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Interregional propagation of the 2024 Rio Grande do Sul flood shock: an input-output analysis of Brazil's production network

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ABSTRACT

This study examines how production losses caused by a localized extreme event propagate through an integrated regional economy. Using an event-calibrated, demand-driven interregional input-output model for Brazil (2019 base year; 27 states and 68 sectors), the analysis translates official estimates of agricultural and livestock losses from the May 2024 floods in Rio Grande do Sul into demand-equivalent shocks and traces their economic, fiscal, and environmental repercussions. The BRL 4.02 billion initial shock (2019 prices) is associated with a BRL 6.55 billion contraction in national output, implying a network amplification factor of 1.63; BRL 2.53 billion, or 38.6% of the total output effect, arises beyond the initial shock. Approximately BRL 1.51 billion (23.1%) of the output contraction occurs outside Rio Grande do Sul, revealing substantial spatial spillovers through Brazil's production network. Value added, wage income, and indirect product taxes decline by BRL 3.23 billion, BRL 0.70 billion, and BRL 0.24 billion, respectively. Environmental satellite accounts indicate lower emissions, water use, and energy consumption as mechanical consequences of reduced production rather than efficiency gains. The results show that regional exposure to extreme events is shaped by interregional production dependencies and identify logistics, critical inputs, utilities, and intergovernmental coordination as key leverage points for regional economic resilience.

KEYWORDS: interregional input-output; spatial spillovers; production networks; regional economic resilience; extreme events; Brazil.

JEL Classification: R15; R11; Q54

HIGHLIGHTS

- Event-calibrated IRIO analysis traces flood-related production losses across 27 Brazilian states and 68 sectors.
- A BRL 4.02 billion shock generates a BRL 6.55 billion output contraction, implying a 1.63 amplification factor.
- About 23.1% of the modeled output contraction occurs outside Rio Grande do Sul, revealing substantial spatial spillovers.
- Logistics, critical inputs, utilities, and intergovernmental coordination emerge as key regional-resilience leverage points.

1. INTRODUCTION

Extreme precipitation and flooding are increasingly important sources of economic and social risk, particularly where infrastructure, production systems, and food supply chains are strongly interconnected. Flood disasters can generate losses that extend well beyond the locations physically exposed to the hazard because firms and regions depend on one another through intermediate-input, logistics, energy, and market linkages (Baqaee and Farhi 2019; Barrot and Sauvagnat 2016; Willner et al. 2018). From a regional-resilience perspective, a central question is not only how much damage occurs at the disaster site, but also how that damage is transmitted through the wider economic system and where interventions can reduce cascading exposure.

Rio Grande do Sul (RS), in southern Brazil, provides a particularly relevant case. In April-May 2024 the state experienced unprecedented flooding that affected most municipalities, displaced hundreds of thousands of people, disrupted essential infrastructure,

and generated extensive productive losses (EBC 2024; IFRC 2024; Pillar and Overbeck 2024). Peer-reviewed studies have subsequently characterized complementary dimensions of the event. Event-attribution analysis found that anthropogenic warming and the preceding El Niño increased the likelihood of the extreme rainfall, although the attribution estimates remain uncertain (Clarke et al. 2026). Atmospheric observations and GNSS-derived precipitable water vapor documented exceptional precipitation and highlighted the potential of near-real-time monitoring for extreme rainfall (Gouveia et al. 2026). A state-wide analysis further documented intensifying hydroclimatic extremes and the spatial overlap between flood exposure, socioeconomic vulnerability, and public-health impacts (Terassi et al. 2026). Together, these studies substantially advance understanding of hazard formation, monitoring, exposure, and local consequences. They do not, however, quantify how observed productive losses propagate through Brazil's interregional production network, which is the distinct question addressed here.

RS is also systemically important to the Brazilian economy. The state is a major producer of grains, livestock, and processed foods and is embedded in national supply chains for fertilizers and chemicals, fuels, electricity, transport, storage, wholesale trade, finance, and business services. Flood damage to roads, bridges, storage facilities, energy systems, and farms can consequently interrupt both the production of agricultural commodities and the flows of inputs and services required to sustain production elsewhere. This network structure means that a geographically concentrated hazard can generate economic and fiscal effects in regions that are not directly flooded.

Existing disaster assessments commonly emphasize direct damages, aggregate macroeconomic effects, or sector-specific production losses. Those approaches are indispensable, but they do not necessarily reveal which intersectoral and interregional linkages transmit the shock, how much of the economy-wide effect occurs outside the affected region, or how associated fiscal and environmental footprints are distributed. For the 2024 RS floods, the comprehensive DaLA assessment led by the IDB, World Bank, and ECLAC estimated total disaster effects of BRL 88.9 billion across productive, social, infrastructure, and environmental dimensions (Suarez et al. 2024). That broad damage-and-loss accounting answers a different question from the one addressed here: how a defined component of observed primary-sector production losses propagates through Brazil's production network.

Against this background, this study combines itemized official estimates of agricultural and livestock losses with Brazil's 2019 interregional input-output (IRIO) system, comprising 27 states and 68 sectors. The event-specific losses are converted into a demand-equivalent shock in RS and propagated through the Leontief inverse. The analysis estimates changes in output, value added, wage income, and product taxes and links the simulated production contraction to satellite accounts for CO_2 emissions, water use, and energy consumption. The spatial dimension is central: the framework identifies how a shock originating in one state is redistributed across sectors and regions through production linkages.

The analysis is organized around three research questions. First, to what extent are the observed primary-sector losses in RS amplified through intersectoral production linkages? Second, which sectors and states absorb the largest indirect effects, and what do those patterns reveal about the spatial transmission of the shock? Third, what are the associated implications for labor income, fiscal capacity, and environmental resource use, and how can these results inform regional economic resilience and policy?

The study's contribution is empirical and integrative rather than a claim to a new input-output technique. It links event-specific loss evidence from the 2024 floods to a high-resolution interstate production network and evaluates economic, fiscal, and environmental consequences in a single framework. Two derived indicators—a network amplification factor and an extra-RS spillover share—quantify the systemic and spatial reach of the shock. The analysis therefore contributes to regional science by showing how local production disruptions become

interregional externalities and by identifying the sectors and territories through which resilience policies can generate benefits beyond the directly affected region.

2. METHOD

2.1. Data Sources and Shock Specification

This study draws the primary physical-loss data from the official technical report published by Emater/RS-Ascar (EMATER 2024). The report provides a consolidated assessment of losses in agricultural, livestock, and forestry activities following the extreme rainfall and flooding that affected Rio Grande do Sul in May 2024. Emater/RS-Ascar is the state's official rural extension and technical-assistance agency and compiled information through municipal extension offices, field assessments, producer reports, and coordination with local authorities. These characteristics provide broad territorial coverage and a level of product detail suitable for calibrating the event-specific shock used in this study.

