Integrated Modeling of Policy Changes: The Case of Foot-and-Mouth Disease Vaccination in Brazil

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Abstract

This study evaluates the economic impact of Brazil's phased suspension of foot-and-mouth disease (FMD) vaccination. We focus on the May 2021 certification by the World Organisation for Animal Health (WOAH), which recognized four early-adopting states as FMD-free without vaccination, and assess its effects on domestic beef and pork production and export unit values. Using a panel of monthly, state-level data from 2017 to 2024, we estimate treatment effects via a two-way fixed effects difference-in-differences model, supplemented by synthetic control and placebo tests. The estimated shocks are then introduced into the GTAP computable general equilibrium model, version 11, updated to 2024 and reaggregated to 12 sectors and 20 regions, to simulate potential global responses in beef and pork prices, bilateral trade flows, and welfare. Our findings offer insights for animal health policy and trade strategy, particularly for export-oriented emerging economies.

Keywords: Foot-and-mouth disease vaccination; Difference-in-differences; Computable general equilibrium; Brazil livestock policy.

JEL Codes: Q17; Q18; C54

1. Introduction

Foot-and-mouth disease (FMD) is an acute, highly contagious viral disease of cloven-hoofed animals, including cattle, swine, sheep and goats, that can spread rapidly within and between herds, leading to severe production losses and widespread trade disruptions (Knight-Jones, McLaws, and Rushton, 2016). Although many regions have achieved FMD-free status, outbreaks have reemerged in several long-standing FMD-free countries. In 2025, for example, Germany, Hungary, and Slovakia reported outbreaks, underscoring the persistent global threat posed by the virus (European Commission, 2025). Beyond the immediate consequences of an outbreak, countries that employ vaccination as a control measure may also suffer trade restrictions: some high-value markets, such as the United States, Mexico, Japan, South Korea, and Taiwan, prohibit imports of meat from nations that vaccinate against FMD, even if they are officially recognized as FMD-free. As a result, FMD-free countries with vaccination programs face more stringent market access constraints compared to those that have maintained freedom from the disease without vaccination (Schroeder et al., 2015; Bradhurst et al., 2019).

The World Organization for Animal Health (WOAH) holds the official mandate from the World Trade Organization (WTO) to recognize countries or zones as free from specific animal diseases for the purposes of international trade. This authority, granted under the framework of the WTO's Sanitary and Phytosanitary (SPS) Agreement, highlights the critical role that internationally recognized animal health status plays in facilitating or restricting market access (WOAH, 2025). In this context, Brazil initiated a national effort in 2017 through the launch of the Strategic Plan of the National Program for the Eradication and Prevention of FMD 2017-2026, aiming to phase out the use of FMD vaccination across the country and secure recognition as FMD-free without vaccination by 2026 (Brazilian Ministry of Agriculture and Livestock – MAPA, 2022). Four Brazilian states (Acre, Rondônia, Paraná, and Rio Grande do Sul) achieved WOAH recognition as FMD-free without vaccination in May 2021 (MAPA, 2021). Brazil as a whole attained this status more recently, in May 2025 (MAPA, 2025).

The strategic rationale for pursuing official recognition as free from FMD without vaccination is rooted in the economic and trade advantages this status offers. Internationally, FMD-free without vaccination status signals a higher level of animal health security and product quality to importing countries, often serving as a proxy for strong veterinary governance and advanced biosecurity infrastructure. In the case of Brazil, both national authorities and livestock producers anticipate that the suspension of routine FMD vaccination will yield multiple benefits: reduced costs for both producers and government agencies, enhanced international perception of Brazil's animal health system, improved reputation for Brazilian meat quality, and expanded access to premium markets, including the United States, Japan, and South Korea, as well as other high-value Asian destinations (Brazilian Agriculture and Livestock Confederation – CNA, 2025).

