**University of São Paulo**
**"Luiz de Queiroz" College of Agriculture**

# Effects of foot-and-mouth disease on the Brazilian economy: a computable general equilibrium analysis

**Taís Cristina de Menezes**

Thesis presented to obtain the degree of Doctor in Science.
Area: Applied Economics

**Piracicaba**
**2022**

**Taís Cristina de Menezes**
**Bachelor of Economic Sciences**

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# CONTENTS

# RESUMO

## Efeitos da febre aftosa na economia brasileira: uma análise de equilíbrio geral computável

Nesta tese são analisados os impactos econômicos de surtos hipotéticos de febre aftosa no Brasil. A primeira análise trata do impacto de surtos de febre aftosa no bem-estar geral do Brasil e outros países e no comércio bilateral de carne bovina e suína entre diferentes países. A segunda consiste na avaliação do impacto de surtos de febre aftosa nas diferentes regiões brasileiras, incluindo a avaliação de mudanças em variáveis macroeconômicas (como produto interno bruto, investimento e exportações), salários e emprego. São aplicados dois modelos de equilíbrio geral computável. Na primeira análise, o modelo GTAP, que inclui dados para 141 países e regiões, é utilizado, ao passo em que a segunda análise aplica o modelo interregional brasileiro TERM-BR. Os resultados de ambos os estudos constituem embasamento para a estimativa de impactos econômicos e sociais de surtos de febre aftosa sobre a economia brasileira e sobre os mercados de exportação de carnes do Brasil. Estes estudos evidenciam a importância da prevenção de doenças animais do Brasil, para a manutenção da produção e das exportações pecuárias. Os resultados desta tese podem ajudar a formular políticas e estratégias para minimizar as perdas socioeconômicas de potenciais surtos de febre aftosa no país. Adicionalmente, a metodologia desenvolvida nesta pesquisa pode contribuir para a formulação de estratégias voltadas para outras doenças animais ainda presentes no Brasil.

**Palavras-chave:** Febre aftosa; Impactos econômicos; Modelo de equilíbrio geral computável; Brasil

# ABSTRACT

## Effects of foot-and-mouth disease on the Brazilian economy: a computable general equilibrium analysis

This thesis analyzes the economic impacts of hypothetical foot-and-mouth disease (FMD) outbreaks in Brazil. The first analysis deals with the impact of FMD outbreaks on welfare in Brazil and other countries and on beef and pork bilateral trade between different countries. The second analysis consists of evaluating the impact of FMD outbreaks in different Brazilian regions, including an assessment of changes in macroeconomic variables (such as gross domestic product, investment and exports), wages and employment. Two computable general equilibrium models are applied. In the first analysis, the GTAP model, which includes data for 141 countries and regions, is employed, while the second analysis applies the Brazilian interregional model TERM-BR. The results of both studies provide a basis for estimating the economic and social impacts of FMD outbreaks on the Brazilian economy and on Brazilian meat export markets. These studies show the importance of preventing animal diseases in Brazil for the maintenance of livestock production and exports. The results of this thesis can help the formulation of policies and strategies to minimize the socioeconomic losses from potential outbreaks of FMD in the country. Additionally, the methodology developed in this research can contribute to the formulation of strategies aimed at other animal diseases still present in Brazil.

**Keywords:** Foot-and-mouth disease; Economic impacts; Computable general equilibrium model; Brazil

# 1. INTRODUCTION

Brazil is a continental country with different soils, weather and water availability, which provide opportunities to grow tropical and temperate products and livestock. This variety in agricultural production plays an important role in the Brazilian economy. In 2020, the Brazilian agribusiness gross domestic product (GDP) accounted for 26.6% of the national GDP, and employed around 18 million people (Cepea, 2021). In the past decades, the agricultural sector has been more reactive to economic crisis, in such a way that it has presented positive growth rates more frequently compared to industrial sectors. In 2020, for example, Brazilian agricultural exports increased 6%, while exports of the extractive and manufacturing industries decreased 2.7% and 11.3%, respectively. Agribusiness exports accounted for 48% of Brazil's total exports in the same year. This growth in the importance of agricultural sectors in exports is mainly due to the increase in sales of coffee, soybeans, cotton, sugar and beef in the international market. Frozen beef is the fifth most exported product by Brazil, representing about 3.2% of national exports in 2020, equivalent to US$6.7 billion (MDIC, 2022).

With 13.7% of the world's cattle stock, Brazil has the largest commercial cattle herd. In addition, the Brazilian hog herd is the fourth largest, representing 3.5% of the world's hog stock. Beef and pork production in Brazil reached 7.8 million and 4.5 million tons, respectively, in 2020, placing the country in second in the beef production ranking, and fifth in pork production (FAOSTAT, 2022). About 22% of beef production is exported, which makes Brazil the largest exporter of this product in the international market, equivalent to 15% of the total world beef exports. The country also exports about 20% of its pork production, being the seventh largest exporter of this product (IBGE, 2022; MDIC, 2022; UN Comtrade, 2022).

As one of the largest meat suppliers in the international market, Brazil faces several challenges to reach consumer markets in other countries. With the reduction of tariff barriers and the establishment of the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) within the scope of the World Trade Organization (WTO), these challenges to international trade have increasingly become related to sanitary and phytosanitary rules (Carneiro, 2015). These rules are important because they establish mutual recognition agreements on food safety regulation. Some of them are related to the control and prevention of foot-and-mouth disease (FMD), a highly infectious animal disease that affects cloven-hoofed animals and causes disruptions in the beef and pork production chain, in addition to resulting in bans to international trade (Lee et al., 2012; Oladosu et al., 2013; OIE, 2021). An FMD outbreak can result in significant economic losses for the affected country, in addition to causing high costs for its control and eradication (Buetre et al., 2013; Knight-Jones et al., 2017).

In this context, the development and improvement of animal health systems around the world began to receive greater attention and funding, especially in the last two decades. In low-income countries the improvement of animal health works as a mechanism for reducing poverty, while in developed countries there is an incentive to prevent productive, commercial, and economic losses, in general, including those caused by FMD (Shankar et al., 2012). The control and eradication of FMD disease are challenging because it is a highly transmissible disease, with complex containment within delimited areas. This implies that FMD is not only a recurring problem for endemically infected countries, but also a constant threat to FMD-free countries. Its control, therefore, generates an international public good, which relevance was evidenced by the launch of a global initiative of the Food and Agriculture Organization of the United Nations (FAO) in conjunction with the World Organization for Animal Health (OIE), aiming to progressively control FMD in the world (FAO and OIE, 2012).

Each FMD surveillance, control and eradication strategy has different implications for human and financial resources and varying impacts on the economy (Bouma et al., 2003; Matthews, 2011; Hagerman et al., 2012). Therefore, for the formulation of FMD policies it is necessary to assess the economic consequences of the guidelines adopted to prevent the disease and control eventual outbreaks, especially given the scarcity of resources that governments face (Pritchett et al., 2005; Knight -Jones et al., 2017). Even if a country is free of FMD, there are ongoing costs as a result of efforts to prevent its reintroduction, including control of animal movements, active and passive surveillance, and control of animals and imported products. Maintaining a response plan and capacity for early detection of FMD generates significant costs, in particular for the public sector (Rushton, 2009; Knight-Jones and Rushton, 2013). To help decision-making, the association of epidemiological and socioeconomic data makes it possible to assess scenarios for the occurrence of FMD and its management, making the country's protection measures more effective in epidemiological, economic and social terms (Rich et al., 2005; Rojas & Romero, 2017).

In the case of Brazil, the country was recognized as FMD-free with vaccination by the OIE in 2018 and has promoted efforts to become an FMD-free country without vaccination by 2023, according to the Strategic Plan of the National Program for the Eradication and Prevention of FMD 2017-2026 (MAPA, 2019). Due to this change in the FMD program guidelines, a preparedness plan was established, assuming a combination of stamping-out and emergency vaccination strategies in case of future FMD outbreaks (MAPA, 2020). However, the potential consequences of outbreaks, considering the measures established by the contingency plan, have not yet been studied, especially the economic consequences. This was the main motivation for this study.

This thesis was influenced by the fact that the strategies established in the response plan for FMD-related emergencies directly affect the economic impacts of potential outbreaks of the disease. In addition, few studies in both technical and scientific literature prospect economic impacts of FMD in Brazil. It is important to emphasize, though, that the purpose of this thesis is not to exhaust the subject, but to contribute to the understanding of the object of study and offer results that support future research and analyzes. In general, the present study evaluates the potential economic impacts of FMD in Brazil based on the results of an epidemiological model of FMD spread in the country recently developed at the University of São Paulo. The analysis was carried out using two computable general equilibrium (CGE) models: the Global Trade Analysis Project (GTAP) model, an international model, and TERM-BR, an interregional model for Brazil. Overall, the next two chapters assess aspects of the potential impacts of FMD outbreaks on the Brazilian economy from different perspectives.

The first chapter applies version 10 in static format of the GTAP model updated for 2017. The simulations assume a hypothetical FMD outbreak in Paraná, South region of Brazil. Two scenarios were constructed, considering the application or not of the Principle of Regionalization by the international market to imports from Brazil in the event of an FMD outbreak in the country. The second chapter also focuses on FMD potential economic impacts, but with a disaggregated and dynamic approach. The TERM-BR model is applied to simulate FMD outbreaks in Brazil in 2022, with impact evaluation until 2025. The simulations are based on two hypothetical outbreak scenarios. Scenario I assumes an outbreak in Paraná, a major producer and exporter of pork, while Scenario II considers an outbreak in Mato Grosso, one of the largest producers and exporters of beef, located in the Midwest region of Brazil.