The report expresses losses primarily in physical units (e.g., tons of crops, liters of milk, and numbers of animals or plants). To operationalize those observations in the IRIO framework, physical losses were converted into monetary values using reference producer prices. For the 2024 valuation, the study used official or sector-recognized sources, including PAM/IBGE, Agrolink, and CEPEA/ESALQ (Agrolink 2025a; ESALQ 2026; IBGE 2025a). Where a direct price conversion was not available, as in selected poultry and swine items, price information was combined with technical coefficients such as average live weight and processing yield (ACSURS 2024; Agroceres 2022; Embrapa 2025).

Because the IRIO system is expressed in 2019 prices, the same physical losses were also valued at 2019 producer prices from the corresponding databases or, where necessary, consistent historical estimates in the literature (Alves et al. 2025). This dual valuation serves two purposes: the 2024 values communicate the contemporaneous scale of the observed primary-sector losses, whereas the 2019 values provide a shock that is internally consistent with the price structure of the input-output table.

The monetary values used in the model are interpreted as demand-equivalent negative shocks in the RS primary sectors. This is an accounting device for tracing short-run propagation in a demand-driven Leontief system rather than a literal representation of the physical supply constraint created by the flood. Accordingly, the results should be read as a first-round structural stress test conditional on fixed production relationships, not as a complete estimate of all disaster damages or welfare losses. Table 1 documents the conversion from physical losses to monetary values and the subset of losses included in the modeled shock.

Table 1 Physical and monetary losses in primary production (Rio Grande do Sul, May 2024)

Impact Category	Loss (Quantity)	Reference Monetary Value per Unit (BRL) for 2024	Reference Monetary Value per Unit (BRL) for 2019	Estimated Monetary Loss (Million BRL) [2024]	Estimated Monetary Loss (Million BRL) [2019]
Primary Sector Losses				**7,091.90**	**4,019.72**
I. Losses in Agricultural Production (t)				**6,995.96**	**3,963.86**
Grains (Production Losses)				**6,456.10**	**3,705.88**
Soybean	2,714,151 t	1,978.54 [a] 2,002.88 [b]	1,115.88 [a] 1,193.70 [b]	5,403.09	3,134.27
Maize (silage)	721,336 t	400.00 [d]	271.52 [h]	288.53	195.86
Rice	160,664 t	2,083.68 [a] 2,243.50 [b]	838.64 [a] 859.28 [b]	347.61	136.40
Maize	354,189 t	922.36 [a] 953.27 [b]	543.69 [a] 536.74 [b]	332.16	191.34
Beans	18,244 t	4,406.86 [a] 4,852.24 [b]	2,733.38 [a] 2,513.30 [b]	84.46	47.86
Canola (rapeseed)/Oats	132 t	1,805.13 [b]	1,174.89 [b]	0.24	0.16
Stored Grains				**93.26**	**36.60**
Rice (compromised in silos)	43,106 t	Same for Rice	Same for Rice	93.26	36.60
Fruit Production (Losses)				**227.88**	**95.20**
Tangerine	62,053.00 t	2,204.36 [a]	969.82 [a]	136.79	60.18
Orange	40,986.50 t	1,895.36 [a]	648.90 [a]	77.68	26.60
Strawberry	4,900.01 t	n.e.	n.e.	n.e.	n.e.
Apple	2,700.00 t	2,860.94 [a]	1,638.15 [a]	7.72	4.42
Lemon	2,524.43 t	2,252.20 [a]	1,586.24 [a]	5.69	4.00
Vegetable Production (Losses)				**218.72**	**126.17**
Potato	51,885.50 t	2,718.37 [a]	1,726.58 [a]	141.04	89.58
Broccoli	39,258.37 t	n.e.	n.e.	n.e.	n.e.
Cassava	21,999.70 t	2,260.65 [a]	1,014.55 [a]	49.73	22.32
Sweet potato	12,742.50 t	2,192.53 [a]	1,119.86 [a]	27.94	14.27
Lettuce	11,612.13 t	n.e.	n.e.	n.e.	n.e.
Cabbage	8,509.39 t	n.e.	n.e.	n.e.	n.e.
II. Livestock and Animal Production				**95.94**	**55.86**
Animal Deaths				**71.69**	**44.22**
Commercial poultry	1,198,489 head	4.39 / kg [e]	2.47 / kg [e]	8.55 [f]	4.81
Beef cattle	14,806 head	8.64 / kg (live weight) [b]	5.38 / kg (live weight) [b]	57.57	35.85
Swine (pig)	14,794 head	5.42 / kg [b]	3.46 / kg [b]	5.58 [g]	3.56
Dairy cattle	2,451 head	n.e.	n.e.	n.e.	n.e.
Fish farming (losses)	937.93 t	n.e.	n.e.	n.e.	n.e.
Commercial beekeeping (losses)	16,054 hives	n.e.	n.e.	n.e.	n.e.
Uncollected Milk Production				**24.25**	**11.65**
Total uncollected milk	9,625,918 liters	2.5189 / liter [c]	1.21 / liter [b]	24.25	11.65
III. Forestry Production (Affected Plants)					
Eucalyptus	571,655 plants	n.e.	n.e.	n.e.	n.e.
Yerba mate	438,880 plants	n.e.	n.e.	n.e.	n.e.
Acacia	84,050 plants	n.e.	n.e.	n.e.	n.e.
Pine	32,102 plants	n.e.	n.e.	n.e.	n.e.

Source: Adapted from the Emater/RS-Ascar report “Impactos das chuvas e cheias extremas no Rio Grande do Sul em Maio de 2024” (EMATER 2024).

Note: a Based on PAM-IBGE data for RS (IBGE 2025b); b based on Agrolink data for RS (Agrolink 2025a); c based on CEPEA/ESALQ data for RS (ESALQ 2026); d based on Agrolink (2025b); e based on Agrolink data for SC (Agrolink 2025a); f based on an average poultry live weight of 2.5 kg/head (Agroceres 2022) and an estimated 65% processing yield from live weight to boneless meat (Agriculture Institute 2023); g based on an average swine live weight at slaughter of 94 kg (ACSURS 2024) and an estimated carcass yield of 74% of live weight (Embrapa 2025); h based on Alves et al. (2025); n.e. = not estimated.

Items reported as “n.e.” (not estimated) in Table 1 were excluded when a defensible producer-level monetary value was unavailable or conceptually inappropriate. This applies

particularly to affected eucalyptus, pine, and yerba mate plants, for which valuation per plant would require assumptions about survival, growth cycles, future yields, harvesting dates, and discounting. Excluding these items makes the modeled shock conservative relative to the complete set of reported physical losses and avoids introducing valuation assumptions that could dominate the precision of the propagation exercise.