From a production perspective, eliminating FMD vaccination protocols reduces the physical and physiological stress associated with animal restraint and vaccine administration, leading to

measurable improvements in zootechnical performance indicators such as average daily gain and final slaughter weight (França Filho et al., 2006; Lorençato, Santos, and Dias, 2018; Lima et al., 2024). Moreover, the removal of vaccination reduces the occurrence of injection-site lesions and related injuries, which helps maintain carcass integrity and improves overall meat quality. This reduction in defects at the slaughter stage decreases the need for carcass trimming and lowers the volume of downgraded or discarded meat cuts, thereby enhancing processing efficiency and product yield (Pfeiffer et al., 2018; Titto and Brandi, 2023; Borders et al., 2025).

This study evaluates the economic implications of suspending FMD vaccination in Brazil's cattle sector, with a primary focus on effects related to beef production and the export unit value of both beef and pork. We focus on WOAH's recognition of four Brazilian states (Acre, Rondônia, Paraná, and Rio Grande do Sul) as FMD-free without vaccination in May 2021. This policy change offers a unique opportunity for early evaluation, as the remaining Brazilian states only suspended vaccination later and achieved official WOAH recognition in May 2025. Due to data limitations, the impacts of the broader national suspension cannot yet be fully assessed yet.

Using a difference-in-differences (DID) framework, we estimate the effects of the certification on gross domestic product (GDP), international beef and pork trade flows, and welfare outcomes in Brazil and key actors in the global meat market. To our knowledge, this is the first application of a DID approach to assess an FMD-related policy in Brazil, and the first empirical study examining the economic impacts of suspending FMD vaccination. This research is methodologically novel in its integration of reduced-form econometric analysis with a global computable general equilibrium (CGE) model. This dual-method framework enables a comprehensive assessment of both localized effects, such as changes in production and export unit values, and broader systemic responses through international trade and welfare channels. By combining empirical and structural modeling techniques, the study fills a critical gap in the literature on the economic consequences of animal health policy reforms. More broadly, we offer a new perspective on how strategic disease control decisions can shape both domestic economic performance and global trade dynamics.

The findings of this study have significant implications for policymakers, producers, and international trade negotiators. As countries around the world seek to balance disease prevention with access to premium markets, Brazil's phased suspension of FMD vaccination offers a timely and policy-relevant case for understanding the trade-offs involved. By quantifying the economic impacts of this shift, both domestically and internationally, this research informs future animal health strategies and trade policy design, particularly for emerging and export-oriented economies. Moreover, the integrated modeling approach developed here provides a scalable framework for evaluating other sanitary policy transitions that affect agricultural production and market access. In doing so, this study contributes not only to the animal health economics literature but also to broader discussions about the intersection of veterinary governance, international trade, and rural development.

2. Background

Brazil's national animal health infrastructure emerged from the country's long-standing efforts to control FMD, which date back to the 1950s (Lyra and Silva, 2004). Early recognition of the need for coordinated regional action led to the establishment of multilateral institutions, such as the Pan American Center for FMD in 1951 and the South American Commission for the Fight Against FMD in 1972. In 1987, the first Hemispheric Plan for the Eradication of FMD in South America was approved, providing a continent-wide framework for disease control. Brazil formalized its domestic commitment with the launch of the National Program for the Prevention and Eradication of FMD (PNEFA) in 1992. PNEFA was built around key principles including regionalization of animal health actions (through the creation of livestock circuits), strong collaboration with the private sector, and large-scale, systematic vaccination campaigns (MAPA, 2018).

The last recorded outbreak of FMD in Brazil occurred in the state of Mato Grosso do Sul in 2006. The state of Santa Catarina became the first zone in the country to be officially recognized by WOAH as FMD-free without vaccination in 2007. By 2018, Brazil had achieved FMD-free status with vaccination for its entire national territory. As part of the country's long-term goal of transitioning to a vaccination-free status, the Brazilian Ministry of Agriculture and Livestock (MAPA) launched the Strategic Plan of PNEFA 2017-2026, which outlined the steps required to achieve WOAH recognition as FMD-free without vaccination nationwide by 2026 (MAPA, 2019).

