x^1 \\ x^R \end{bmatrix} = \begin{bmatrix} L^{11} & L^{1R} \\ L^{R1} & L^{RR} \end{bmatrix} \begin{bmatrix} f^1 \\ f^R \end{bmatrix} \quad (3)$$

With the hypothetical extraction of region 1, Equation 2 takes the following form:

$$x^{-R} = (I - A^{RR})^{-1} f^R \quad (4)$$

The difference $x^R - x^{-R}$ measures the impact of removing region 1 on the rest of the economy and can be formally expressed as:

$$x^R - x^{-R} = (I - A^{RR})^{-1} A^{R1} L^{11} [f^1 + A^{1R} (I - A^{RR})^{-1} f^R] \quad (5)$$

In turn, the dependence of region 1 on the others is evaluated through inter-regional feedbacks, following Dietzenbacher et al. (1993), where the superscripts 1 and R are exchanged in the equations.

$$x^1 - x^{-1} = (I - A^{11})^{-1} A^{1R} L^{RR} [f^R + A^{R1} (I - A^{11})^{-1} f^1] \quad (6)$$

This vector quantifies the degree of integration of region 1 in the interregional production chains, allowing the assessment of its sensitivity to the loss of links with the other regions.

Additionally, the approach is extended to consider dependence on the external sector, based on the formulation by (Los et al. 2016), who propose the decomposition of exports via hypothetical extraction to measure the value added incorporated in them. However, as noted by (Haddad et al. 2020b), the absence of detailed data on interregional flows with the external sector limits its direct application in the Brazilian interregional context. To overcome this limitation, it is suggested to treat the external sector as an exogenous region, represented by a vector in the final demand.

The value added in region 1 (VA_1) can be expressed as:

$$VA_1 = v_1 (I - A)^{-1} f_1 \quad (7)$$

Based on hypothetical configurations that exclude, for example, transfers to other regions or to the external sector, it is possible to isolate the components of value added dependent on these interactions. The differences between scenarios with and without these relationships, represented by $VA_{(1,n)}^*$ and VA_1 , respectively, allow the measurement of the dependence of region 1 on the other regions ($DVA_{(1,n)}^*$) and on international trade ($DVA_{(1,Exp)}^*$):

$$DVA_{(1,n)}^* = VA_1 - VA_{(1,n)}^* \quad \text{e} \quad DVA_{(1,Exp)}^* = VA_1 - VA_{(1,Exp)}^* \quad (8)$$

For a more disaggregated assessment, the approach is extended to consider the effects of extraction by sector within each region. In this case, the vector of sector- and region-specific value added, v_1^s , is defined, allowing the isolation of the contribution of a regional sector to value added generation.

2. Although the formal structure is centered on output, it is possible to apply the same procedures using the value-added vector.

The total value added of region 1, considering the sectoral structure, is given by:

$$VAS_1 = v_1^s (I - A)^{-1} f_1 \quad (9)$$

The hypothetical extraction of sector 1's participation in region 1's interactions with the other regions can be expressed by:

$$VAS_{(1,n)}^* = v_1^s \left(I - A_{(1,n)}^* \right)^{-1} h_{(1,n)}^* i \quad (10)$$

Similarly, the exclusion of this sector's participation in external trade is represented by:

$$VAS_{(1,Exp)}^* = v_1^s \left(I - A_{(1,n)}^* \right)^{-1} h_{(1,Exp)}^* i \quad (11)$$

where $h_{(1,Exp)}^*$ represents the hypothetical final demand matrix in which sector 1 of region 1 has no participation in the external sector.

The differences between the observed and hypothetical scenarios allow for measuring the effects of sectoral removal on value added:

$$DVAS_{(1,n)}^* = VAS_1 - VAS_{(1,n)}^* \quad (12)$$

Similarly, it is possible to analyze the impact on the value added of region 1 by hypothetically extracting the participation of sector 1 of this region in international trade.

$$DVAS_{(1,Exp)}^* = VAS_1 - VAS_{(1,Exp)}^* \quad (13)$$

Based on the proposed extractions, scenarios³ are constructed that simulate regional resistance to hypothetical shocks through two types of extraction: (i) removal of each of the 27 federative units and the external region, capturing regional systemic impacts; and (ii) exclusion of regional participation in a specific sector, including the external region, assessing sectoral and interregional effects.