Treating the calibrated loss as a demand-equivalent shock follows a common tradition in disaster input-output applications (Hallegatte 2008; Okuyama 2007; Okuyama and Santos 2014), but the interpretation requires care. In the Leontief model, a change in final demand translates into proportional changes in gross output through fixed technical coefficients and constant returns to scale (Leontief 1986; Miller and Blair 2009). The approach therefore identifies the production requirements associated with the initial contraction and the resulting intersectoral and interregional dependencies. It does not endogenously model damaged productive capacity, price responses, inventories, supplier substitution, imports, reconstruction demand, or behavioral adaptation.

2.2. Application of the Leontief Interregional Model and Shock Implementation

This study evaluates the intersectoral and interregional repercussions of the 2024 flood-induced primary-sector losses through the 2019 Brazilian interregional input-output matrix (Haddad et al. 2025). The IRIO system represents the Brazilian economy as an integrated production network of 68 sectors distributed across 27 states. Gross output is determined by intermediate-input requirements and exogenous final demand, allowing a localized shock in RS to be traced through both sectoral and interstate linkages.

Formally, total gross output is represented by the vector x, which satisfies the accounting identity

$$x = Ax + f \qquad \text{[eq. 1]}$$

where A denotes the matrix of technical input coefficients and f represents final demand. Solving for output yields

$$x = (I - A)^{-1} f \qquad \text{[eq. 2]}$$

in which $(I-A)^{-1}=L$ corresponds to the Leontief inverse matrix. Each element of L captures the total direct and indirect production required in each sector–region to satisfy a one-unit variation in final demand in any given sector–region.

The model introduces negative final-demand-equivalent shocks in two RS sector-region entries: (i) Agriculture, including agricultural support and post-harvest activities, with a contraction of BRL 3,963.86 million (2019 prices), and (ii) Livestock, including support activities, with a contraction of BRL 55.86 million. Together, these components form the BRL 4,019.72 million modeled shock. All other entries in the variation vector Δf remain unchanged.

The total variation in gross output generated by the disaster is obtained as

$$\Delta x = L \Delta f \qquad \text{[eq. 3]}$$

This expression captures the contraction in the directly shocked RS activities and the indirect reductions transmitted through intermediate-input requirements to other sectors and states. Aggregation of Δx by region identifies the territorial distribution of spillovers, whereas

aggregation by sector reveals the production-chain channels through which the shock propagates.

Beyond output effects, this study derives impacts on value added, labor income, tax revenues, and environmental indicators through proportional coefficient matrices consistent with the Leontief quantity framework. Let $v_i = VA_i/x_i$ denote the value-added coefficient of each sector–region. The variation in value added is therefore given by

$$\Delta VA = v\Delta x \quad \text{[eq. 4]}$$

where v is a diagonal matrix containing sector–region value-added coefficients.

Similarly, labor income effects are obtained through wage coefficients $w_i = W_i/x_i$, such that

$$\Delta W = w\Delta x \quad \text{[eq. 5]}$$

This formulation implies that reductions in output proportionally reduce labor remuneration, under the assumption of fixed production techniques and constant factor shares.

Fiscal impacts are estimated using sector-specific tax coefficients $t_i=T_i/x_i$, allowing computation of total tax losses as

$$\Delta T = t\Delta x \quad \text{[eq. 6]}$$

The fiscal analysis further decomposes the total change in indirect product taxes into ICMS, IPI, and other taxes using the corresponding sector-specific coefficients. This disaggregation is relevant for regional resilience policy because disasters can weaken tax bases at the same time that public expenditure needs increase, creating a fiscal-resilience problem across different levels of government.

All model calculations are performed in constant 2019 prices, consistent with the base year of the IRIO matrix. For communication and international comparison, the resulting monetary values are also expressed as nominal 2024 equivalents using the accumulated Brazilian GDP implicit deflator reported by IPEADATA (2026). The updating procedure applies the compounded annual deflator variation between 2020 and 2024:

$$V_{2024} = V_{2019} \times \prod_{t=2020}^{2024} (1 + \pi_t) \quad \text{[eq. 7]}$$

where π_t denotes the annual variation of the GDP implicit deflator in year t.

Using annual GDP implicit-deflator variations of 6.47% (2020), 13.05% (2021), 8.57% (2022), 5.16% (2023), and 3.80% (2024), the cumulative factor is 1.4284. Thus, each 2019-price result is multiplied by 1.4284 to obtain its nominal 2024 equivalent. This conversion changes the unit of presentation but does not alter the technical coefficients or propagation structure of the 2019 model.

The 2024 BRL equivalents are additionally converted to U.S. dollars using the World Bank's 2024 average nominal exchange rate of BRL 5.39 per USD (World Bank 2025). USD values are reported only to facilitate international comparison; all structural results originate from the 2019-price model.

Environmental and resource-use implications are estimated with satellite-account intensity coefficients defined as sector-region emissions or resource use per unit of gross output. Let $e_iCO_2 = CO_{2i}/x_i$, $e_i\text{Water} = \text{Water}_i/x_i$, and $e_i\text{Energy} = \text{Energy}_i/x_i$. Applying these coefficients to

the modeled output changes yields the associated changes in CO_2 emissions, water use, and energy consumption:

$$\Delta CO2 = e^{CO2}\Delta x \quad \text{[eq. 8]}$$

$$\Delta Water = e^{Water}\Delta x \quad \text{[eq. 9]}$$

$$\Delta Energy = e^{Energy}\Delta x \quad \text{[eq. 10]}$$

Within this linear satellite-account structure, negative environmental variations are mechanical consequences of lower modeled production. They should not be interpreted as improvements in environmental efficiency, changes in technology, or durable mitigation outcomes.

2.3. Analytical interpretation of network propagation

To move beyond a descriptive listing of sectoral and regional effects, two summary indicators are derived from the model results. The network amplification factor is defined as the absolute national change in gross output divided by the absolute value of the initial modeled shock. Values above one indicate that intermediate-input dependencies magnify the initial contraction. The extra-RS spillover share is defined as the difference between the absolute national output change and the absolute RS output change, divided by the absolute national output change; it measures the proportion of the national output effect occurring outside the directly affected state. These indicators are not resilience scores; rather, they provide compact measures of systemic propagation that can be interpreted alongside the sectoral and territorial results.

The framework is intentionally static and should be interpreted as a short-run structural stress test. It assumes 2019 production technology and trade relationships, fixed input coefficients, no price adjustment, and proportional factor, tax, and environmental intensities. It also excludes reconstruction demand and adaptive responses that may attenuate or redistribute losses over time. These restrictions limit predictive interpretation but preserve transparency about the channels through which the observed primary-sector shock is transmitted in the national production network.