Implementation of vaccination suspension began in 2019 and proceeded through a phased grouping of states. The first group, designated Group I, included six zones across five federative units: Paraná, Rio Grande do Sul, Acre, Rondônia, and specific portions of the states of Amazonas and Mato Grosso. These areas suspended vaccination between 2019 and 2020 and were officially recognized by WOAH as FMD-free without vaccination in May 2021 (MAPA, 2021). The remaining 22 Brazilian federative units (21 states plus the Federal District) followed in subsequent phases, with all receiving international recognition as FMD-free without vaccination in May 2025.

The grouping of states for vaccination suspension was determined by MAPA based primarily on geographic and logistical considerations. Once a region is recognized as FMD-free without vaccination, it is not permitted to receive vaccinated animals from other zones, to prevent contamination or false seropositive results. For this reason, the first group originally included only Acre and Rondônia, two relatively isolated states. However, parts of neighboring states were also included due to the movement of animals across borders. Specifically, 14 municipalities in southern Amazonas (Apuí, Boca do Acre, Canutama, Eirunepé, Envira, Guajará, Humaitá, Itamarati, Ipixuna, Lábrea, Manicoré, Novo Aripuanã, Pauini, and part of Tapauá) and 5 municipalities in western Mato Grosso (Aripuanã, Colniza, Comodoro, Juína, and Rondolândia) were added to Group I. These municipalities maintain commercial livestock flows to slaughterhouses in Rondônia, and without suspending vaccination, they would have been excluded from these value chains. Despite their inclusion, the relative size of the cattle herd in these

municipalities is minimal compared to the overall herds of their respective states and of the other members of Group I.

Importantly, the states of Paraná and Rio Grande do Sul were not initially included in Group I. Under the original plan, they belonged to Group V, the final group scheduled to suspend vaccination. However, both states opted to accelerate their transition after undergoing technical evaluations by MAPA and state-level veterinary authorities. Paraná and Rio Grande do Sul invested in the necessary institutional upgrades, including risk analysis, infrastructure improvements, and expanded surveillance personnel, to meet MAPA and WOAH requirements ahead of schedule.

In the case of Rio Grande do Sul, the decision was partly driven by geographic constraints. The state shares a border only with Santa Catarina, which had already suspended FMD vaccination in the 2000s. As a result, Rio Grande do Sul was unable to send animals to Santa Catarina and could only trade with other Brazilian states via sanitary corridors that passed through Santa Catarina, making transport more logistically complex and costly. Paraná's motivations were tied more closely to trade incentives. As one of Brazil's leading pork-producing and -exporting states, Paraná had long pursued FMD-free without vaccination status. Although swine were not vaccinated against FMD, their susceptibility to the disease meant that international pork trade was still restricted based on the state's FMD status. Consequently, both Paraná and Rio Grande do Sul took independent steps to join the first group to suspend vaccination.

With these changes, Group I in the revised 2022 Strategic Plan came to include Acre, Rondônia, Paraná, Rio Grande do Sul, and the aforementioned municipalities in Amazonas and Mato Grosso (MAPA, 2022). The remaining three groups completed vaccination suspension between 2021 and 2024, culminating in WOAH certification for the rest of the country in May 2025. The comparison between the original and revised grouping of states is presented in **Figure 1**.

Parallel to its successful FMD control efforts, Brazil has ascended to a leading role in global animal protein markets. Since the early 2000s, sustained growth in beef, poultry, and pork production has been driven by a combination of land expansion, productivity improvements, technological diffusion, and supportive policies (Martha Jr., Alves, and Contini, 2012; Pereira et al., 2012; Arias et al., 2017; Mores et al., 2022; Pereira et al., 2024). Sustained public investment in veterinary services and sanitary control programs, particularly those targeting FMD, played a critical role in opening export channels (Florindo, Medeiros, and Mauad, 2015; OECD, 2015; Salvarani et al., 2025).

Currently, Brazil ranks as the world's top beef exporter and among the six largest pork exporters, accounting for approximately 15% of global beef output and exports in 2024. Brazilian pork exports have also grown steadily, especially into Asian markets such as China, the Philippines, and Vietnam (FAO, 2025; UN Comtrade, 2025). As importing countries tighten SPS requirements, Brazil has shifted its strategy from maximizing volume to securing higher-value markets that demand stricter animal-health certification. Achieving the status of FMD-free without vaccination

not only removes vaccination-related costs and enhances animal performance and meat quality but can also potentially unlock access to premium destinations. Given that approximately one-quarter of Brazilian beef and an increasing share of pork production are exported, even marginal gains in market access or product value translate into substantial economic benefits across the agribusiness supply chain. However, while sanitary certification is a necessary condition for entry into these markets, political negotiations and broader trade strategies remain critical determinants of actual market opening and share gains.