3.2 Network Analysis

Network analysis is employed as a tool to synthesize the results of the hypothetical extractions, allowing for a visual and direct interpretation of economic interactions. This approach is based on classical studies (Albert and Barabási 2002; Newman 2006) and integrates with input-output analysis in recent works (Chen and Chen 2015; Wang and Chen 2016; Zhang et al. 2021). Unlike studies that use direct flows from the input-output matrix (Han and Goetz 2019; Santana Ribeiro et al. 2023; Giannakis et al. 2024), the network constructed in this study is unidirectional, with vertices (nodes) representing regions or sectors and edges (lines) representing monetary flows derived from the extractions.

This unidirectional configuration excludes path-based metrics such as betweenness and closeness centrality, and renders in-degree and out-degree measures inadequate. Instead, measures such as eigenvector centrality and weighted degree are used, which evaluate the relative importance of nodes based on their connections and weights. Eigenvector centrality is effective

3. The analysis includes approximately 700 simulations of regional extraction and around 33,000 simulations capturing sectoral impacts of regional extraction.

in measuring the influence of a vertex based on its connections with other structurally relevant vertices in the network. The measure is calculated from the eigenvalues λ and eigenvectors \mathbf{x} of the adjacency matrix, as described by (Koschützki et al. 2005), and can be expressed as:

$$CE(i) = \frac{1}{\lambda} \sum_{j \in V} a_{ij} x_j \quad (14)$$

where a_{ij} is the element of the adjacency matrix A , indicating the weight of the connection between vertex i and vertex j ; and x_j represents the centrality value associated with vertex j .

In addition, the weighted degree measure quantifies the influence of a vertex in the network by considering both the number of connections and the weights of those connections. This reflects the intensity of interdependence between regions or sectors. The calculation of this measure, as presented by (Newman 2006; Barthélemy 2011), is given by the following equation:

$$s_i = s(i) = \sum_{j \in V(G)} a_{ij} w_{ij} \quad (15)$$

where $w_{ij} = w(e_{ij})$; e_{ij} is the weight assigned to the edge connecting vertices i and j ; a_{ij} is the element of the adjacency matrix A ; and G represents the graph or the network under analysis.

The main difference between these metrics is that eigenvector centrality captures the global influence of a node in the network by considering its connections with relevant vertices, whereas weighted degree reflects only the direct connectivity of a node.

3.3 Machine Learning Techniques

To identify groups of federative units based on regional resilience, the K -means algorithm is used, a non-supervised learning technique that employs three metrics: eigenvector centrality, weighted degree, and the Leontief linkage index. The K -means algorithm, as described by (Kodinariya, Makwana, et al. 2013), begins by defining centroids and then assigns data points to clusters based on proximity, recalculating the centroids until the process stabilizes.⁴ The segmentation obtained by K -means is validated in the supervised phase of machine learning using logistic regression. The three metrics are used as predictor variables, while the clusters generated by K -means are treated as the response variable.⁵ Once the model is trained, the Permutation Importance (PI) technique is used to assess the contribution of each variable to the model's performance. As described by (Altmann et al. 2010; Silveira et al. 2023), the process follows three steps: (i) randomly permuting one variable, (ii) generating new predictions with the permuted values and evaluating their quality, and (iii) ranking the variables based on the reduction in prediction quality. In summary, the method identifies the variables with the greatest impact on the model's ability to predict cluster classifications (Molnar 2020).⁶

4. The number of clusters is determined using the Elbow and Silhouette Score methods, and the data are standardized using the Yeo-Johnson transformation.

5. To avoid overfitting, the data are split into training and testing sets, and the regression coefficients are adjusted to ensure model stability. The robustness of the logistic regression is ensured by maximizing the log-likelihood function, estimating the coefficients that best fit the model to the observed data.