2.4. Use of generative AI in manuscript preparation

During manuscript preparation, ChatGPT (OpenAI) was used to support language revision, wording, and textual organization. All analytical decisions, calculations, interpretations, and the final manuscript were reviewed by the author, who assumes full responsibility for the content.

3. RESULTS

3.1. Event context and regional economic exposure

The April-May 2024 floods in Rio Grande do Sul were among the most severe disasters recorded in the state. More than 90% of municipalities reported damages or losses, while the Guaíba and several major river basins reached exceptional levels and flood-protection, transport, energy, and water-service systems experienced widespread disruption (EBC 2024; IFRC 2024; Pillar and Overbeck 2024). The event was therefore not only a hydrological

emergency but also a compound infrastructure and production shock affecting urban and rural systems simultaneously.

The hazard context is supported by complementary peer-reviewed evidence. Event-attribution analysis concluded that the extreme precipitation was rare even in the 2024 climate and estimated that anthropogenic warming had increased its likelihood, while the preceding El Niño also contributed to the event (Clarke et al. 2026). Atmospheric observations over affected areas documented exceptional rainfall and showed that GNSS-derived precipitable water vapor can support near-real-time monitoring of extreme precipitation (Gouveia et al. 2026). A state-wide analysis identified significant warming and intensification of precipitation extremes and examined the spatial relationship between flood exposure, socioeconomic vulnerability, and public-health impacts (Terassi et al. 2026). These studies establish the meteorological, hydroclimatic, and local-impact context of the disaster; the present analysis begins with observed productive losses and traces their cascading economic footprint through intersectoral and interregional linkages.

The total disaster burden extended far beyond agriculture. The joint IDB-World Bank-ECLAC DaLA assessment estimated BRL 88.9 billion in damages, losses, and additional costs across productive sectors, social sectors, infrastructure, and the environment (Suarez et al. 2024). This broader estimate is useful context for interpreting the present study because the input-output exercise intentionally models only a narrower component: monetized losses in selected agricultural and livestock production reported by Emater/RS-Ascar.

The modeled shock should therefore not be compared one-for-one with the DaLA total. Instead, it isolates a specific transmission mechanism: how a BRL 4.02 billion contraction associated with observed primary-sector production losses can trigger additional output, income, tax, and resource-use effects through Brazil's production network. This narrower design improves causal interpretation of the accounting exercise while acknowledging that infrastructure damage, household losses, business closures, service interruptions, and reconstruction expenditures fall outside the modeled shock.

3.2. Aggregate effects and network amplification

This subsection evaluates the first research question: the extent to which the event-calibrated primary-sector shock is amplified through national production linkages. Table 2 summarizes the aggregate economic, fiscal, and environmental results, while the derived amplification indicators quantify how much of the modeled contraction lies beyond the initial shock and beyond the borders of Rio Grande do Sul.

Table 2 reports national totals in million BRL at 2019 prices, nominal 2024 BRL equivalents, and 2024 USD equivalents. Environmental outcomes are retained in physical units—CO_2 emissions (t), water use (hm^3), and energy consumption (10^3 toe)—because their interpretation depends on production intensities rather than on monetary conversion.

Table 2 Aggregate economic, fiscal, and environmental effects of the modeled flood shock

	Unit.	Values
Total ΔOutput	1,000,000 BRL 2019	- 6,547.85
	1,000,000 BRL 2024 [a]	- 9,353.17
	1,000,000 USD 2024 [b]	- 1,735.28
Total ΔValue-Added	1,000,000 BRL 2019	- 3,232.11
	1,000,000 BRL 2024 [a]	- 4,616.86
	1,000,000 USD 2024 [b]	- 856.56
Total ΔWageBill	1,000,000 BRL 2019	- 700.75
	1,000,000 BRL 2024 [a]	- 1,000.97
	1,000,000 USD 2024 [b]	- 185.71
Total Δ∑Taxes	1,000,000 BRL 2019	- 238.87
	1,000,000 BRL 2024 [a]	- 341.21
	1,000,000 USD 2024 [b]	- 63.30
Total ΔICMS	1,000,000 BRL 2019	- 112.43
	1,000,000 BRL 2024 [a]	- 160.60
	1,000,000 USD 2024 [b]	- 29.80
Total ΔIPI	1,000,000 BRL 2019	- 2.58
	1,000,000 BRL 2024 [a]	- 3.69
	1,000,000 USD 2024 [b]	- 0.68
Total ΔOther Tax	1,000,000 BRL 2019	- 123.86
	1,000,000 BRL 2024 [a]	- 176.93
	1,000,000 USD 2024 [b]	- 32.82
Total Δ CO_2 Emissions	t 2019	-2,754,681.68
Total Δ Water use	hm^3 2019	-4207.88
Total Δ Energetic consumption	1000 toe 2019	-145.30

Note: a Nominal 2024 equivalents were obtained using the Brazilian GDP implicit deflator (IPEADATA 2026); b USD values use the 2024 average nominal exchange rate of BRL 5.39 per USD (World Bank 2025).

The BRL 4.02 billion initial shock generates a BRL 6.55 billion contraction in national gross output (2019 prices), equivalent to BRL 9.35 billion in nominal 2024 terms (approximately USD 1.74 billion). The implied network amplification factor is 1.63: for each BRL 1.00 represented in the modeled primary-sector shock, the Leontief system associates approximately BRL 1.63 with total national output contraction. The difference between the initial shock and total output effect is BRL 2.53 billion, meaning that 38.6% of the modeled output contraction is generated through interindustry propagation rather than contained in the initial loss vector. This is the central systemic result of the analysis.

The shock also propagates to income and fiscal bases. Value added declines by BRL 3.23 billion and the wage bill by BRL 0.70 billion (2019 prices), showing that the production-network effect is transmitted to both business income and labor remuneration. Indirect product taxes fall by BRL 238.87 million, of which ICMS accounts for BRL 112.43 million (47.1%). This matters for regional resilience policy because affected governments can face a simultaneous increase in emergency and reconstruction expenditure and a reduction in revenue generated by disrupted economic activity.

The associated changes in environmental accounts are -2.75 million t of CO_2, -4,207.88 hm^3 of water use, and -145.30 $\times 10^3$ toe of energy consumption. These values are not environmental benefits of the flood. They are the resource and emission footprint of foregone production under fixed 2019 intensities. Treating them as mitigation gains would confound lower economic activity with structural decarbonization; in practice, recovery and reconstruction may later reverse part of these reductions.