The combination of historical veterinary policy, rapid agribusiness growth, and evolving trade requirements places Brazil at the center of a critical global policy discussion: how do improvements in animal health governance affect economic outcomes in a globally integrated food system? The present study builds on this context to empirically assess the economic implications of suspending FMD vaccination, providing evidence to inform both domestic policymaking and international trade discussions.

3. Empirical Approach

3.1 Data

Our empirical analysis relies on a panel of monthly, state-level observations for January 2017 through December 2024. We draw production and economic indicators from the Brazilian Institute of Geography and Statistics (IBGE, 2025), cattle and hog price series from the Center for Advanced Research in Advanced Economics (Cepea, 2025), and export quantities and revenue from Comex Stat (Brazilian Ministry of Development, Industry and Foreign Trade – MDIC, 2025). All monetary values are adjusted to 2024 BRL using the real exchange rate (from USD to BRL) and the Brazilian General Market Price Index (Ipeadata, 2025a, 2025b).

3.2 Difference-in-Differences Specification

We assess the May 2021 WOAH certification of Brazil's Group I states (Acre, Rondônia, Paraná, and Rio Grande do Sul) as FMD-free without vaccination with a two-way fixed effects (TWFE) approach. Control states comprise beef and pork producers not included in Group I (Bahia, Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Pará, São Paulo, and Tocantins). Our baseline specification is:

$$\ln Y_{it} = \alpha + \beta(Post_t \times Treat_i) + \boldsymbol{X_{it}'\theta} + \lambda_i + \nu_t + \epsilon_{it}$$

where: $\ln Y_{it}$ denotes the log of beef/pork production and export unit value in state i at time t; α is the intercept; $Post_t$ equals 1 for $t \geq June\ 2021$ and 0 otherwise; $Treat_i$ equals 1 for Group I states and 0 otherwise. The vector X_{it} includes time-varying covariates. Fixed effects λ_i and ν_t absorb all time-invariant state characteristics and common monthly shocks, respectively; and ϵ_{it}

is the error term. The coefficient beta thus measures the average proportional change in outcome attributable to certification. Standard errors are clustered at the state level and complemented by a two-way wild-cluster bootstrap (Cameron, Gelbach, and Miller, 2008).

Identification requires three conditions: (i) parallel trends, tested via event-study lead and lags; (ii) no spillovers, so that certification in treated states does not mechanically alter control-state outcomes; and (iii) stable unit treatment value, ensuring treatment uniformity with no anticipatory or heterogeneous implementation (Wooldridge, 2021). We formally assess (i) by estimating the event-study version of our model following Sun and Abraham (2021), which allows for heterogeneous dynamic effects and a test of pre-treatment trend equality.

3.2.1 Robustness Checks

To reinforce causal credibility, we conduct two additional exercises. First, we construct a counterfactual Group I using the synthetic control method (Abadie, Diamond, and Hainmueller, 2010). By optimally weighting control states on pre-certification trajectories of production, exports, and covariates, we estimate the aggregate impact of certification on Group I's outcomes. Divergence between the treated aggregate and its synthetic counterpart after June 2021 provides a complementary estimate to our TWFE results.

Second, we re-estimate the TWFE model with placebo certification dates (e.g., June 2019 and June 2020) to verify that significant treatment effects arise only at the true policy date. Then, we test for effects on "untreated" outcomes that should remain unaffected by FMD-free certification. Insignificant estimates in these falsification checks bolster our claim that observed effects on beef and pork outcomes stem from certification rather than spurious shocks.