6. To ensure robustness, we repeat the PI procedure 100 times and report the mean and standard deviation of the resulting importance scores. These values reflect how strongly each structural feature influences the model's predictive accuracy. A higher average score indicates that the variable plays a more decisive role in distinguish-

of industrialization, urbanization, and productive diversification, especially in states such as São Paulo (SP), Minas Gerais (MG), and Rio de Janeiro (RJ) (Martine and Diniz 1991; Sobrinho and Azzoni 2015). In the South, the integration of the states into the Industrial Polygon stands out, strengthened by agro-industrial complexes and the industrial decentralization toward medium- and small-sized cities (Diniz 1993). The Central-West presents varied patterns: Goiás (GO) shows high resilience due to industrial and agricultural diversification (Tupy et al. 2021), while Mato Grosso (MT) and Mato Grosso do Sul (MS) are more dependent on commodity exports. In the North, resilience varies with the region’s productive heterogeneity, shaped by specific hubs like the Manaus Free Trade Zone in Amazonas (AM), but also shows some uniformity due to the broader integration of local economies into the agricultural frontier and global commodity markets. Finally, in the Northeast, Bahia (BA) and Pernambuco (PE) deviate from the regional pattern, driven by industrial hubs and agribusiness (Haddad et al. 2024), whereas the other states maintain low resilience.

These results support the central hypothesis of the study, according to which greater productive integration and interregional articulation confer higher capacity to face shocks. The analysis of sectoral interdependencies, represented by interregional value-added networks, allows the identification of the centrality of federative units in the national productive structure. Using eigenvector centrality as one of the metrics to measure the degree of regional resilience, it is observed that regions with intense connections to other relevant regions tend to occupy strategic positions in the network, reflecting greater systemic influence by considering both their direct links and their articulation with the rest of the economy. The approach partially reinforces the central hypothesis that the resistance of regional economies to exogenous shocks relates to their productive articulation at different scales.

These findings are further corroborated by the results of the Permutation Importance (PI) analysis, which evaluates the relative contribution of each metric to the classification of regional resilience. The PI score (Table 1) reflects how much each metric contributes to correctly distinguishing between more and less resilient regions; higher scores indicate that the variable plays a more decisive role in the classification. It is important to note that the Leontief Linkage Index reflects the strength of intersectoral input-output relationships under normal conditions, while the network measures, such as Weighted Degree and Eigenvector Centrality, capture the relative importance of each region within the productive network based on its role across a wide range of simulated crisis scenarios. In this context, increases in a region’s score imply that its position becomes more central or influential in sustaining interregional flows under stress, while decreases reflect a weakening of that strategic role.

Table 1: Permutation Importance of factors used for capturing regional resilience

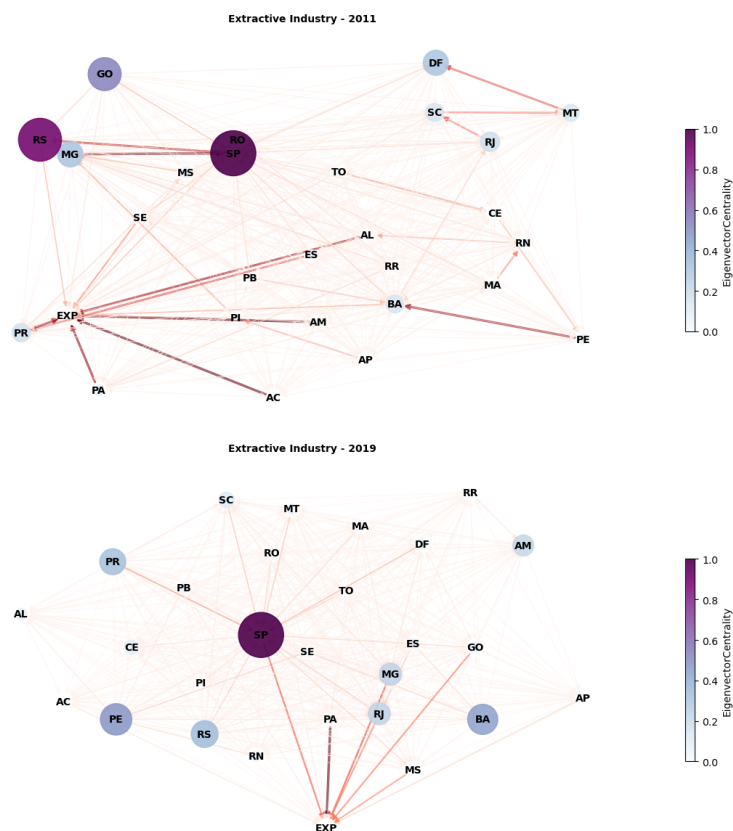
Metric	2011		2019	
	Mean	Std. Dev.	Mean	Std. Dev.
Weighted Degree	0.391	0.102	0.413	0.105
Leontief Linkage Index	0.358	0.122	0.460	0.087
Eigenvector Centrality	0.347	0.109	0.256	0.089