3.3. Sectoral propagation through production linkages

Table 3 Intersectoral economic effects of the flood-induced primary-sector shock (million BRL, 2019 prices)

Sectors	Δ Output	Δ Value Added	Δ Wage Bill
Agriculture, including agricultural support and post-harvest activities	- 4,058.17	- 2,388.62	- 346.86
Manufacture of organic and inorganic chemicals, resins and elastomers	- 554.13	- 84.45	- 37.64
Manufacture of pesticides, disinfectants, paints and other chemicals	- 273.01	- 50.67	- 27.62
Petroleum refining and coke production	- 260.12	- 30.70	- 4.89
Wholesale and retail trade, except motor vehicles	- 254.42	- 152.13	- 73.19
Electricity, natural gas and other utilities	- 148.11	- 57.77	- 9.07
Land transport	- 142.71	- 54.60	- 27.59
Financial intermediation, insurance and pension funds	- 122.20	- 80.16	- 29.28
Extraction of petroleum and natural gas, including support activities	- 74.04	- 33.65	- 5.32
Livestock, including livestock support activities	- 69.89	- 32.24	- 8.67
Legal, accounting, consulting activities and head offices	- 59.41	- 40.66	- 15.44
Manufacture of non-metallic mineral products	- 37.34	- 10.44	- 8.18
Other food products	- 35.46	- 6.45	- 3.73
Warehousing, support activities for transportation and postal services	- 33.83	- 18.71	- 9.82
Other administrative and support service activities	- 30.30	- 20.28	- 13.39
Trade and repair of motor vehicles and motorcycles	- 28.99	- 15.88	- 7.25
Manufacture of rubber and plastic products	- 24.41	- 5.96	- 4.45
Repair and installation of machinery and equipment	- 17.54	- 6.58	- 2.97
Other professional, scientific and technical activities	- 17.03	- 6.29	- 2.56
Forestry, fishing and aquaculture	- 15.81	- 11.72	- 1.11
Manufacture of fabricated metal products, except machinery and equipment	- 15.34	- 5.28	- 3.15
Real estate activities	- 15.24	- 13.95	- 0.19
Computer programming and other information service activities	- 14.76	- 9.64	- 4.71
Architectural and engineering activities, technical testing and analysis, and R&D	- 14.58	- 8.99	- 4.70
Mining of coal and non-metallic minerals	- 14.31	- 5.74	- 2.79
Manufacture of pulp, paper and paper products	- 13.89	- 3.89	- 1.86
Manufacture of biofuels	- 13.35	- 3.20	- 2.00
Non-ferrous metal production and metal casting	- 13.23	- 2.64	- 1.13
Production of pig iron and ferroalloys, steelmaking and seamless steel tubes	- 13.12	- 2.11	- 1.20
Non-real estate rentals and management of intellectual property assets	- 10.57	- 6.50	- 2.41
Manufacture of pharmaceutical and medicinal products	- 9.74	- 4.49	- 1.82
Manufacture of parts and accessories for motor vehicles	- 9.45	- 2.67	- 1.80
Public administration, defense and social security	- 8.97	- 6.53	- 5.56
Telecommunications	- 8.55	- 3.62	- 1.05
Manufacture of cleaning products, cosmetics, perfumes and personal care products	- 8.45	- 2.01	- 1.03
Water supply, sewerage and waste management	- 8.14	- 5.20	- 2.09
Manufacture and refining of sugar	- 7.88	- 0.96	- 1.00
Manufacture of wood products	- 7.69	- 2.77	- 1.52
Manufacture of textiles	- 7.31	- 2.16	- 1.45
Security and investigation activities	- 6.85	- 5.49	- 4.80
Manufacture of electrical equipment	- 6.56	- 1.63	- 1.10
Water transport	- 6.05	- 2.56	- 1.23
Membership organizations and other personal service activities	- 5.77	- 2.92	- 1.40
Construction	- 5.54	- 2.38	- 1.03
Television, radio, film, and sound recording/editing activities	- 5.54	- 2.16	- 1.56
Manufacture of machinery and mechanical equipment	- 5.44	- 1.63	- 1.11
Air transport	- 5.38	- 1.30	- 0.85
Slaughtering and meat products, including dairy and fish products	- 3.80	- 0.55	- 0.37
Private education	- 3.17	- 2.29	- 2.00
Food services	- 3.06	- 1.40	- 0.61
Printing and reproduction of recorded media	- 3.00	- 1.31	- 0.90
Iron ore mining, including processing and agglomeration	- 2.53	- 1.07	- 0.08
Accommodation	- 2.49	- 1.32	- 0.90
Manufacture of computer, electronic and optical products	- 2.18	- 0.33	- 0.21
Manufacture of furniture and other manufacturing industries	- 1.89	- 0.83	- 0.39
Mining of non-ferrous metallic minerals, including processing	- 1.32	- 0.47	- 0.16
Publishing and integrated publishing and printing	- 1.23	- 0.59	- 0.45
Manufacture of motor vehicles (cars, trucks and buses), except parts	- 1.19	- 0.14	- 0.12
Manufacture of beverages	- 0.90	- 0.23	- 0.10
Creative, arts and entertainment activities	- 0.85	- 0.48	- 0.27
Manufacture of wearing apparel and accessories	- 0.65	- 0.26	- 0.18
Public education	- 0.33	- 0.27	- 0.26
Manufacture of other transport equipment, except motor vehicles	- 0.33	- 0.09	- 0.08
Manufacture of leather and footwear products	- 0.19	- 0.07	- 0.05
Manufacture of tobacco products	- 0.09	- 0.02	- 0.01
Private health services	- 0.04	- 0.02	- 0.01
Public health services	- 0.02	- 0.01	- 0.01
Domestic services	0.00	0.00	0.00
Grand Total	**- 6,547.85**	**- 3,232.11**	**- 700.75**

Table 3 shows that Agriculture absorbs BRL 4.06 billion of the BRL 6.55 billion national output contraction, or approximately 62.0% of the total. Conversely, about 38.0% of the output effect occurs in sectors other than the directly dominant agricultural activity. This distribution is important because it demonstrates that the flood is not only an agricultural loss event: a substantial share of its modeled footprint is transmitted to input suppliers and service providers.

The largest non-agricultural output effects occur in organic and inorganic chemicals (BRL 554.13 million), pesticides and other chemicals (BRL 273.01 million), petroleum refining (BRL 260.12 million), wholesale and retail trade (BRL 254.42 million), and utilities (BRL 148.11 million). Together, these five sectors account for roughly 22.8% of the total national output contraction. The concentration of losses in chemicals, fuels, and utilities reveals a dependency channel in which modern agricultural production transmits shocks upstream through reduced demand for energy- and input-intensive intermediate goods.