4. Structural Approach

While the DID framework effectively identifies the localized, empirical impacts of Brazil's recognition as free of FMD without vaccination, it does not capture the broader general equilibrium effects that arise from potential trade reallocation, production shifts, and global price adjustments. To account for these systemic feedbacks, we complement our quasi-experimental approach with a global computable general equilibrium (CGE) model. This integrated modeling strategy links micro-level policy impacts observed through DID with macro-level responses in global markets, enabling a more comprehensive, policy-relevant analysis of Brazil's transition away from FMD vaccination.

By combining DID and CGE approaches, we quantify both the direct domestic consequences of policy change and the potential indirect international spillovers. This dual-method framework provides a richer understanding of how improvements in animal health status can enhance export competitiveness, reshape trade patterns, and influence global welfare. The integrated approach is

particularly relevant in the context of agri-food trade, where sanitary status plays a critical role in market access.

4.1 Computable General Equilibrium Model

To simulate the global economic effects of Brazil's improved FMD status, we employ the Global Trade Analysis Project (GTAP) model, a widely-used, multi-region, multi-sector CGE framework designed to evaluate international trade policy, economic integration, and structural changes in the global economy (Hertel, 1997). The GTAP model is particularly well-suited for this application as it captures the complex interdependencies among countries and sectors through bilateral trade linkages, input-output relationships, and factor market interactions.

The CGE model incorporates the empirically estimated production and export shocks, derived from the DID analysis, as exogenous inputs. These shocks are imposed on the Brazilian beef and pork sectors to evaluate how such changes could potentially propagate through the global economic system. The model captures general equilibrium effects such as: price adjustments across meat markets; reallocation of trade flows due to shifts in comparative advantage; and changes in regional welfare, measured using equivalent variation.

The GTAP framework assumes perfectly competitive markets and constant returns to scale, with consumers modeled using a regional representative agent who maximizes utility subject to a budget constraint. The production system follows a nested structure allowing substitution among intermediate inputs and primary factors. These features allow for a robust simulation of both direct effects and economy-wide spillovers from domestic policy changes in Brazil.

4.2 Data

We use the GTAP database version 11, which originally represents 65 sectors and 160 regions, considering 2017 as base year (Aguiar et al., 2022). We update the database to 2024 using the GTAPAdjust tool (Horridge, 2011), using production data from FAOStat, international trade data from UN Comtrade, and GDP and population data from the World Bank. Additionally, we disaggregate the hog and pork sectors from the original database sectors for other animal products and other meat products, respectively, resulting in a 67-sector database. These 67 sectors are then aggregated into 12 sectors including: feed, other agricultural products, cattle, hogs, poultry and other animals, beef, pork, poultry and other meat, other processed foods, other primary products, manufacturing, and services. We also aggregate the original 160 regions into 20 strategic areas that capture the major beef and pork exporters and importers, comprising of: Brazil; Argentina; Uruguay; Chile; Paraguay; Mexico; U.S.; Canada; Australia; New Zealand; China and Hong Kong; Japan and South Korea; Russia; India; Western Europe; Middle East and North Africa (MENA);

Association of Southeast Asian Nations (ASEAN); Rest of Latin America; Rest of Europe; and Rest of the World.