In 2011, Weighted Degree and the Leontief Linkage Index registered the highest PI scores, with Eigenvector Centrality following closely behind. By 2019, however, the Leontief Linkage Index emerged as the most influential metric, while the importance of Eigenvector Centrality

In this context, sectoral analysis plays a central role not only in understanding regional resilience but also in identifying the sectors with the greatest capacity to sustain central positions within the productive network through the articulation of economic flows. Activities such as extractive industries and agriculture capture the dynamics of external demand, while the manufacturing industry stands out for its strong potential to foster internal intersectoral linkages. The trade and services sector, given its cross-cutting nature, strengthens intersectoral connections across the territory. Depending on the nature of the activity, this sector either provides local support or promotes productive integration capable of fostering broader interdependencies.

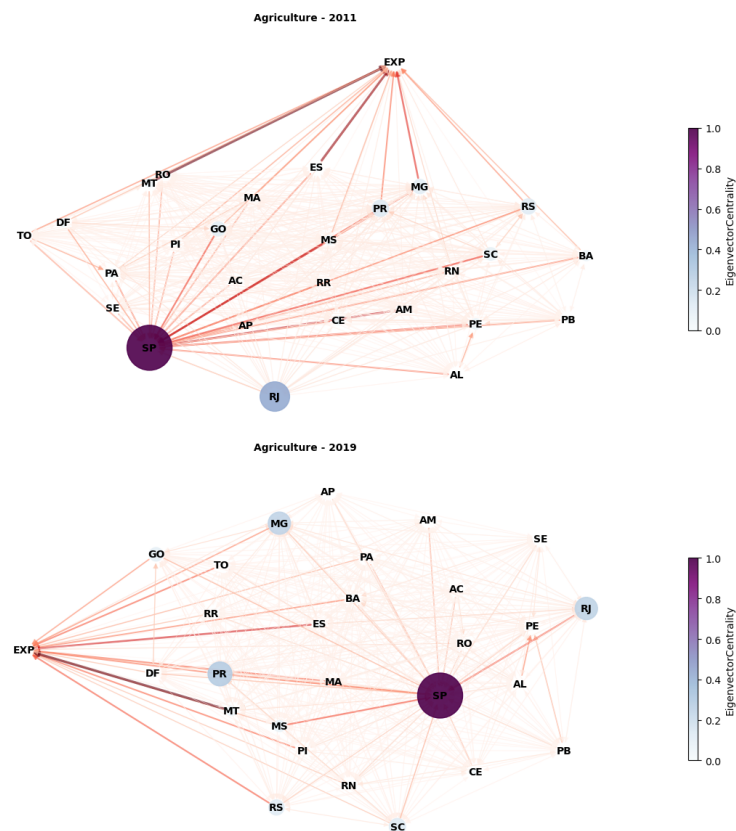
Specialization in extractive activities, for example, shapes how states position themselves within the productive network, as Figure 3 illustrates. Rio de Janeiro (RJ) and Minas Gerais (MG) maintain a strong presence in this sector, which deepens their ties to the international market but also heightens their exposure to external shocks, as (Silva et al. 2021; Tupy et al. 2021) note, consistent with European evidence (Fratesi and Rodríguez-Pose 2016). Espírito Santo (ES) shows a similar pattern, with a moderate degree of resilience and a notable concentration in the extractive sector (9.89% of value added in 2019). This structural dependence creates domestic fragilities, especially after the disruption of regional supply chains triggered by the environmental disaster involving mining companies in Mariana, Minas Gerais. This case reveals how specific shocks expose vulnerabilities rooted in sectoral concentration and regional interdependencies.