Commercialization and logistics form a second transmission channel. Land transport contracts by BRL 142.71 million, while wholesale and retail trade and financial services also record sizeable declines. These results are consistent with the disruption of movement, storage, market access, and working-capital flows that accompanies major floods. From a resilience perspective, the sectoral pattern implies that risk-reduction measures confined to farms would leave important systemic vulnerabilities untreated.

The sectoral evidence therefore identifies concrete resilience leverage points. Redundancy and flood-proofing in roads, bridges, storage, electricity, and fuel supply can protect multiple downstream and upstream sectors at once; geographically diversified sourcing of fertilizers and other critical inputs can reduce dependence on a single disrupted corridor; and continuity plans for transport, wholesale, finance, and energy services can shorten the period during which a primary production shock cascades through the economy. The model does not estimate the benefits of these interventions directly, but it identifies where such benefits are most likely to propagate.

3.4. Environmental footprint: production contraction is not mitigation

Table 4 Sectoral environmental footprint of the modeled output contraction (ΔCO_2 in t, ΔWater in hm^3, and ΔEnergy in 10^3 toe; 2019 intensities)

Sectors	Δ CO_2	Δ Water	Δ Energy
Agriculture, including agricultural support and post-harvest activities	-2,378,186.84	-4,184.47	-83.15
Livestock, including livestock support activities	-171,475.39	-10.63	-1.43
Land transport	-59,899.29	-0.01	-26.73
Electricity, natural gas and other utilities	-40,679.13	-0.04	-3.56
Manufacture of organic and inorganic chemicals, resins and elastomers	-28,509.48	-0.29	-6.85
Forestry, fishing and aquaculture	-27,328.10	-11.69	-0.32
Petroleum refining and coke production	-15,918.19	-0.07	-6.26
Manufacture of non-metallic mineral products	-11,660.82	-0.02	-3.33
Water supply, sewerage and waste management	-8,661.34	-0.26	-0.02
Extraction of petroleum and natural gas, including support activities	-3,206.68	-0.00	-1.78
Production of pig iron and ferroalloys, steelmaking and seamless steel tubes	-2,772.78	-0.01	-1.56
Air transport	-1,462.18	-0.00	-0.37
Manufacture of pesticides, disinfectants, paints and other chemicals	-1,425.20	-0.14	-3.38
Mining of coal and non-metallic minerals	-806.52	-0.03	-0.34
Non-ferrous metal production and metal casting	-725.40	-0.01	-0.32
Other food products	-487.21	-0.02	-0.86
Manufacture of pulp, paper and paper products	-444.80	-0.01	-1.35
Water transport	-266.53	-0.00	-0.29
Manufacture and refining of sugar	-172.65	-0.03	-0.19
Wholesale and retail trade, except motor vehicles	-121.37	-0.01	-0.44
Iron ore mining, including processing and agglomeration	-115.77	-0.00	-0.05
Manufacture of textiles	-87.31	-0.01	-0.11
Mining of non-ferrous metallic minerals, including processing	-41.51	-0.00	-0.03
Manufacture of cleaning products, cosmetics, perfumes and personal care products	-36.36	-0.00	-0.10
Slaughtering and meat products, including dairy and fish products	-34.11	-0.00	-0.09
Manufacture of rubber and plastic products	-19.33	-0.01	-0.30
Manufacture of pharmaceutical and medicinal products	-18.47	-0.01	-0.12
Trade and repair of motor vehicles and motorcycles	-13.77	-0.00	-0.05
Other administrative and support service activities	-13.11	-0.00	-0.05
Warehousing, support activities for transportation and postal services	-12.99	-0.00	-0.06
Manufacture of beverages	-10.73	-0.00	-0.02
Manufacture of biofuels	-9.47	-0.05	-0.32
Financial intermediation, insurance and pension funds	-9.37	-0.00	-0.21
Legal, accounting, consulting activities and head offices	-7.26	-0.00	-0.10
Manufacture of fabricated metal products, except machinery and equipment	-5.32	-0.01	-0.37
Manufacture of parts and accessories for motor vehicles	-4.85	-0.00	-0.04
Manufacture of wood products	-4.69	-0.00	-0.03
Manufacture of electrical equipment	-3.09	-0.00	-0.03
Repair and installation of machinery and equipment	-2.65	-0.01	-0.08
Non-real estate rentals and management of intellectual property assets	-2.58	-0.00	-0.02
Architectural and engineering activities, technical testing and analysis, and R&D	-2.35	-0.00	-0.03
Accommodation	-2.02	-0.00	-0.00
Membership organizations and other personal service activities	-1.95	-0.00	-0.01
Public administration, defense and social security	-1.54	-0.00	-0.02
Telecommunications	-1.44	-0.00	-0.01
Manufacture of machinery and mechanical equipment	-1.17	-0.00	-0.02
Construction	-1.16	-0.00	-0.02
Computer programming and other information service activities	-1.13	-0.00	-0.03
Security and investigation activities	-1.00	-0.00	-0.01
Private education	-0.91	-0.00	-0.01
Other professional, scientific and technical activities	-0.77	-0.00	-0.03
Television, radio, film, and sound recording/editing activities	-0.76	-0.00	-0.01
Food services	-0.56	-0.00	-0.01
Printing and reproduction of recorded media	-0.54	-0.00	-0.29
Creative, arts and entertainment activities	-0.37	-0.00	-0.00
Manufacture of furniture and other manufacturing industries	-0.35	-0.00	-0.01
Manufacture of motor vehicles (cars, trucks and buses), except parts	-0.23	-0.00	-0.01
Real estate activities	-0.21	-0.00	-0.03
Manufacture of computer, electronic and optical products	-0.19	-0.00	-0.01
Publishing and integrated publishing and printing	-0.16	-0.00	-0.00
Manufacture of wearing apparel and accessories	-0.08	-0.00	-0.00
Manufacture of other transport equipment, except motor vehicles	-0.06	-0.00	-0.00
Manufacture of leather and footwear products	-0.04	-0.00	-0.00
Public education	-0.04	-0.00	-0.00
Manufacture of tobacco products	-0.01	-0.00	-0.00
Private health services	-0.00	-0.00	-0.00
Public health services	-0.00	-0.00	-0.00
Domestic services	–	–	–
Grand Total	**-2,754,681.68**	**-4,207.88**	**-145.30**

Table 4 confirms that the environmental effects are highly concentrated in the sectors whose output contracts most strongly. At the national level, the model associates the shock with reductions of 2.75 million t of CO_2, 4,207.88 hm^3 of water use, and 145.30 $\times 10^3$ toe of energy consumption. Because the satellite coefficients are fixed, these changes describe foregone environmental pressures embedded in foregone production rather than changes in production efficiency or technology.