The results of each chapter are complementary. The first chapter presents the economic impacts of FMD on general welfare in Brazil and other countries, as well as changes in beef and pork bilateral trade for several countries. The results of the second chapter show the impact of FMD outbreaks on different Brazilian regions, considering macroeconomic variables (such as GDP, investment and exports), production, wages and employment. The two chapters of this thesis elaborated in the form of scientific papers, although complementary, can be read independently. However, it is noteworthy that, as the papers were developed under a common theme, there are repetitions and redundancies in some parts of the chapters, especially in introductory sections and primary data information.

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# 2. ECONOMIC ASSESSMENT OF FOOT-AND-MOUTH DISEASE OUTBREAKS IN BRAZIL

**Abstract:** Foot-and-mouth disease (FMD) outbreaks in cloven-hoofed animals cause substantial economic impacts because of animal slaughter, increased government spending on control, eradication and surveillance measures, and bans on international trade. This study employs a computable general equilibrium (CGE) modeling framework in tandem with results from an epidemiological model to evaluate the economic consequences of a hypothetical FMD outbreak in Brazil. FMD-induced productivity losses and restrictions on international trade of livestock and meat products are applied as exogenous shocks in the economic model. Results show increased bilateral trade of beef and pork, mainly in South America, North Africa and Russia. Simulated welfare losses in Brazil range from $132 million to $271 million depending on the severity of trade restrictions imposed. This study expands the rich literature on animal health economics. Results highlight the importance of maintaining the health of Brazilian herds, especially when considering Brazil's position as one of the main meat suppliers in the international market.

**Keywords:** Animal health economics, Brazil, Foot-and-mouth disease, International trade.

## 2.1. Introduction

Globalization intensified the flow of animals, products and people around the world. At the same time, livestock production and its associated value chains have become more complex. Consequently, the risk of transmitting pathogens from one country to another has increased, leading to new challenges for the management of animal diseases, especially dealing with the inflicted costs related to surveillance, control and prevention (FAO & OIE, 2012; Martins et al., 2015). All impacts associated with animal diseases can influence changes in the behavior of economic agents (Narrod et al., 2012). Therefore, it is essential to take the economic impacts into account in the decision-making process during the formulation of public policies related to animal health. The recent African swine fever epidemic, which devasted the swine industry in Asia, Africa, Europe and Central America, and the coronavirus pandemic highlight how fast animal and human diseases can spread and their potentially catastrophic effects on national economies. Disease events raise concerns about bioterrorism and biological threats and underline the importance of studies that contribute to the understanding of the various effects of animal diseases.

Foot-and-mouth disease (FMD) is included in this scenario, being considered one of the most economically important animal diseases in the world due to its highly infectious nature (Boisvert et al., 2012; Tadesse et al., 2020). Once found in a previously free country, strict control measures are implemented to eradicate FMD, including the slaughter of animals on infected properties and restriction of movement of animals, animal products, people and objects susceptible to contamination. Furthermore, restrictions on international trade of animals and animal products are imposed on the country in crisis until, and oftentimes long after, FMD-free status is achieved. Outbreaks of FMD in the United Kingdom in 2001 (National Audit Office, 2002; Thompson et al., 2002; Blake et al., 2003; Mort et al., 2005), Japan in 2010 (Hayama et al., 2017) and South Korea in 2011 (Pendell & Cho, 2013; Kim et al., 2013; Kim, 2015; Kim et al., 2015) have shown that FMD can be reintroduced and spread in previously free countries that maintain sophisticated biosecurity systems.

Despite 75% of the world’s cattle living in low- and middle-income countries, livestock product exports from these countries account for less than 15% of the total global value, with exception of Brazil (Baluka, 2016).

This is partly explained by the presence of transboundary animal diseases, such as FMD, that restrict livestock trade in those countries. The endemic presence of FMD in Uganda, for example, limits the country's ability to access major export markets of livestock and livestock products (Baluka, 2016). Hsu et al. (2005) estimate a trade loss of $15 billion for Taiwan as a result of the total closure of export markets due to the FMD outbreak in 1997. Sinkala et al. (2014) estimate that Zambia has an annual loss of $1.6 billion in exports of beef and sable antelopes due to the FMD endemic situation in the country. This loss is caused by the ban on imports of live animals and animal products from important Zambian buyers such as Botswana and South Africa. Pendell and Cho (2013) state that the FMD outbreaks in South Korea between 2000 and 2010 culminated in the total loss of the South Korean red-meat export market, especially pork exports. In 2000, after the first reported case, Japan banned imports from South Korea and took more than three years to lift the restrictions. The FMD outbreak in the United Kingdom in 2001 led to a 67% reduction in red meat exports during that year, and a 45% decrease in those exports in 2002 (Oladosu et al., 2013).

The last FMD outbreak in Brazil in a previously disease-free area happened in 2005. From the official notification made to the World Organization for Animal Health (OIE) in October 2005, 58 import markets imposed restrictions on Brazilian beef and pork, which represented approximately 87% of Brazil's export market (Garcia et al., 2015). Chile, a major market, imported 97% less from Brazil in the year following the outbreak. Vietnam, South Korea and Indonesia completely closed their markets to Brazilian beef and pork for two years. Other countries partially banned imports from Brazil for one year after the outbreak, including Argentina, South Africa, China, Canada, Uruguay, Peru, Spain, Japan, Germany, Australia, Russia, Iran, the Netherlands and Algeria. The Brazilian region directly affected by the outbreak suffered an 81% decrease in beef exports. France, Italy, Switzerland, Venezuela, Russia, Lebanon and Egypt took two years to resume imports from the affected region, and Chile took four years to reopen its market. To date, the losses caused by this FMD outbreak on the Brazilian economy are still unknown (Menezes, 2018). In 2021, the risk that animal diseases impose on the maintenance of Brazilian meat exports was highlighted by the closure of the Chinese market (main importer of meat from Brazil) for more than three months due to two atypical cases of bovine spongiform encephalopathy (BSE) (MAPA, 2021).

The protection of beef and pork production in Brazil is increasingly relevant for the country, which is the second largest producer and largest exporter of beef in the world, and the fifth largest producer and seventh largest exporter of pork. In terms of beef production and export, Brazil competes closely with the United States, Argentina, and Australia. In terms of pork production and export, Brazil competes mainly with the United States and European Union countries. Barriers to Brazilian meat exports can culminate in extensive economic losses for the country. In this sense, this study analyzes the potential economic impacts of a simulated FMD outbreak in Brazil. Epidemiological simulations considered that the FMD outbreak would occur in Paraná, a large cattle and hog producing state located in the southern region of Brazil. This research provides a summary of the simulated epidemiological impacts of FMD, estimates of the direct costs associated with mitigation during an FMD outbreak, and the corresponding consequences on the Brazilian economy. FMD-related factors for this analysis include loss in cattle production, increased government spending for mitigation, reduction in domestic beef and pork consumption, loss of export markets and corresponding welfare changes.

As one of the most substantial direct impacts of FMD is the loss of export markets, evaluating the behavior of bilateral trade is important for the estimation of the economic impacts of potential outbreaks. Accordingly, this research employs a global computable general equilibrium (CGE) modeling framework to investigate the economic effects of a simulated FMD outbreak in Brazil. This study provides insights for policymakers on the potential negative consequences of an FMD outbreak. This relates to the importance of animal health program investments in Brazil as a strategy to maintain the growth and development of the Brazilian livestock industry in domestic and foreign markets.

## 2.2. The FMD Program in Brazil

Over the past two decades, the Brazilian animal health service has strived to eradicate FMD in the country and, Brazil was recognized as an FMD-free country with vaccination[1] by the OIE in 2018. Concomitantly, Brazilian cattle raising evolved at an accelerated pace and currently maintains the largest commercial herd in the world with nearly 215 million head (IBGE, 2021). Brazilian swine production also evolved substantially in this period, maintaining the third largest swine herd in the world, only behind China and the European Union (USDA, 2020). This growth helped Brazil become the world's largest producer and exporter of beef, and the fourth largest producer and exporter of pork. Despite the growing volume of meat exports, the Brazilian livestock sector is constantly subdued by trade barriers imposed by large import markets, largely related to animal health. The restrictions applied by trade partners include tariff and non-tariff barriers, the latter including sanitary restrictions related to the FMD status in Brazil (Gonçalves & Neto, 2010; Florindo et al.; 2015; Ferreira et al., 2019).

The last FMD outbreak in Brazil in an area previously free of the disease took place between September 2005 and April 2006 in the state of Mato Grosso do Sul (OIE, 2021a) and had substantial consequences for Brazilian exports of beef and pork, as mentioned previously. Although FMD has been eradicated throughout the country, import markets considered more demanding, such as Australia, New Zealand, Japan, South Korea, Canada, United States, Mexico and Taiwan, impose barriers on Brazilian exports due to periodic vaccination of cattle against FMD. Therefore, Brazil seeks to improve its FMD status in global markets. Based on the Strategic Plan of the FMD National Monitoring Program for 2017-2026, the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA) started the suspension process of FMD vaccination in some states, including Paraná - the state for which outbreak simulations are the basis of this paper. The goal of MAPA is to have the entire country FMD-free without vaccination by 2026. It is noteworthy, however, that this schedule may be delayed because of the coronavirus pandemic. Consequently, with the suspension of vaccination against FMD in Brazil, the contingency strategy in the event of a sanitary emergency related to this disease was redefined by the "Contingency Plan for FMD: Tactical and Operational Levels" as described subsequently (MAPA, 2020).