Figure 3: Eigenvector centrality for the extractive industry based on value added (2011 and 2019).



Regional responses to external perturbations change depending on the nature of the shock, as Di Pietro et al. (2021) emphasize. This insight helps explain why primary activities, predominantly focused on commodity exports, grant productive centrality to certain regions while simultaneously increasing their vulnerability to external shocks and disruptions in territorial linkages. Although these sectors play a crucial role in Brazil’s insertion into international trade, their ability to sustain regional resilience depends largely on the strength of productive linkages and the diversification of local economic interactions.

Figure 4: Eigenvector centrality for the agricultural sector based on value added (2011 and 2019).

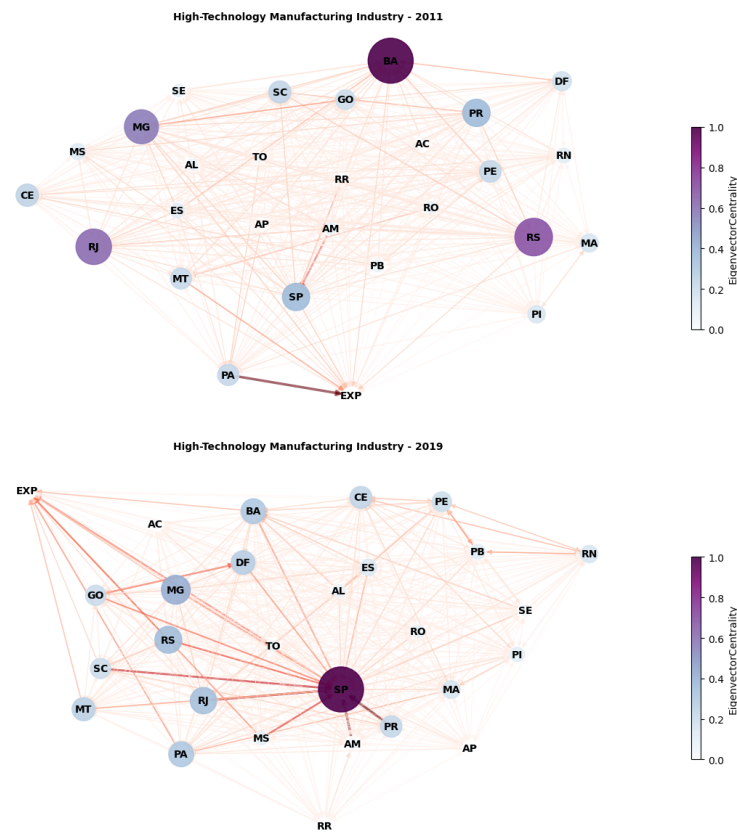


This external dependence is partially mitigated by the adaptive capacity observed in the Midwest, although internal differences persist. Mato Grosso is more connected to the external market, while Mato Grosso do Sul depends on demand from São Paulo; Goiás, in turn, displays greater diversification with industrial hubs, which makes it more susceptible to national shocks but less exposed to sector-specific crises.

Heterogeneity also characterizes the North region. Tocantins (TO) and Rondônia (RO) show a high share of agriculture and livestock in value added (14.17% and 13.92%, respectively). Pará (PA), although classified as having a low degree of regional resilience, has an economy connected to national and international flows through its port infrastructure. In terms of economic activity, the extractive industry stands out, accounting for 19.72% of the state’s value added and revealing a pronounced dependence on exports. An interruption in external demand could lead to losses of 85.83% in sectoral value added, reflecting a vulnerability asso-

ciated with specialization oriented toward the external market, which undermines its regional resilience.