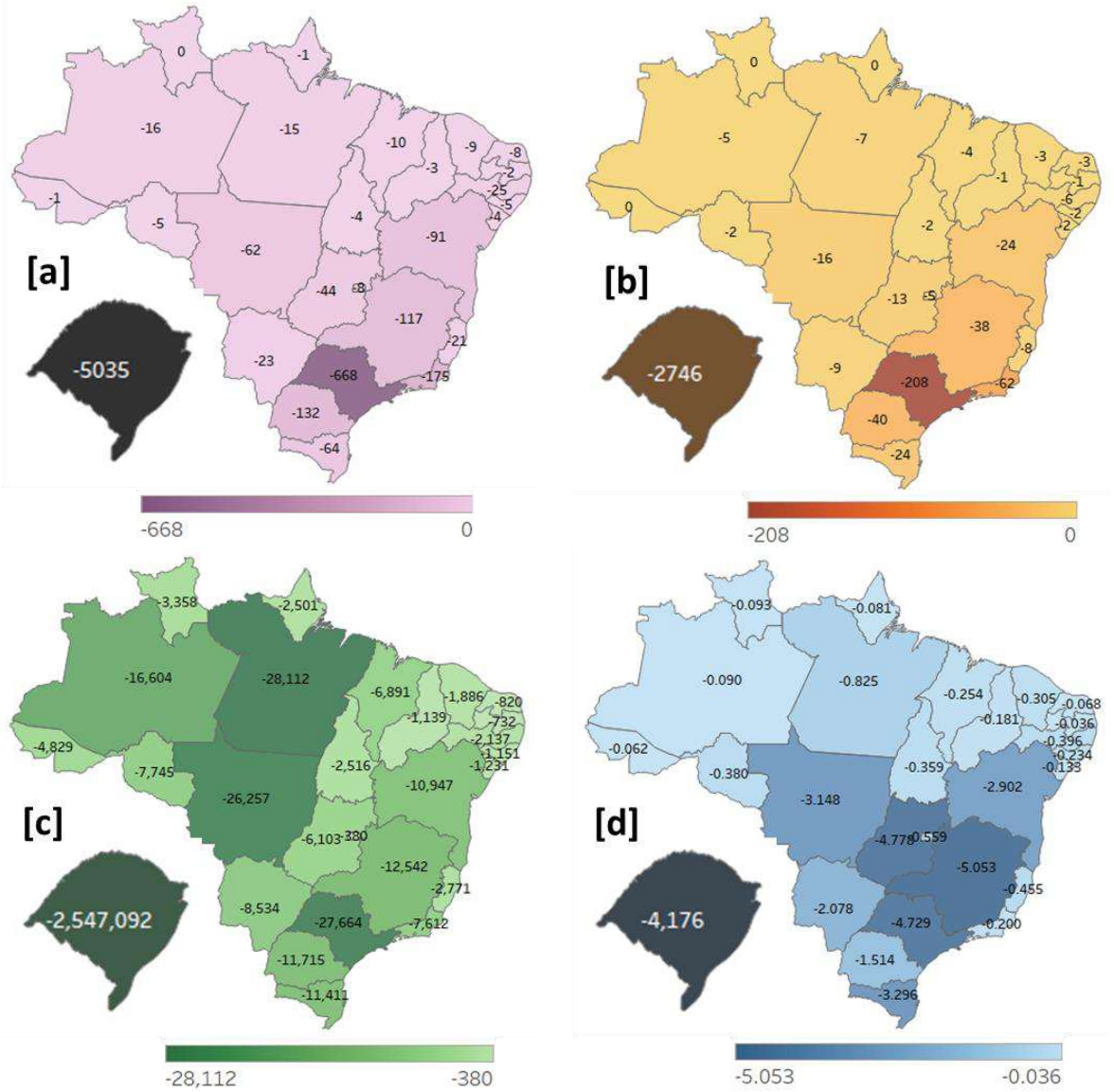
Agriculture alone accounts for approximately 86.3% of the modeled CO_2 reduction, 99.4% of the water-use reduction, and 57.2% of the energy-use reduction. This concentration reflects the resource intensity of the affected production structure and the dominant scale of the agricultural output shock. It also shows why environmental accounts should be interpreted jointly with welfare and production outcomes: a fall in resource use caused by disaster-related production losses is qualitatively different from a resilience or mitigation strategy that lowers environmental intensity while maintaining productive capacity.

Livestock, land transport, utilities, chemicals, petroleum refining, and selected heavy industries account for much of the remaining emissions and energy effect. The pattern mirrors the same production-chain dependencies identified in the economic results: when agricultural activity contracts, fossil-energy use, transport services, electricity demand, and chemical-input production also decline. These linked environmental effects provide an additional map of where recovery can restore economic activity and environmental pressures simultaneously.

Accordingly, the environmental results have two policy implications. First, temporary disaster-induced emission reductions should not be counted as evidence of mitigation progress. Second, reconstruction provides an opportunity to avoid simply restoring the pre-disaster resource intensity of damaged systems. Resilient infrastructure, energy-efficient rebuilding, lower-carbon logistics, and improved water management could convert recovery expenditure into resilience-mitigation synergies, but those gains require technological or structural change that is outside the present static model.

3.5. Interregional spillovers and spatial exposure

Fig. 1 Interstate distribution of modeled effects: (a) ΔOutput, (b) ΔValue Added, (c) ΔCO_2, and (d) ΔWater, Brazil



Note: Monetary panels are in million BRL (2019 prices); CO_2 is in t (2019 intensity coefficients); water is in hm^3 (2019 intensity coefficients).

Figure 1 shows that Rio Grande do Sul remains the dominant locus of the modeled losses, with BRL 5.03 billion in output contraction and BRL 2.75 billion in value-added contraction. However, comparing these state values with the national totals reveals an important cross-border effect: approximately BRL 1.51 billion of output loss occurs outside RS, equivalent to 23.1% of the national output contraction, while about BRL 486 million of value-added loss occurs outside RS, or 15.0% of the national total. The disaster footprint is therefore national even though the physical flood is subnational.

The largest non-RS economic effects are concentrated in highly connected states in the South and Southeast, particularly São Paulo, Rio de Janeiro, Paraná, and Santa Catarina. This pattern is economically intuitive: these states host important industrial suppliers, logistics hubs, wholesale markets, and service activities linked to RS production. Rather than geographic proximity alone, the results point to production-network centrality as a mechanism through which climate shocks are transmitted across territorial boundaries (Acemoglu et al. 2012; Carvalho 2014; Willner et al. 2018).

This interregional result has a direct regional-policy implication. Investments that reduce disruption in RS can generate benefits outside the state by protecting supplier and customer relationships elsewhere in Brazil. In a federal system, such cross-jurisdiction spillovers create a rationale for coordinated and partly co-financed resilience policies, because the jurisdiction paying for stronger transport, storage, drainage, energy, or agricultural risk-management systems may not capture the full national benefit of avoided disruption. The same logic applies to emergency finance and intergovernmental transfers: stabilizing activity in the affected state can help contain secondary losses in connected regions.