Historically, the response strategy to FMD outbreaks in Brazil included regionalization, depopulation, animal transit control and reinforcement of herd vaccination (Sutmoller & Casas Olascoaga, 2002; Countryman & Hagerman, 2017). With the suspension of vaccination against FMD, Brazil will maintain a vaccine bank for use in emergency situations. The new contingency plan for FMD considers a combined strategy of stamping-out[2] and emergency vaccination in case of reintroduction of FMD in Brazil. In economic terms, the strategy chosen for the

[1] Only the state of Santa Catarina has been recognized as FMD-free without vaccination so far.
[2] Stamping-out involves depopulation and thorough cleaning and disinfection of detected infected premises, tracing and containment of contacts, active surveillance to detect all sources of infection, and movement restrictions to limit disease spread (Sanson et al., 2017).

control and eradication of FMD is extremely important, given the direct impacts on public costs and international market sanctions on exports of animals and derived products (Countryman & Hagerman, 2017). Furthermore, the control strategy influences the duration and spatial spread of the outbreak and alters the societal costs (Tozer et al., 2015). In general, a FMD outbreak in Brazil is expected to result in production and export losses and introduce considerable disease management and eradication costs, in addition to other impacts on economic welfare. For the maintenance of contingency plans, it is essential to demonstrate the economic importance of keeping the country free of FMD.

## 2.3. Methods and Data

This research simulates the economic effects of a hypothetical FMD outbreak in Brazil in a computable general equilibrium modeling framework that employs estimates from an epidemiological model, and data from the Center for Advanced Studies on Applied Economics (Cepea – University of São Paulo), the Brazilian Institute of Geography and Statistics (IBGE), and the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA) to calculate FMD-related production losses and costs. Production shocks are simulated in tandem with increased government expenditure for disease mitigation, decreased domestic demand, and international policy interventions expected from an FMD outbreak.

### 2.3.1. GTAP Modeling Framework

Four types of economic models are commonly used to examine impacts of animal diseases: cost-benefit analysis, input-output models, partial equilibrium models and computable general equilibrium (CGE) models (Rich et al., 2005). CGE models are considered adequate to assess regional, national, and international economic impacts and policy effects (Partridge & Rickman, 2010, Oladosu et al., 2013). CGE modeling has been employed to investigate the economic effects of FMD outbreaks in Taiwan in 1997 (Hsu et al., 2005) and in the United Kingdom in 2001 (Blake et al., 2003). Tozer and Marsh (2012) assess the potential impacts on Australian exports due to hypothetical FMD outbreaks. Philipidis and Hubbard (2005) analyze the consequences of restrictions on beef exports from the United Kingdom due to the 2001 FMD outbreak. Countryman and Hagerman (2017) also consider trade restrictions imposed on beef exports from Latin American countries due to outbreaks in South America in 2001, and Boisvert et al. (2012) assess the impacts of a hypothetical FMD outbreak in the United States on global trade, both using the GTAP model. Accordingly, this study employs the GTAP modeling framework (Hertel, 1997) to investigate the potential economic impacts of a hypothetical FMD outbreak in Brazil. The model consists of a static, general equilibrium structure for 141 regions and 65 products and is based on annual data (Aguiar et al, 2019). The main structure of the model is described below, and full model documentation can be found in Corong et al. (2017) and Aguiar et al. (2019).

GTAP is a multi-region, computable general equilibrium model that can be used for a wide range of economic and policy analyses. The standard GTAP model is implemented using GEMPACK software (Harrison and Pearson, 1996) and the equations of the model are recorded in percentage change form. For a given length of run (short, medium or long), the model represents a corresponding equilibrium position of the economy. The theoretical framework of GTAP considers the optimizing behavior of agents, given by firms and households.

Households maximize utility, firms minimize costs, and all agents are price takers. The model adopts a representative household of infinitesimal identical households and an industry as representative of infinitesimal identical firms, keeping the participation of each agent in the input-output rates for each sector of the economy (Corong et al., 2017).

The input-output structure of the GTAP database provides a framework that identifies the supply and use of economic goods, accounting for products (goods and services), distinguished by region of origin, and primary factors, called tradable and endowment commodities. Sources of supply are imported and produced domestically. Uses are current production activities (use in particular industries) and final demands, the latter comprised of investment (fixed capital formation), private consumption, government consumption and exports. The regional household allocates regional income between private consumption, government consumption and savings to maximize regional utility. The unitary regional utility function, together with the reliance on optimizing behavior, supports welfare decomposition that distinguishes between endowment, technological, and allocative efficiency effects. Private demand is modeled using the non-homothetic constant difference of elasticities (CDE) functional form. On the production side, each producing activity combines a set of intermediate goods and factors to produce output. The production structure is based on a sequence of nested Constant Elasticity of Substitution (CES) functions, which represents all the substitution possibilities across the full set of inputs (Corong et al., 2017). The possibility to model variations in international trade is a substantial advantage of the GTAP model, given by the application of the Armington specification, which allows the substitution between domestic and imported products, and product differentiation by import source (Armington, 1969). Consequently, firms make decisions on importing goods according to their origin, and the prevailing composite import price drives the optimal mix of imported and domestic goods.

In general, within the GTAP framework, production generates income accumulated in endowments that is returned to the regional household and then spent on three sources of final demand: private expenditures, government spending and savings, which are translated into investment spending. Each source of spending comprises both domestic and import purchases, thereby generating both domestic and export sales by firms. This structure highlights the model's ability to link all sectors of the supply chain, across all countries and regions in the world. The model also accounts for changes in welfare, measured by the equivalent variation (EV). EV provides a monetary equivalent equal to the difference between the expenditure required to obtain a new level of utility at initial prices and the level of utility initially available. Changes in welfare can be decomposed into i) contributions from terms of trade effects, ii) impacts of induced technological changes resulting from FMD-related shocks to production and exports, iii) allocative efficiency effects, and iv) contribution of changes in savings and investments. Allocative efficiency is composed of both the direct effects of the change in efficiency related to production and the indirect gain resulting from the reallocation of labor to sectors with a product of relatively higher marginal social value (Huff & Hertel, 2001).

Another benefit of this structure is the simultaneous examination of production losses and bilateral trade impacts for several countries because of an FMD outbreak. However, it is necessary to emphasize that this benefit comes at the cost of the loss of detail and sensitivity at the production level, when compared to a country-level, or sector-specific model. Furthermore, the GTAP model allows the analysis of market responses to exogenous shocks applied directly to the sectors most affected by FMD outbreaks. For this study, the sectors of hogs and pork were disaggregated from the original other animals and other meats GTAP sectors to specifically account for shocks to hogs and pork separate from poultry and poultry products.

The economic impacts simulated by the model can be divided between changes attributable to initial shocks in sectors directly affected by FMD and additional impacts given restrictions on Brazilian livestock and meat exports. This study assumes a medium run closure including full employment, therefore, changes in employment reflect the reallocation of employment to the sectors with the highest marginal social value product of work. Some of the direct economic impacts of FMD, such as production loss and increased government expenditure, are calculated based on the results of an epidemiological model for Brazil. The economic analysis proposed in this research benefits from an economy-wide model to understand the impacts of the disease throughout the global supply chain. This paper employs the standard GTAP model closure which imposes equilibrium in all markets, firms earn zero-profits, the regional household is on its budget constraint, and global investment equals global savings. The global trade balance condition determines the equilibrium world price of a given commodity.

The GTAP database is composed of 65 sectors of economic activity, including 21 agricultural and food processing sectors and 44 other sectors including manufacturing and services.  Ten agriculture and food sectors are modeled including grains; other agricultural products; cattle; hogs; poultry and other animals; beef; pork; other meat; dairy products; other processed foods. This required two sectors to be disaggregated from the original GTAP database. Hogs were disaggregated from the other animals sector, and pork was disaggregated from the other animal products sector (**Appendix Table A1**). The remaining sectors were combined into three aggregate sectors: other primary products; manufacturing; and services (see **Appendix Table A2**). The 141 GTAP countries/regions were aggregated into 24 countries/regions that are key producers and traders of livestock and animal products as listed in **Appendix Table A3**. The GTAP database was updated from 2014 to 2017 given shocks on macroeconomic variables including population, investment and Gross Domestic Product (GDP), following the approach implemented by Hertel et al. (2010), Diffenbaugh et al. (2012), Boulanger et al. (2016), Beckman and Countryman (2021) and Beckman et al. (2021). Data on population, investment and GDP were collected from the World Bank and the International Monetary Fund (IMF) databases.

### 2.3.2. FMD Outbreak Scenarios in Brazil

The use of simulated outbreak scenarios is widely employed in studies for countries where FMD no longer exists, such as in the United States, where the last FMD outbreak occurred in 1929 (Lee et al., 2012), and in Australia, which has not had an outbreak since 1872 (Garner & Beckett, 2005; Buetre et al., 2013). In Brazil, the biggest challenge for estimating the economic impacts of a potential FMD outbreak had been the absence of a nationwide epidemiological model to understand the potential of disease spread. Country-specific models exist to determine the potential size and the geographic spread pattern of FMD to understand disease effects (Thornley & France, 2009; Sanson et al., 2017; Sellman et al., 2020). In the United States, for example, the Department of Agriculture (USDA) developed the North American Animal Disease Spread Model (NAADSM), used in several studies of the American government (Gale et al., 2015). Similarly, a model of FMD virus spread in Brazil was developed in 2020[3] and is being used by the Department of Animal Health and Livestock Supplies (DSA) of MAPA to investigate and explore potential public policies related to FMD. The model consists of a Susceptible-Exposed-Infectious-Removed (SEIR) specification for cattle[4], including parameters obtained from the literature for other countries due to the lack of epidemiological information for the Brazilian reality. The model is stochastic and programmed in Python[5]. The data used in the model are provided by the MAPA property registry database and by Animal Transit Guides (GTAs), which are official mandatory documents for the movement of animals in Brazil. Information from the animal movement database allows the model to perform simulations on observed data, which is a substantial advantage over models that are based on hypothetical animal flows.