Figure 5: Eigenvector centrality for the High-Technology Manufacturing Industry (2011 and 2019).



Overall, the results indicate that, in 2019, with the exception of the states of Amazonas (AM), Rondônia (RO), and Tocantins (TO), the remaining states in the North region show low levels of regional resilience. This condition reflects a productive structure concentrated in agricultural and extractive activities, with limited sectoral diversification. The main contribution to regional value added comes from public services, such as education and public administration, whose economic effects tend to remain confined within the intraregional space. This characteristic limits integration with national production chains and, consequently, reduces the capacity to respond to shocks, which does not support the central hypothesis of the present study.

This scenario reinforces the historical concentration of industrial activities in the South and Southeast, especially in São Paulo, where a consolidated productive structure hinders the inland expansion of the manufacturing industry. Deconcentration policies, such as the Manaus Free Trade Zone, seek to alter this pattern through tax incentives, and input-output matrix data show that Amazonas increases its share of value added in the high-tech industry from 5.82% in 2011 to 7.80% in 2019, while the medium-high-tech industry in the state declines from 11.36% to 7.27%, along with contractions in other categories. Despite these gains, industrial expansion in Amazonas remains subordinated to the hegemonic hub of São Paulo, as shown in Figure 5, preserving regional asymmetry and revealing a pattern of “concentrated deconcentration,” in

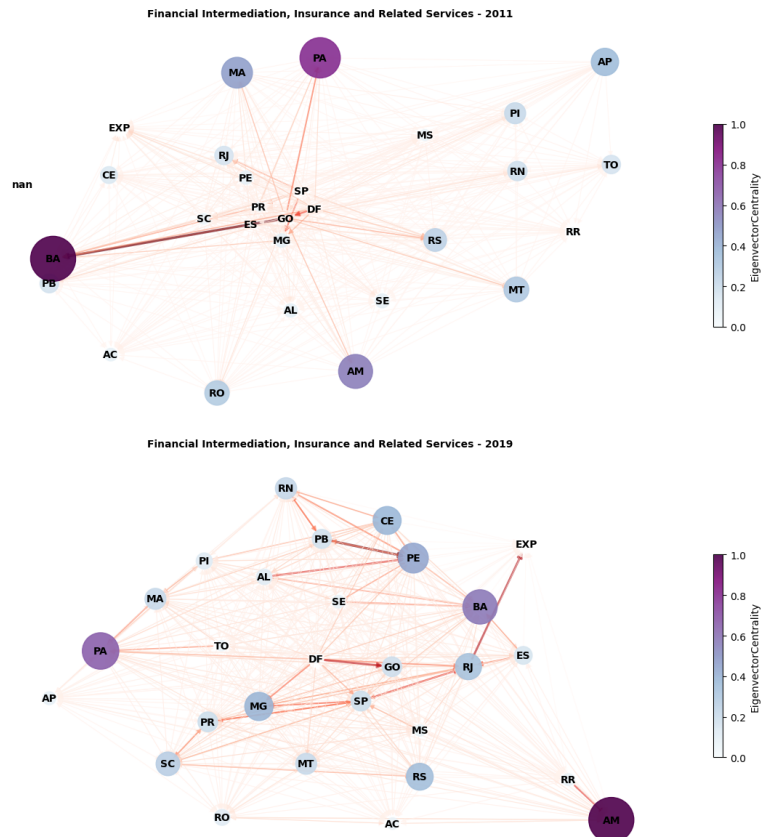
which the disruption of interregional connections could result in a 36.56% loss in sectoral value added, while an intraregional interruption would lead to an 18.69% loss. This is an example of an exogenous regional growth policy, disconnected from the local productive structure, which results in spatial spillovers and dependence on other regions— a limitation captured by the resilience measures used in this study, but not by traditional approaches.