4. DISCUSSION

The results extend existing analyses of the 2024 Rio Grande do Sul floods by adding a production-network dimension to the hazard, exposure, and impact evidence already available. Previous studies have characterized atmospheric conditions and near-real-time rainfall monitoring (Gouveia et al. 2026) and examined hydroclimatic extremes together with socioeconomic vulnerability and public-health impacts (Terassi et al. 2026). The present study begins from itemized, observed primary-sector losses and asks how those losses travel through a 27-state, 68-sector production network. By integrating value added, wages, taxes, CO_2, water, and energy, the analysis converts an event-specific shock into a transparent map of cascading economic, fiscal, and environmental dependencies relevant to regional resilience policy and regional resilience.

The network amplification factor of 1.63 makes the production-network mechanism explicit. Approximately 38.6% of the modeled national output contraction lies beyond the initial loss vector, and the largest non-agricultural effects occur in chemicals, fuels, trade, utilities, and transport. This finding is consistent with theory showing that input specificity and limited short-run substitution can transmit localized shocks through production networks (Baqaee and Farhi 2019; Barrot and Sauvagnat 2016). For regional resilience, the important implication is that resilience cannot be evaluated only at the farm or municipality where the physical hazard occurs. Critical intermediate inputs, storage, energy, and logistics are part of the same risk system.

The territorial results reinforce this systemic interpretation. Nearly one quarter of the modeled output contraction occurs outside Rio Grande do Sul. This creates an interregional resilience externality: measures that reduce disruption in the affected state can protect production and income in other states as well. That result strengthens the case for federal coordination of resilience investments and disaster response, especially for infrastructure and supply chains whose economic function crosses state boundaries. It also complements the broader 'disaster footprint' literature, in which local hazards generate remote economic consequences through trade and production linkages (Quante et al. 2024; Sun et al. 2024; Willner et al. 2018).

The fiscal and labor-income effects add a second policy channel. The modeled reduction of BRL 700.75 million in wages and BRL 238.87 million in indirect product taxes means that a disaster can weaken household income and public revenue while simultaneously increasing demand for emergency relief, infrastructure repair, and social protection. The ICMS component is particularly relevant in the Brazilian federal context because it links productive disruption to state fiscal capacity. Pre-arranged disaster finance, contingent credit, emergency transfer rules, and insurance mechanisms can therefore be interpreted not only as post-disaster funding tools but also as mechanisms for preventing temporary production shocks from becoming prolonged fiscal and social crises (Hallegatte et al. 2018; World Bank 2019).

The environmental satellite accounts require a different interpretation. The modeled reductions in emissions, water use, and energy consumption are a consequence of reduced

activity and should not be presented as mitigation co-benefits. This distinction is important for hazard and disaster research because disasters can temporarily lower measured environmental pressures while simultaneously reducing welfare, employment, food availability, and productive capacity. True mitigation gains would require a reduction in environmental intensity through changes in technology, energy sources, infrastructure, or production organization; those mechanisms are not represented by the fixed-coefficient satellite accounts used here.

The magnitude of the present results should also be read in relation to the much broader DaLA estimate for the 2024 disaster. Suarez et al. (2024) estimated BRL 88.9 billion in total effects across multiple sectors and dimensions, whereas the present model begins with BRL 4.02 billion in selected primary-sector production losses and estimates a BRL 9.35 billion nominal-2024 output contraction. The difference is not a contradiction: the two exercises measure different objects. DaLA captures damages, losses, and additional costs across the disaster economy, while the IRIO model isolates the production-network footprint generated by a specific observed shock. Making this distinction explicit prevents the model result from being misinterpreted as a total economic cost of the floods.

For public and private regional resilience policy, the sectoral pattern suggests a portfolio rather than a single intervention. Public priorities include flood-resilient transport and drainage, protection and redundancy of electricity and water services, stronger storage systems, early warning, and agricultural risk-management instruments. Private priorities include supplier diversification, inventory buffers for critical inputs, business-continuity planning, flood-proof facilities, and stress testing of logistics and working-capital exposure. Because the model identifies where economic dependence is concentrated, it can support the targeting of detailed cost-benefit studies that estimate the avoided-loss value of specific resilience measures.

Several limitations define the appropriate interpretation of the findings. The model is static and calibrated to 2019 technology and trade patterns; it does not capture price changes, inventories, capacity constraints, import or supplier substitution, firm closures, reconstruction demand, or dynamic recovery. The event is represented as a demand-equivalent shock even though the physical disaster also created supply constraints, so the model should be viewed as a transparent first-round accounting approximation rather than a structural forecast. The shock includes only primary-sector items that could be monetized defensibly and therefore excludes important infrastructure, household, commercial, and service-sector damages. In addition, uncertainty in physical-loss estimates and producer-price conversions is not propagated through formal sensitivity intervals. Future work should combine dynamic IO or IO-CGE approaches with alternative shock specifications, uncertainty analysis, freight and firm-level data, and explicit resilience scenarios to estimate avoided losses rather than only exposure.

5. CONCLUSION

This study shows how event-specific primary-sector losses from the 2024 Rio Grande do Sul floods propagate through Brazil's interregional production network. A BRL 4.02 billion modeled shock is associated with BRL 6.55 billion in national output contraction at 2019 prices, corresponding to a network amplification factor of 1.63. About 38.6% of the total output effect arises beyond the initial shock, and 23.1% occurs outside the directly affected state. These results summarize the paper's central regional-science contribution: a geographically concentrated disruption can generate a materially larger and spatially broader economic footprint through production dependencies.

The sectoral and fiscal results identify regional-resilience priorities that are more specific than a generic call for greater preparedness. Chemicals and agricultural inputs, fuels, utilities, trade, and transport are major transmission channels; wage and tax losses create additional social and fiscal exposure; and interstate spillovers imply that the benefits of

resilience investments extend beyond Rio Grande do Sul. Flood-resilient logistics and storage, continuity of critical utilities and inputs, supplier diversification, agricultural risk management, and coordinated intergovernmental finance should therefore be viewed as components of a regional resilience strategy.

The model remains a static, fixed-coefficient stress test and does not represent substitution, price responses, reconstruction, or the full set of disaster damages. The environmental reductions are temporary footprints of lower activity rather than mitigation outcomes. Within those boundaries, the analysis provides a transparent baseline for evaluating how localized production shocks propagate across a federated and agriculturally specialized economy. Future research can extend this baseline with alternative shock and recovery scenarios and explicit estimates of the economy-wide losses avoided by regional resilience investments.

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