Although it is not the purpose of this paper to discuss the full structure of the epidemiological model, it is important to point out key details that are relevant for this analysis. The epidemiological model considers two types of disease dissemination processes: intra-herd (among animals on the same farm) and inter-herd (between animals from different farms). The transmission between properties involves two mechanisms: one due to proximity and the other due to animal movement. Proximity transmission results in local spread and animal movement results in long-distance spread. Furthermore, the model assumes that government intervention to control and eradicate FMD outbreaks consists of a combination of stamping-out[6] and emergency vaccination. Epidemiological model results show: i) number of infected properties; ii) number of infected animals; iii) number of properties close to the infected properties, called contacting properties; iv) number of animals in the contacting properties, called contacting animals. Thus, it is considered that infected animals would be slaughtered and contacting animals would be vaccinated. The state selected for the simulation of the outbreak was Paraná, located in the southern region of Brazil, recognized for being a large beef and pork producer and one of the main meat exporters in the country. The descriptive results of the simulations for Paraná are presented in **Table 1** below. To provide data for this study, 100 stochastic simulations were performed[7].

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[3] The FMD spread model for Brazil was developed by Professor Fernando Ferreira from the Laboratory of Epidemiology and Biostatistics of the School of Veterinary Medicine and Animal Science from the University of São Paulo. The model has not been published. For more information, please contact Professor Fernando Ferreira: fferreir@usp.br

[4] Cattle move substantially more than hogs in Brazil. Beef cattle generally pass through at least two or three properties during their lifetime before slaughter, whereas hogs are usually born and remain on the same property until slaughter. Thus, cattle are at greater risk of contracting and transmitting the FMD virus than hogs, which live in controlled properties and typically do not move during their lifetime.

[5] Van Rossum, G., & Drake Jr, F. L. (1995). *Python reference manual*. Centrum voor Wiskunde en Informatica Amsterdam.

[6] Stamping-out is defined in the OIE Terrestrial Animal Health Code as the killing of animals which are affected and those suspected of being affected in the herd (OIE, 2021b).

[7] The epidemiological simulations assume that the initial focus consists of one property infected on day 0 and the number of infected animals at the initial focus on day 0 equals 10 animals. The initial focus was selected in a region close to the international border and with large animal movement. It is also assumed that contacting properties are within a radius of 15 kilometers from the infected properties. In case of an FMD outbreak, a risk zone is established, defined by an area of 15 kilometers in radius, centered on the infected property. The properties in this zone are considered at risk of infection. This zone is used as a safety or buffer area, to separate the free zone from the infected zone (PANAFTOSA, 2007).

**Table 1.** FMD Epidemiological Simulation Results for Paraná

| Scenario | Infected properties | Infected animals | Contacting properties | Contacting animals |
|---|---|---|---|---|
| Best case | 668 | 19,287 | 5,376 | 181,441 |
| Mean | 1,298 | 42,670 | 9,515 | 395,643 |
| Worst case | 2,482 | 114,425 | 26,955 | 1,466,085 |

Source: Epidemiological model simulations
Note: The best- and worst-case scenarios were defined based on the minimum and maximum number of infected animals.

The simulations assume that the action of the official animal health service would manage to extinguish the outbreak within 30 days. This timeframe is an explicit objective of the Brazilian Ministry of Agriculture (MAPA), given the current structure of the official animal health service in the country. Consequently, the epidemiological simulations result in focal outbreaks of FMD, contained in a single state. Therefore, this study is based on epidemiological results in line with the assumptions established by MAPA for the implementation of FMD policies in Brazil.

### 2.3.3. Direct Economic Impacts of FMD

#### 2.3.3.1. Production Loss

Production losses were calculated from the number of animals slaughtered, given epidemiological model results. To calculate the losses from slaughtered animals, the number of head of slaughtered cattle are multiplied by the average price per head in the state of Paraná in 2017, which is equal to $1,288.45 (Cepea, 2021). This price does not consider the devaluation of animals due to the FMD outbreak, which may end up overestimating the losses from stamping-out. **Table 2** presents the production losses according to the epidemiological scenarios given data on the Brazilian cattle herd (IBGE, 2021). This study assumes that the carcasses of all slaughtered animals would be eliminated. Thus, it was not considered that the meat of slaughtered animals could be sold at a lower price in the domestic market, or that there would be loss of productivity due to infected and recovered animals. Furthermore, the price per head is difficult to determine, as the infected animals are not necessarily at the right age for slaughter. Since there are no data on the age of infected animals from the epidemiological model, nor data on prices of animals other than animals destined for slaughter, different types of animals with different prices are not considered in this estimation. The limitations related to production loss estimates likely lead to overestimation of FMD-related production losses.

**Table 2.** Production Loss

| Scenario | Infected animals | Loss due to culling (US$)† | % National Value |
|---|---|---|---|
| Best case | 19,287 | 24,850,345.16 | 0.010% |
| Mean | 42,670 | 54,978,183.64 | 0.020% |
| Worst case | 114,425 | 147,430,950.63 | 0.053% |

Source: Authors' calculations
† Note: 2017 prices

### 2.3.3.2. Government Costs

Typical government costs associated with eradication FMD outbreaks on farms were calculated based on the simulated epidemiological scenarios. Following the literature, eradication costs included in this study are the costs of slaughtering animals, carcass disposal, laboratory tests, cleaning and disinfection, emergency vaccination, indemnification, and agricultural inspector visits to properties[8] (described in **Table 3**) (Elbakidze et al., 2009; Pendell et al., 2015). There are additional public costs as a result of FMD outbreaks, such as the cost of quarantine and surveillance. However, it was not possible to estimate such costs, because of substantial variability depending on the circumstances of the FMD outbreak. The Agricultural Defense Agency of Paraná could not obtain additional information to account for further public costs associated with the disease, leading to a possible underestimation of total government expenditures on FMD eradication. Government costs accounted for as described as follows.

- **a. Depopulation:** The most viable method for depopulation of many animals in Brazil is by rifle carried out by the Brazilian army. The only additional cost to the government is ammunition. Thus, the cost of depopulation of animals infected with FMD only considers the price of ammunition given the fixed salaries of army personnel.
- **b. Carcass Disposal:** Excavators are used for trenching for carcass disposal. Estimated excavator rental and labor cost was provided by the Agricultural Defense Agency of Paraná, totaling $1,658.45 to eliminate 1,000 animals. The total disposal cost for each scenario is shown in **Table 3**.
- **c. Surveillance:**
  - **I. Laboratory Tests:** Tests for FMD in Brazil are carried out in a Federal Agricultural Defense Laboratory, therefore, there is no exact cost for processing the samples and the labor for the analysis of the samples is already funded by the government. The Agricultural Defense Agency of Paraná provided an estimate of the cost of inputs for sample collection and processing, in addition to the cost of sending the samples to the official laboratory. The total cost includes testing positive animals (later slaughtered) and testing vaccinated animals, considering that vaccinated animals would have to be tested so Paraná could regain its FMD-free status.
  - **II. Visits of Agricultural Inspectors to Properties:** According to the Agricultural Defense Agency of Paraná, a property is usually visited twice by two agricultural inspectors given a suspected FMD case. Inspectors make at least ten visits to an infected property. After emergency vaccination, at least two more visits are necessary to test animals and prove the absence of the FMD virus to regain free status. This study follows the epidemiological assumption that inspectors visit each infected property ten times and each contacting property four times with a fixed cost per visit informed by the Agricultural Defense Agency.
- **d. Cleaning and Disinfection:** This research only considers properties of extensive cattle production. There are only a few facilities and limited equipment that would require cleaning and disinfection with a specific sanitizer in case of FMD outbreaks. While the cost of these activities varies substantially, the average

[8] The costs of slaughtering animals, carcass disposal, laboratory tests, cleaning and disinfection and agricultural inspectors property visits were obtained by a personal communication with the Animal Health Manager of the Agricultural Defense Agency of Paraná, Rafael Gonçalves Dias on January 27, 2021.

price of the sanitizer was considered a proxy to estimate the cost for cleaning and disinfection of infected properties.

e. **Indemnification:** The "Contingency Plan for FMD" (MAPA, 2020) states that the Brazilian government must indemnify 50% of the price of the culled animal in cases of an FMD outbreak. Government indemnity expenditures were estimated for each epidemiological scenario based on the price of live cattle from Cepea (2021). Indemnification payments reflect the value of culled animals at average market prices in 2017, not considering the devaluation of animals after the FMD outbreak.

f. **Emergency Vaccination:** Emergency vaccination would be applied on the entire contacting herd. The cost per applied dose of FMD vaccine in Paraná is estimated to equal $0.45 including the price per dose and cost of labor to apply the vaccine (Miranda et al., 2018). The cost was multiplied by the number of contacting animals to estimate government expenditure on emergency vaccination.