In the Northeast region, resilience reveals structural weaknesses similar to those observed in the North. Despite the increase in public investment, limitations in productive diversification, commercial integration, and the reduction of inequalities persist, compromising economic centrality and the capacity to absorb shocks (Tupy et al. 2021). Recent reconfigurations, driven by tax incentives and political decisions, have led to the establishment of automobile plants in Bahia (BA) and Pernambuco (PE), as well as refineries and petrochemical complexes (Diniz and Mendes 2021). Bahia stands out as a strategic federative unit in the Northeast by combining the highest value added in the region with strong economic centrality. This performance reflects, in part, its diversified productive base, with a strong presence of both agriculture and industry. In certain periods, its influence in the high-technology manufacturing sector surpasses that of São Paulo in terms of centrality (Figure 5), highlighting Bahia's potential for integration into the national productive network. Pernambuco also exhibits a high degree of regional resilience, although through mechanisms distinct from those observed in Bahia. While Pernambuco's interdependencies are concentrated within the intraregional context, Bahia stands out for its greater productive diversification and its capacity for coordination on a national scale.

It is essential, in this context, to consider the role of the service sector, whose composition is particularly heterogeneous across different Brazilian regions. In the North and Northeast, activities that mimic typical service sector functions play a significant role in the formation of regional value added. However, the high level of aggregation of these activities in the input-output matrices hinders a more precise assessment of their impacts. This limitation compromises the interpretative capacity regarding their contribution to productive interdependencies and regional integration, especially in contexts with limited industrial presence.

Given this limitation, the analysis focuses on three key economic activities: financial intermediation, insurance and related services; real estate activities; and public administration, defense, and social security. In 2019, these activities accounted for 27.15% of national value added. Notable cases include states such as São Paulo (28.35%), Sergipe (SE) (30.41%), Paraíba (PB) (31.37%), Amapá (AP) (44.45%), and Roraima (RR) (44.19%), highlighting the centrality of the service sector, particularly in the North and Northeast, where these activities often fill the gap left by underdeveloped industrial chains, becoming essential for sustaining regional economies. Although São Paulo shows the highest centrality in most of the activities analyzed, the results for the financial intermediation sector (Figure 6) reveal a distinct pattern. This is due to the high concentration of these activities in the state, which operate with less dependence on interregional flows.

Figure 6: Eigenvector centrality for the Financial intermediation, insurance, and related services sector (2011 and 2019).



In contrast, states such as Amazonas, Pará, and Bahia exhibit higher centrality within the financial services network, associated with demand generated by productive interactions with other regions. In the case of Amazonas, the Manaus Free Trade Zone drives these flows; In Pará, the Port of Belém and the abundance of natural resources strengthen the state’s connections with international markets; and in Bahia, the diversified productive structure fosters links with different regions of the country. Unlike São Paulo, whose financial sector is more autonomous, these states face local constraints that make their external interdependencies more relevant to the sustainability of their economies.

A similar trend of regional reconfiguration is observed in Real Estate Activities, where a shift in the distribution of importance emerges over the period analyzed. In 2011, this sector was mainly concentrated in the Southeast, with São Paulo, Rio de Janeiro, and Minas Gerais standing out, in addition to Bahia in the Northeast. By 2019, a relative increase is observed in federative units such as Mato Grosso, Pará, and Rio Grande do Sul (RS). This shift may be associated with the expansion of urban areas in emerging regions or the strengthening of new economic hubs.

These dynamics reinforce the growing importance, but also the limitations, of the service sector in sustaining regional economies. While financial intermediation and real estate activities demonstrate increasing integration and evolving spatial patterns, other service activities remain more constrained. Public administration, defense, and social security, although significant in the composition of value added in regions such as the Northeast, show low regional

interdependence due to their institutional nature and close ties to the public sector. In the Federal District, this productive concentration results in low regional resilience: in 2019, the sector accounted for 31.50% of local value added, yet in a scenario of intraregional crisis, the estimated loss reaches 63%, indicating a strong dependence on other regions. Conversely, in most other regions, the sector's dependence is primarily intraregional, as in Amapá (98.50%).