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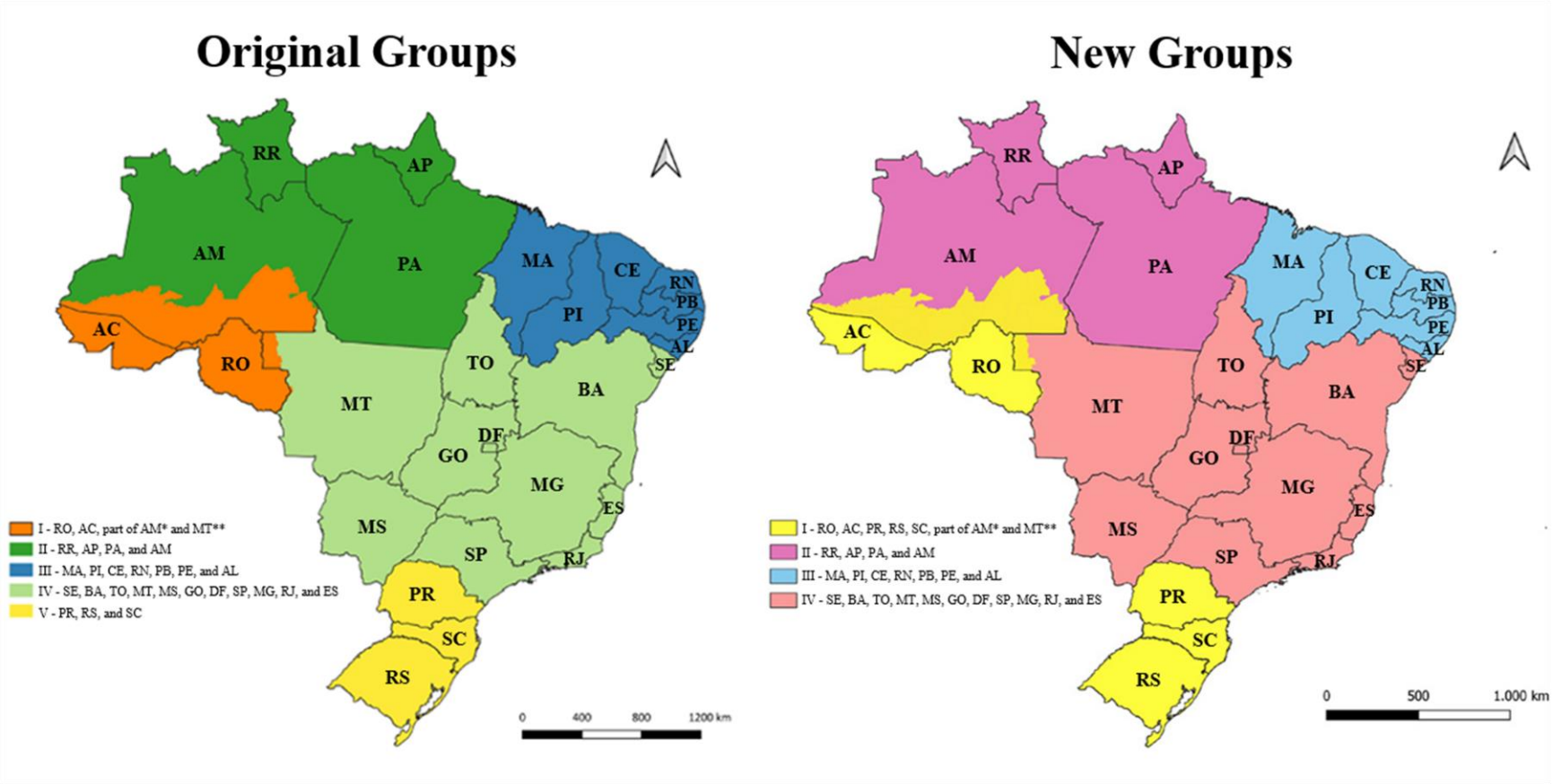

Figure 1. Regional Grouping of Brazilian States According to FMD Vaccination Suspension

Source: Authors' design based on MAPA (2019) and MAPA (2022).

Notes: *Part of AM refers to the municipalities of Apuí, Boca do Acre, Canutama, Eirunepé, Envira, Guajará, Humaitá, Itamarati, Ipixuna, Lábrea, Manicoré, Novo Aripuanã, Pauini and part of Tapauá. **Part of MT includes the municipalities of Aripuanã, Colniza, Comodoro, Juína, and Rondolândia. State abbreviations: AC = Acre; AL = Alagoas; AM = Amazonas; AP = Amapá; BA = Bahia; CE = Ceará; DF = Distrito Federal; ES = Espírito Santo; GO = Goiás; MA = Maranhão; MG = Minas Gerais; MS = Mato Grosso do Sul; MT = Mato Grosso; PA = Pará; PB = Paraíba; PE = Pernambuco; PI = Piauí; PR = Paraná; RJ = Rio de Janeiro; RN = Rio Grande do Norte; RO = Rondônia; RR = Roraima; RS = Rio Grande do Sul; SC = Santa Catarina; SE = Sergipe; SP = São Paulo; TO = Tocantins