**Table 3.** Public Costs for Outbreak Control and Eradication, in US$†

| Cost Category | Scenario | | |
|---|---|---|---|
| | **Best case** | **Mean** | **Worst case** |
| Depopulation | 12,070.41 | 26,704.22 | 71,610.73 |
| Carcass Disposal | 31,986.58 | 70,766.17 | 189,768.44 |
| Laboratory Tests | 2,261,193.15 | 4,937,578.97 | 17,804,383.95 |
| Visits of Agricultural Inspectors | 1,058,305.56 | 1,916,545.41 | 4,980,614.88 |
| Cleaning and Disinfection | 209,027.61 | 406,164.44 | 7,766,56.50 |
| Indemnification | 12,425,172.58 | 27,489,091.82 | 73,715,475.32 |
| Emergency Vaccination | 81,189.28 | 177,038.09 | 656,028.02 |
| **Total Government Cost** | **16,078,945.16** | **35,023,889.13** | **98,194,537.84** |
| % of Government Expenditures | 0.03% | 0.08% | 0.21% |

Source: Authors' calculations
† Note: 2017 prices

#### 2.3.3.3. Decrease in Domestic Demand

Domestic demand for beef and pork are assumed to decrease due to an expected change in consumer perceptions of food safety resulting from the FMD outbreak. Brazilian society is expected to react similarly to the situation observed during "Operation Weak Meat" in 2017, when there was an extensive investigation into a corruption scheme related to food safety in meat supply chains in Brazil (DIEESE, 2017). This is considered a reasonable assumption, given that FMD affects consumers' perceptions of food safety risk, even though the disease is not transmissible to humans through the consumption of animal products. Several studies assume an arbitrary shock related to changes in consumer market preferences in the face of an FMD outbreak, such as Zhao et al. (2006), Nogueira et al. (2011), Lee et al. (2012), Tozer & Marsh (2012), Tozer et al. (2015), Gohin and Rault (2013), Schroeder et al. (2015), Pendell et al. (2015) and Miller et al. (2018). However, Mu et al. (2015) estimate demand for beef in the United States would decrease by 0.42% following an announcement of a bovine spongiform encephalopathy (BSE) outbreak. The estimated impact on domestic demand was relatively small and of short duration because the United States market is comprised of consumers with strong preferences for beef, in general, as in the case in Brazil. Accordingly, this research assumes a 0.42% decrease in Brazilian domestic beef and pork demand as a proxy for the impact of an FMD outbreak on Brazilian consumers.

#### 2.3.3.4. Export Loss

Countries free from FMD generally close their markets to animal products from infected areas (Mason & Grubman, 2009). As sanitary policies vary widely and depend on bilateral negotiations country by country, estimating the duration of trade bans is a challenge. While it is difficult to predict exactly how export markets would behave in the event of an FMD outbreak in Brazil, experience shows that bans on livestock and meat tend to persist for years after the outbreak notification. Accordingly, it is reasonable to consider that export markets would remain closed until the area affected by the outbreak regained its FMD-free status. The time for recovery of this status depends directly on the measures implemented to control and eradicate the outbreak according to the OIE Terrestrial Animal Health Code. If stamping-out measures are applied, the zone can regain its FMD-free status three months after the slaughter of the last infected animal. On the other hand, if emergency vaccination is implemented along with stamping-out, the recovery of FMD-free status may take at least six months after the last animal was vaccinated, considering that vaccinated animals would not be slaughtered later (OIE, 2021b). This assumption based on the OIE Code is common in research on the economic impacts of FMD (Zhao et al., 2006; Junker et al., 2009; Nogueira et al., 2011; Lee et al., 2012; Tozer and Marsh, 2012; Hagerman et al., 2012; Boisvert et al., 2012; Buetre et al., 2013; MPI, 2014; Schroeder et al., 2015; Pendell et al., 2015; Tozer et al., 2015; Halasa et al., 2015; Feng et al., 2017; Porphyre et al., 2018).

This study considers two possible trade policy scenarios. In the first scenario, a total ban is applied to cattle, hogs, beef and pork exports from Paraná during the outbreak and for the subsequent six months, as the epidemiological simulations consider the combination between stamping-out and emergency vaccination to control the outbreak. After six months without new outbreaks, the state would recover 75% of its export markets, similar to the assumptions of Pendell et al. (2015). This study assumes that the region affected by the outbreak would fully recover its export market one year after the outbreak. Additionally, exports of cattle, hogs, beef and pork from all of Brazil would stop for 30 days, until the outbreak is eradicated[9]. This strategy highlights the fact that the duration of an FMD outbreak is a critical element in determining the economic effects of FMD on international trade. This scenario assumes that the Principle of Regionalization[10] would be applied by all importers of animals and animal products from Brazil. In the second scenario, we considered a 25% reduction in Brazilian exports until the recovery of Paraná's FMD-free status in addition to the restrictions on exports from the affected region described previously. In other words, cattle, hogs, beef and pork exports from Brazil would be banned for one month and would recover 100% just 7 months after the beginning of the outbreak. Accordingly, this scenario assumes that the principle of regionalization would not be respected by the international market during the occurrence of the outbreak. The importance of considering different scenarios related to the application and absence of the regionalization principle is highlighted by Cairns et al. (2017).

All other factors affecting world meat prices and quantities in 2017, the base year for this analysis, remained constant in this framework. The only change made in the world meat market was applying the negative

[9] This assumption follows the goals of the Brazilian Ministry of Agriculture to eradicate the outbreak in 30 days.
[10] The Principle of Regionalization allows a country to declare part of its territory free from a given disease even though there have been outbreaks in other regions to prevent the total suspension of exports. However, importing countries may or may not recognize this differentiation between areas of the country affected by the disease (WTO, 2017).

shocks related to FMD in Brazil. A limitation of these shocks is that the impacts on demand and supply in the global beef and pork sectors do not account for other possible changes during the timeframe analyzed.

**Table 4** highlights the importance of considering the restrictions related to FMD in the international market. Assuming that the principle of regionalization would be applied, Brazil's export losses are estimated to be approximately $806.64 million, whereas without regionalization this loss could reach $1.68 billion (MDIC, 2021). The role of the state of Paraná as one of the main exporters of hogs and pork is evident from the greater relative shocks to trade in these sectors. Nevertheless, the initial monetary impact on the cattle and beef sectors from lost trade would be substantially greater than on the hogs and pork sectors.

**Table 4.** Export Loss Estimates

| Export Scenario | Product | Exports Loss (US$) | % of Export Value |
|---|---|---|---|
| Principle of regionalization applied | Cattle | 23,003,532.50 | 8.33% |
| | Hogs | 708,229.65 | 16.95% |
| | Beef | 513,201,575.10 | 9.45% |
| | Pork | 269,725,844.70 | 17.13% |
| Principle of regionalization not applied | Cattle | 57,508,831.25 | 20.83% |
| | Hogs | 1,156,032.65 | 27.67% |
| | Beef | 1,179,570,720.85 | 21.72% |
| | Pork | 437,864,400.80 | 27.81% |

Source: Authors' calculations based on export data from ComexStat (MDIC, 2021)
Note: 2017 prices

### 2.3.4. FMD-Related Shocks

From all estimates of losses and costs arising from hypothetical FMD outbreaks, this research considers two scenarios including specifications for impacts resulting from FMD imposed as exogenous shocks in the GTAP model, as shown in **Table 5**. The scenarios assume the mean case from the epidemiological results and vary international trade restrictions. The production loss, changes in domestic demand, increase in government expenditure, and the description of international trade policies are previously described in detail. The production and demand shocks were applied to technical change variables to allow the production and demand variables to remain endogenous in the model, so that the combined effects of all shocks on these variables could be evaluated. The model closure is the standard, medium term, with constant capital stock in the aggregate moving between firms commonly considered for GTAP applications (Hertel, 1997).

The shock on cattle production was applied to the output augmenting technical change parameter (*aoall*), an exogenous variable in the standard GTAP closure (Hertel et al., 2001). To calculate this shock, the production variable of the Brazilian cattle sector (*qo*) was swapped with *aoall* to be exogenous. The production shock presented in **Table 5** was applied to *qo*, and the effect of this shock on *aoall* (endogenous) was evaluated. The variable *aoall* was then swapped back to be exogenous, so that the combined effect on *qo* of all shocks could be analyzed in the main simulation. The same was done for shocks to domestic demand and international demand. For export shocks, for example, the exported quantity variable (*qxs*) of the cattle, hog, beef, and pork sectors was swapped to be exogenous, and *ams* (import-augmented technological change) became endogenous. The shocks described in **Table 5** were applied to *qxs* and the effects on *ams* were analyzed. Subsequently, *ams* was swapped back as an exogenous variable, and the previously evaluated effects were imposed on this variable as exogenous shocks, so that the effects on the exported quantity (back to being endogenous) of all the combined shocks (production, government expenditure, and demand) could be evaluated from the endogenous adjustments in the model.

**Table 5.** Scenarios of Direct FMD-Related Shocks

| Scenario | Production Loss (-) | Domestic Demand (-) | | Government Expenditure (+) | Export Loss (-) | | | |
|---|---|---|---|---|---|---|---|---|
| | | Beef | Pork | | Cattle | Hogs | Beef | Pork |
| **I** | 0.02% | 0.42% | 0.42% | 0.08% | 8.33% | 16.95% | 9.45% | 17.13% |
| **II** | 0.02% | 0.42% | 0.42% | 0.08% | 20.83% | 27.67% | 21.72% | 27.81% |

Source: Authors' calculations

The *ams* variable is introduced in the model in the following equations for import demand and composite import price:

$$qxs_{irs} = ams_{irs} + qim_{is} - \sigma_m^i \times [pms_{irs} - ams_{irs} - pim_{is}] \quad (1)$$

$$pim_{is} = \sum_k \theta_{iks} \times [pms_{iks} - ams_{iks}] \quad (2)$$

where:

$\sigma_m^i$ : elasticity of substitution among imports of commodity $i$

$qxs_{irs}$ : percentage change in bilateral exports of commodity $i$ from region $r$ to region $s$

$qim_{is}$ : percentage change in total imports of commodity $i$ into region $s$

$\theta_{iks}$ : share of imports of $i$ in region $k$ in the composite imports of $i$ in region $s$

$pms_{irs}$ : percentage change in price of imports of commodity $i$ from region $r$ to region $s$

$pim_{is}$ : percentage change in average import price of commodity $i$ in region $s$

$ams_{irs}$ : percentage change in effective price of commodity $i$ from region $r$ in region $s$ due to change in unobserved trade costs

Import demand, Equation 1, shows two different effects related to changes in the *ams* variable. First, a negative change in *ams* increases the effective import price of commodity $i$ from exporter $r$ imported into country $s$, inducing a substitution effect towards other exporters, determined by the elasticity parameter. The second effect works in the opposite direction. The effective export quantity of the commodity decreases, indicating that more is required to meet the needs of the importer. At the same time, the composite import price equation, Equation (2), demonstrates that a negative shock to *ams* increases the average import price, which leads to a contraction of imports and a loss in efficiency. In theory, the total impact of a negative shock to *ams* is uncertain. However, Hertel et al. (2001) state that, considering the trade elasticity parameters included in the GTAP model, it could be expected that an increase in trade costs would decrease both observed expenditures on imports and the share of imports from the exporting region to which this increase in trade costs is applied. In the case of the present study of Brazil, the *ams* shock applies uniformly to all trade partners in both experiments (Scenarios I and II).