These dynamics underscore both the growing importance and structural limitations of the service sector in sustaining regional economies. While financial intermediation and real estate activities show increasing integration, public administration, defense, and social security remain constrained by low interregional interdependence. In the Federal District, where these services accounted for 31.50% of value added in 2019, an intraregional crisis could lead to a 63% loss, reflecting strong external dependence. In contrast, most other regions rely primarily on intraregional flows, as in Amapá (98.50%).

The results show that the low resilience of Brazilian regions is associated with a reliance on services marked by low productive interdependence, limited value added, and low skill levels, which replace rather than integrate with industry, reflecting an unbalanced productive structure. In contrast, in European economies, services play a central role in regional resilience (Navarro-Espigares et al. 2012). This role is often linked to the predominance of knowledge-intensive business services (KIBS), which are highly skilled, integrated into production chains, and capable of adding value to industrial output.

5 Conclusions

The measurement of regional resilience we adopt in this study relies on an innovative and multifaceted approach that considers regional and productive interdependencies, as well as their systemic effects. This approach enables the simulation of scenarios that project shocks along value chains, adopting an ex-ante perspective aimed at anticipating disruptions, regardless of past events. Although artificial, such shocks mimic the diversity of real risks to which sectors or regions are susceptible, reflecting structural and dynamic vulnerabilities that may emerge in crisis contexts. This allows for a comprehensive identification of the limitations and potentialities of regional economic structures, including cases in which exogenous growth policies, disconnected from local structures, generate spatial spillovers and intensify dependence on other regions, an aspect that traditional measures of resilience scarcely capture.

Based on this methodology, the results reveal a spatial configuration characterized by a strong agglomeration effect, with similar levels of resilience among neighboring states and specific regions of the country. This pattern reflects the historical legacy of productive concentration and the unequal development of the Brazilian economy, highlighting a clear territorial division. In this context, the Southeast-South region stands out, particularly the state of São Paulo, which emerges as the main hub of regional resilience.

In summary, regional resilience in Brazil reveals structural disparities, with federative units that exhibit greater productive diversification and a higher degree of interdependence tending to respond more effectively to shocks, while those with lower integration face more pronounced constraints. This contrast intensifies in regions marked by dependence on service-related activities, especially those linked to the public sector, whose limited integration into production chains hinders growth. The central position of São Paulo, although strategic, raises a concern: an exogenous event that severely affects its productive structure may trigger a cascading effect,

impacting other regions and compromising the regional resilience of the Brazilian economy, exposing it to a contagion process.

The analysis of regional resilience results, when comparing the years 2011 and 2019, reveals that changes in resilience levels do not occur simply or quickly, indicating that integration into the Brazilian production chain is unlikely to happen exogenously. Therefore, it is essential to promote public policies that encourage this integration sustainably, leveraging each region's endogenous capacities to foster its development and resilience.

Integration, initially, does not need to be national, as the results show that regional connectivity is limited within macro-regions with lower levels of resilience. This suggests that geographically distant states hold greater regional relevance than the connections among states within those same regions. Hence, it is necessary to prioritize integration among states within each region, promoting interdependencies and strengthening local production chains before pursuing broader national integration. Furthermore, the expansion of primary activities into less resilient regions, especially the North, deserves attention. Although such expansion stimulates these areas through investments and new opportunities, they become more susceptible to specific shocks, repeating patterns observed in federative units with similar paths of specialization. This process, by consolidating production structures centered on specific activities, tends to undermine regional resilience.

Although this study advances the understanding of regional and productive interdependence, it also faces limitations. Economic and social heterogeneities at the municipal level, for example, may affect the applicability of the results at more disaggregated scales. Building a regionalized input-output matrix involves complex procedures, and applying it to more specific spatial units introduces methodological and data-related challenges that can influence result validity. Even so, the study contributes to the understanding of regional resilience by integrating productive interdependence and adopting an ex-ante analytical approach. By simulating crisis scenarios and their effects on regional interdependencies, the analysis identifies vulnerabilities and potentialities, offering insights that support the design of public policies aimed at enhancing shock response capacity and strengthening regions in a sustainable way, in line with their specific characteristics.

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