To test the robustness of model results, this research includes a systematic sensitivity analysis (SSA). To test the sensitivity of model results to variations of shock values, it is necessary to specify the range of values over which each shock will be tested. This tool estimates the mean and standard deviation of results for every variable in the model as the shock values vary in the specified range. The estimated means and standard deviations can be used to calculate the confidence intervals for the model results. In this study, the Chebyshev's theorem is used for this calculation because it does not require any assumptions on the shape of the probability distribution of the results for each variable (Burfisher, 2017). The SSA implemented in this study was based on the variation of shocks given by the production loss and the increase in government expenditure, according to the best-case and worst-case results of the epidemiological model. The SSA of shocks on domestic demand and on exports was also carried out, considering the regionalization scenario and the scenario when there is no regionalization. This approach allows for the systematic investigation of the impact of the uncertainty over the values of changes in key exogenous variables (Domingues and Haddad, 2005; Hertel et al., 2007).

## 2.4. Results

Key findings investigated in this analysis are Brazil's export and import volume, output, and producer price in live animals and meat sectors, as well as changes in bilateral trade of beef and pork, and welfare changes in several regions. In Scenario I, hog and pork exports from Brazil are the most affected by the FMD outbreak, with a decrease of 16.08% and 17.13%, respectively (**Table 6**). It is important to note, though, that Brazil's hog exports are relatively small[11], so the level impact of reducing these exports is not substantial. Export effects presented in **Table 6** differ from the exogenous percentage shocks in **Table 5** because the export quantity is maintained endogenous in the model.

Imports into Brazil decrease in general, for products except in the beef and pork sectors, that import 0.79% and 0.94% more in Scenario I, respectively. This can be explained by the slight change in domestic market preferences, as consumers buy fewer domestic products due to food safety concerns. Brazilian pork production is the most negatively impacted compared to other meat sectors, with a drop of 4.87% in output. Although there would be a greater supply in the domestic market due to the international bans on Brazilian exports, the reduction in both output and imports could prevent a drastic fall in domestic prices. Producer prices present a decrease between 0.7% and 0.11% in live animals and meat sectors. The results do not show a substitution effect for live poultry or other types of meat on either the demand or supply sides.

**Table 6.** Changes in Key Variables in Brazilian Meat Sectors (%)

| Product | Export Volume | | Import Volume | | Output | | Producer Price | |
|---|---|---|---|---|---|---|---|---|
| | SI | SII | SI | SII | SI | SII | SI | SII |
| Cattle | -8.35 | -20.76 | -0.87 | -1.98 | -0.96 | -2.17 | -0.11 | -0.28 |
| Hog | -16.08 | -15.30 | -0.19 | -0.34 | -0.38 | -0.59 | -0.08 | -0.16 |
| Poultry and Other Animals | 0.19 | 0.38 | -0.20 | -0.36 | -0.33 | -0.54 | -0.08 | -0.16 |
| Beef | -9.61 | -21.77 | 0.79 | -0.13 | -1.03 | -2.30 | -0.09 | -0.22 |
| Pork | -17.13 | -27.79 | 0.94 | 0.78 | -4.87 | -7.88 | -0.07 | -0.14 |
| Other Meat | 0.51 | 1.02 | -0.22 | -0.44 | 0.07 | 0.17 | -0.07 | -0.14 |

Source: Authors' simulations
Note: SI = Scenario I, Principle of Regionalization applied; SII = Scenario II, Principle of Regionalization not applied.

In Scenario II, the beef sector is the second most affected, which is explained by the greater reduction in beef exports (-21.77%). Cattle and hog exports reduce by 20.76% and 15.30%, respectively, at the same time pork exports decrease by 27.79%. Only pork imports show a slight increase of 0.78%. Cattle imports drop by almost 2%, but at the level this effect is not substantial, since live cattle imports in Brazil represent less than 0.1%

[11] Brazil exports approximately 2% of the cattle production, and only 0.1% of the hog production.

of the cattle production. Pork output decreases in in Scenario II by almost 8%, while cattle and beef output decrease by 2.17% and 2.3%, respectively. Even though the decreases in domestic prices are still relatively small in Scenario II (between -0.14% and -0.28%), the effects on prices are double or more than double compared to Scenario I.

### 2.4.1. World Import Markets

Considering the possible effects caused by negative shocks on international demand for Brazilian livestock products due to FMD, results for both scenarios show an increase in beef import prices, especially in Paraguay (1.72% – 4.15%), Venezuela (1.33% – 3.14%), Chile (0.47% – 1.04%), Uruguay (0.90% – 2.08%), Russia (0.58% – 1.31%), North Africa (0.37% – 0.82%), China and Hong Kong (0.28% – 0.63%). The only country where beef import prices decrease is Brazil: -0.35% in Scenario I, and -0.28% in Scenario II (**Table 7**). In Scenario II, the variation in beef import prices more than doubles compared to Scenario I in the most affected regions (Paraguay, Venezuela, Chile, Uruguay, Russia, North Africa, and China and Hong Kong). However, it is important to emphasize that Brazil imports less than 1.5% of the total beef consumed by the domestic market. Pork import prices also increase across countries, except for Brazil. South American countries are most affected, mainly Argentina (increase in pork import prices between 1.43% and 2.39%), Paraguay (1.69% – 2.83%), and Uruguay (1.51% – 2.52%). The same effect is observed for pork import prices in Russia with increases of 0.67% in Scenario I and 1.10% in Scenario II (**Table 7**).

As Brazil leads the world in beef exports, the increase in international market bans on Brazilian beef in Scenario II compared to Scenario I justifies the greater increase in the beef price variation than the increase in the pork price variation. In scenario II, the negative shock on Brazilian beef exports is substantially greater, which implies a more drastic reduction in the international market supply. As the Brazilian share in the supply of beef is relatively greater than in the supply of pork in the world market, it is expected that the impact on international prices caused by a decrease in supply will be greater in the beef sector. In other words, when a substantial part of beef exports from one of the world's main suppliers is suspended, import prices rise and, consequently, import quantities decrease in the near term.

When import prices rise, import quantities fall, especially in countries that highly depend on Brazilian exports. In Scenario I with regionalization in trade beef imports decrease by 1.15% in Chile, 5.57% in Paraguay, 3.02% in Uruguay, 2.84% in Venezuela, 1.97% in Russia. Only Brazil increases beef imports 0.79% (**Table 8**). In Scenario II when regionalization is not applied, beef imports in Brazil decrease by 0.13%. The country with the largest decrease compared to the baseline is Paraguay, which imports 13% less in Scenario II. Imports of beef decrease by 6.84% in Uruguay, 6.03% in Venezuela, 2.53% in Chile, and 4.38% in Russia. Other regions also reduce beef imports, including North Africa (-1.51%), China and Hong Kong (-1.68%), and Rest of Africa (-1.15%). The world average beef imports decrease from 0.69% with regionalization (Scenario I) to 1.63% without regionalization (Scenario II).

**Table 7.** Percentage Changes in Import Prices in the Global Market of Beef and Pork (%)

| Country/Region | Beef | | Pork | |
|---|---|---|---|---|
| | SI | SII | SI | SII |
| Brazil | -0.35 | -0.28 | -0.42 | -0.41 |
| Argentina | 0.04 | 0.07 | 1.43 | 2.39 |
| Chile | 0.47 | 1.04 | 0.47 | 0.76 |
| Paraguay | 1.72 | 4.15 | 1.69 | 2.83 |
| Uruguay | 0.90 | 2.08 | 1.51 | 2.52 |
| Venezuela | 1.33 | 3.14 | 0.00 | 0.01 |
| Mexico | 0.00 | 0.01 | 0.00 | 0.00 |
| USA | 0.01 | 0.03 | 0.19 | 0.31 |
| Canada | 0.01 | 0.02 | 0.02 | 0.03 |
| Europe (28) | 0.02 | 0.05 | 0.01 | 0.01 |
| Russia | 0.58 | 1.31 | 0.67 | 1.10 |
| North Africa | 0.37 | 0.82 | 0.38 | 0.61 |
| Southern Africa | 0.01 | 0.03 | 0.01 | 0.01 |
| Western Asia | 0.14 | 0.31 | 0.24 | 0.39 |
| India | 0.01 | 0.03 | 0.00 | 0.00 |
| China, Hong Kong | 0.28 | 0.63 | 0.06 | 0.09 |
| Japan | 0.01 | 0.02 | 0.00 | 0.01 |
| South Asia | 0.01 | 0.03 | 0.04 | 0.07 |
| Australia | 0.01 | 0.03 | 0.01 | 0.01 |
| Rest of South America | 0.05 | 0.10 | 0.10 | 0.16 |
| Rest of Europe | 0.06 | 0.14 | 0.05 | 0.08 |
| Rest of Africa | 0.15 | 0.33 | 0.28 | 0.45 |
| Rest of Asia and Oceania | 0.02 | 0.04 | 0.02 | 0.03 |
| Rest of the world | 0.03 | 0.06 | 0.08 | 0.13 |

Source: Authors' simulations
Note: SI = Scenario I, Principle of Regionalization applied; SII = Scenario II, Principle of Regionalization not applied.

Changes in global pork imports are greater than changes in beef imports in Scenario I. Average pork imports decrease by 0.88%, in Scenario I while in Scenario II, 1.46% less pork is imported on average worldwide, as expected due to exogenous shocks on Brazilian exports. Paraguay is again the most affected country, with a reduction in pork imports between 6.48% and 10.60%. Argentina also suffers a substantial decrease in pork imports: -5.73% in Scenario I and -9.33% in Scenario II (**Table 8**). The third most affected country is Uruguay, with a decrease in imports between 2.56% and 4.08%. Chile imports between 1.59% and 2.46% less, Russia between 1.85% and 3.0%, and the United States, which reduces pork imports by -0.73% and -1.16%. In both scenarios, only Brazil increases pork imports, although the increase is smaller without regionalization.

Results show that the occurrence of an FMD outbreak in Brazil has an impact on international trade of several other countries. South American countries neighboring Brazil (Argentina, Uruguay, Paraguay and Venezuela) would suffer substantial reductions in meat imports as a result of their reliance on Brazilian meat. Russia, which is also highly dependent on meat imports from Brazil, would also be more affected than other regions of the world. Without regionalization, which results in a greater reduction in Brazilian exports, even the

United States would buy less pork from the international market. This demonstrates the spillover effect of a local outbreak on world meat trade, especially when the outbreak occurs in a major supplier.

**Table 8.** Percentage Changes in Import Quantities in the Global Market of Beef and Pork (%)

| Country/Region | Beef | | Pork | |
|---|---|---|---|---|
| | SI | SII | SI | SII |
| Brazil | 0.79 | -0.13 | 0.94 | 0.78 |
| Argentina | -0.04 | -0.09 | -5.73 | -9.33 |
| Chile | -1.15 | -2.53 | -1.59 | -2.56 |
| Paraguay | -5.57 | -13.01 | -6.48 | -10.60 |
| Uruguay | -3.02 | -6.84 | -2.56 | -4.08 |
| Venezuela | -2.84 | -6.03 | -0.01 | 0.04 |
| Mexico | 0.01 | 0.02 | 0.00 | -0.01 |
| USA | -0.04 | -0.08 | -0.73 | -1.16 |
| Canada | -0.01 | -0.03 | 0.06 | 0.10 |
| Europe (28) | -0.06 | -0.12 | -0.01 | -0.02 |
| Russia | -1.97 | -4.38 | -1.85 | -3.00 |
| North Africa | -0.68 | -1.51 | -0.68 | -1.09 |
| Southern Africa | -0.04 | -0.08 | -0.02 | -0.03 |
| Western Asia | -0.27 | -0.59 | -0.50 | -0.81 |
| India | -0.04 | -0.08 | 0.00 | 0.00 |
| China, Hong Kong | -0.74 | -1.65 | -0.24 | -0.38 |
| Japan | -0.02 | -0.05 | 0.00 | -0.01 |
| South Asia | -0.01 | -0.03 | -0.07 | -0.12 |
| Australia | 0.03 | 0.06 | -0.01 | -0.01 |
| Rest of South America | -0.13 | -0.24 | -0.39 | -0.62 |
| Rest of Europe | -0.15 | -0.34 | -0.11 | -0.17 |
| Rest of Africa | -0.53 | -1.15 | -0.91 | -1.46 |
| Rest of Asia and Oceania | -0.01 | -0.03 | -0.05 | -0.08 |
| Rest of the world | -0.06 | -0.13 | -0.28 | -0.45 |

Source: Authors' simulations
Note: SI = Scenario I, Principle of Regionalization applied; SII = Scenario II, Principle of Regionalization not applied.

### 2.4.2. Bilateral Trade Impacts

Changes in bilateral trade of beef and pork from Scenario I are included in **Tables 9 and 10**. Results from Scenario II are included in **Appendix Tables A4 and A5** and are described below. The decrease in Brazilian exports does not occur homogeneously for all markets in both scenarios. In Scenario I, Brazil's beef exports to Paraguay, Uruguay, Chile, Venezuela, Russia and North Africa fall less than to other regions, between 5.7% and 9.7% (**Table 9**). The remaining regions reduce imports from Brazil between approximately 11% to 12%. The countries that present a smaller decrease in their imports from Brazil begin to import beef from several other regions. This effect can be explained by the high dependence of these markets on Brazilian beef exports. When trade barriers are raised for Brazilian products, demand for imports must be supplied by other exporters, which causes trade diversion from Brazil to other sources. Paraguay and Venezuela increase imports from other regions by more than 7%. Uruguay increases beef purchases from other countries by 4%. Chile and Russia begin to buy about 2.5% more from regions other than Brazil.

**Appendix Table A4** shows changes in bilateral beef trade in Scenario II. The magnitude of the reduction in Brazilian exports is substantially greater than in Scenario I. Paraguay and Venezuela import 12% less from Brazil, and Uruguay reduces purchases by 19.6%. All other regions decrease imports from Brazil between 22% and 26.3%. In addition to being the countries that least reduce imports from Brazil, Venezuela and Paraguay increase imports from other regions by around 19%, which demonstrates their high dependence on the Brazilian beef supply. Uruguay increases imports from other regions by 9%, while Chile and Russia increase their purchases from the rest of the world by 5%, and China starts to import 3% more from countries other than Brazil. Other regions not described do not show substantial changes in bilateral beef trade.

Similar effects are observed in bilateral trade of pork shown in **Table 10** and **Appendix Table A5**. Countries that are highly dependent on pork exports from Brazil, such as Argentina, Paraguay, Uruguay, and Russia show a smaller reduction in their imports compared to other regions that depend less on Brazil (**Table 10**). Uruguay reduces pork purchases from Brazil by 10.24%, Paraguay by 12.51%, Argentina by 13.73%, and Russia by 15.93% in Scenario I. Other regions decrease their pork imports from Brazil by between 17% and 19%. Uruguay starts to import around 11% more from other countries, Paraguay 8.3%, Argentina 6.8%, and Russia 4.1%. Other regions, such as Chile, North Africa, Western Asia, and Rest of Africa also increase pork imports from countries other than Brazil. The results of pork bilateral trade in Scenario II are presented in **Appendix Table A5**. Variations in international trade of pork are of greater magnitude, but the most affected countries are the same as in Scenario I. Uruguay reduces its imports from Brazil by 17.4% while increasing imports from other regions by around 19.4%. Paraguay buys almost 21% less from Brazil compared to the baseline and starts to import 14.3% more from other regions. A similar effect is observed in Argentina. In Scenario II, the United States imports 30% less pork from Brazil and imports 1.5% more from several other countries. Changes in pork import sources are more substantial in South American countries and Russia. However, this does not necessarily imply welfare losses, as discussed in the next section.

**Table 9.** Changes in Regional Bilateral Beef Exports (%): Scenario I

| Exporting Regions | Importing Regions: Brazil | Argentina | Chile | Paraguay | Uruguay | Venezuela | Mexico | USA | Canada | Europe (28) | Russia | North Africa | Southern Africa | Western Asia | India | China, Hong Kong | Japan | South Asia | Australia | Rest of South America | Rest of Europe | Rest of Africa | Rest of Asia and Oceania | Rest of the world |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Brazil** | -13.56 | -11.72 | -9.74 | -5.17 | -8.48 | -5.26 | -11.88 | -11.85 | -11.85 | -11.82 | -9.73 | -10.03 | -11.87 | -11.21 | -11.85 | -10.66 | -11.87 | -11.84 | -11.81 | -11.73 | -11.62 | -11.38 | -11.83 | -11.80 |
| **Argentina** | 0.73 | 0.02 | 2.28 | 7.46 | 3.71 | 7.36 | -0.17 | -0.13 | -0.13 | -0.08 | 2.29 | 1.95 | -0.14 | 0.62 | -0.13 | 1.24 | -0.14 | -0.11 | -0.08 | 0.03 | 0.15 | 0.42 | -0.08 | -0.06 |
| **Chile** | 0.54 | -0.16 | 2.08 | 7.25 | 3.52 | 7.15 | -0.34 | -0.31 | -0.31 | -0.27 | 2.10 | 1.76 | -0.33 | 0.44 | -0.32 | 1.06 | -0.32 | -0.30 | -0.27 | -0.16 | -0.04 | 0.24 | -0.27 | -0.24 |
| **Paraguay** | -0.17 | -0.87 | 1.37 | 6.47 | 2.76 | 6.37 | -1.08 | -1.04 | -1.04 | -0.98 | 1.39 | 1.05 | -1.04 | -0.27 | -1.04 | 0.34 | -1.06 | -0.99 | -1.00 | -0.85 | -0.74 | -0.46 | -0.97 | -0.95 |
| **Uruguay** | 0.22 | -0.48 | 1.76 | 6.92 | 3.17 | 6.82 | -0.67 | -0.63 | -0.63 | -0.59 | 1.78 | 1.44 | -0.64 | 0.11 | -0.65 | 0.74 | -0.66 | -0.61 | -0.60 | -0.47 | -0.36 | -0.08 | -0.58 | -0.56 |
| **Venezuela** | -2.86 | -3.53 | -1.37 | 3.63 | 0.02 | 3.53 | -3.72 | -3.69 | -3.68 | -3.64 | -1.35 | -1.65 | -3.70 | -2.97 | -3.68 | -2.36 | -3.70 | -3.66 | -3.64 | -3.53 | -3.41 | -3.15 | -3.64 | -3.61 |
| **Mexico** | 0.91 | 0.21 | 2.46 | 7.66 | 3.90 | 7.56 | 0.02 | 0.06 | 0.06 | 0.10 | 2.48 | 2.14 | 0.04 | 0.80 | 0.06 | 1.43 | 0.04 | 0.08 | 0.10 | 0.21 | 0.33 | 0.61 | 0.10 | 0.12 |
| **USA** | 0.90 | 0.21 | 2.46 | 7.65 | 3.90 | 7.55 | 0.01 | 0.05 | 0.05 | 0.09 | 2.47 | 2.13 | 0.04 | 0.80 | 0.05 | 1.42 | 0.04 | 0.07 | 0.10 | 0.21 | 0.32 | 0.60 | 0.09 | 0.12 |
| **Canada** | 0.89 | 0.20 | 2.45 | 7.64 | 3.89 | 7.54 | 0.01 | 0.04 | 0.04 | 0.08 | 2.46 | 2.12 | 0.03 | 0.79 | 0.04 | 1.41 | 0.03 | 0.07 | 0.09 | 0.20 | 0.31 | 0.59 | 0.08 | 0.11 |
| **Europe (28)** | 0.90 | 0.21 | 2.45 | 7.65 | 3.90 | 7.55 | 0.01 | 0.05 | 0.05 | 0.09 | 2.47 | 2.13 | 0.04 | 0.79 | 0.05 | 1.42 | 0.04 | 0.07 | 0.10 | 0.21 | 0.32 | 0.60 | 0.09 | 0.12 |
| **Russia** | 0.72 | 0.03 | 2.27 | 7.46 | 3.71 | 7.36 | -0.16 | -0.13 | -0.13 | -0.08 | 2.29 | 1.95 | -0.14 | 0.62 | -0.13 | 1.24 | -0.14 | -0.10 | -0.08 | 0.03 | 0.15 | 0.42 | -0.08 | -0.06 |
| **North Africa** | 0.88 | 0.19 | 2.44 | 7.63 | 3.88 | 7.53 | 0.00 | 0.03 | 0.03 | 0.07 | 2.45 | 2.11 | 0.02 | 0.78 | 0.03 | 1.40 | 0.02 | 0.06 | 0.08 | 0.19 | 0.30 | 0.58 | 0.07 | 0.10 |
| **Southern Africa** | 0.91 | 0.22 | 2.47 | 7.66 | 3.91 | 7.56 | 0.02 | 0.06 | 0.06 | 0.10 | 2.48 | 2.14 | 0.05 | 0.81 | 0.06 | 1.43 | 0.05 | 0.08 | 0.11 | 0.22 | 0.33 | 0.61 | 0.10 | 0.13 |
| **Western Asia** | 0.59 | -0.10 | 2.14 | 7.33 | 3.58 | 7.22 | -0.29 | -0.26 | -0.26 | -0.21 | 2.15 | 1.82 | -0.27 | 0.49 | -0.26 | 1.11 | -0.27 | -0.23 | -0.21 | -0.10 | 0.02 | 0.30 | -0.21 | -0.19 |
| **India** | 0.90 | 0.20 | 2.45 | 7.65 | 3.89 | 7.55 | 0.01 | 0.05 | 0.05 | 0.09 | 2.47 | 2.13 | 0.03 | 0.79 | 0.05 | 1.42 | 0.03 | 0.07 | 0.09 | 0.20 | 0.32 | 0.60 | 0.09 | 0.11 |
| **China, Hong Kong** | 0.80 | 0.10 | 2.35 | 7.54 | 3.79 | 7.44 | -0.09 | -0.06 | -0.05 | -0.01 | 2.36 | 2.02 | -0.07 | 0.69 | -0.05 | 1.32 | -0.07 | -0.03 | -0.01 | 0.10 | 0.22 | 0.50 | -0.01 | 0.02 |
| **Japan** | 0.91 | 0.22 | 2.47 | 7.66 | 3.91 | 7.56 | 0.02 | 0.06 | 0.06 | 0.10 | 2.48 | 2.14 | 0.05 | 0.81 | 0.06 | 1.43 | 0.05 | 0.08 | 0.11 | 0.22 | 0.33 | 0.61 | 0.10 | 0.13 |
| **South Asia** | 0.91 | 0.22 | 2.46 | 7.66 | 3.90 | 7.56 | 0.02 | 0.06 | 0.06 | 0.10 | 2.48 | 2.14 | 0.04 | 0.80 | 0.06 | 1.43 | 0.04 | 0.08 | 0.11 | 0.21 | 0.33 | 0.61 | 0.10 | 0.13 |
| **Australia** | 0.80 | 0.10 | 2.35 | 7.53 | 3.78 | 7.43 | -0.09 | -0.06 | -0.05 | -0.01 | 2.36 | 2.02 | -0.07 | 0.69 | -0.05 | 1.32 | -0.07 | -0.03 | -0.01 | 0.10 | 0.22 | 0.50 | -0.01 | 0.01 |
| **Rest of South America** | 0.84 | 0.15 | 2.40 | 7.59 | 3.84 | 7.49 | -0.04 | -0.01 | -0.01 | 0.04 | 2.41 | 2.07 | -0.02 | 0.74 | -0.01 | 1.36 | -0.02 | 0.02 | 0.04 | 0.15 | 0.27 | 0.55 | 0.04 | 0.06 |
| **Rest of Europe** | 0.83 | 0.14 | 2.38 | 7.57 | 3.82 | 7.47 | -0.06 | -0.02 | -0.02 | 0.02 | 2.40 | 2.06 | -0.03 | 0.73 | -0.02 | 1.35 | -0.03 | 0.00 | 0.03 | 0.13 | 0.25 | 0.53 | 0.02 | 0.05 |
| **Rest of Africa** | 0.89 | 0.19 | 2.44 | 7.63 | 3.88 | 7.53 | 0.00 | 0.03 | 0.03 | 0.08 | 2.45 | 2.11 | 0.02 | 0.78 | 0.03 | 1.40 | 0.02 | 0.06 | 0.08 | 0.19 | 0.31 | 0.59 | 0.08 | 0.10 |
| **Rest of Asia and Oceania** | 0.85 | 0.16 | 2.41 | 7.60 | 3.85 | 7.50 | -0.03 | 0.00 | 0.00 | 0.05 | 2.42 | 2.08 | -0.01 | 0.75 | 0.00 | 1.37 | -0.01 | 0.03 | 0.05 | 0.16 | 0.28 | 0.55 | 0.04 | 0.07 |
| **Rest of the world** | 0.88 | 0.19 | 2.44 | 7.63 | 3.88 | 7.53 | 0.00 | 0.03 | 0.03 | 0.07 | 2.45 | 2.11 | 0.02 | 0.78 | 0.03 | 1.40 | 0.02 | 0.05 | 0.08 | 0.19 | 0.30 | 0.58 | 0.07 | 0.10 |

Source: Authors' simulations

**Table 10.** Changes in Regional Bilateral Pork Exports (%): Scenario I

| Exporting Regions | Importing Regions | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Brazil | Argentina | Chile | Paraguay | Uruguay | Venezuela | Mexico | USA | Canada | Europe (28) | Russia | North Africa | Southern Africa | Western Asia | India | China, Hong Kong | Japan | South Asia | Australia | Rest of South America | Rest of Europe | Rest of Africa | Rest of Asia and Oceania | Rest of the world |
| **Brazil** | -21.43 | -13.73 | -17.20 | -12.51 | -10.24 | -19.24 | -19.25 | -18.48 | -19.09 | -19.22 | -15.93 | -17.12 | -19.24 | -17.94 | -19.24 | -19.04 | -19.23 | -19.01 | -19.22 | -18.86 | -19.01 | -18.00 | -19.18 | -18.92 |
| **Argentina** | 0.51 | 6.83 | 2.53 | 8.33 | 11.15 | 0.01 | -0.01 | 0.94 | 0.18 | 0.01 | 4.11 | 2.63 | 0.00 | 1.62 | -0.01 | 0.25 | 0.01 | 0.29 | 0.02 | 0.48 | 0.28 | 1.54 | 0.08 | 0.39 |
| **Chile** | 0.38 | 6.68 | 2.39 | 8.18 | 11.00 | -0.13 | -0.15 | 0.80 | 0.04 | -0.12 | 3.97 | 2.49 | -0.13 | 1.47 | -0.15 | 0.12 | -0.13 | 0.15 | -0.12 | 0.34 | 0.15 | 1.40 | -0.06 | 0.26 |
| **Paraguay** | -0.75 | 5.48 | 1.24 | 6.96 | 9.75 | -1.25 | -1.27 | -0.33 | -1.08 | -1.25 | 2.84 | 1.34 | -1.25 | 0.34 | -1.27 | -0.99 | -1.25 | -0.97 | -1.24 | -0.78 | -0.98 | 0.28 | -1.18 | -0.87 |
| **Uruguay** | -0.29 | 5.97 | 1.72 | 7.45 | 10.25 | -0.78 | -0.82 | 0.14 | -0.62 | -0.79 | 3.28 | 1.82 | -0.80 | 0.80 | -0.81 | -0.55 | -0.78 | -0.52 | -0.79 | -0.33 | -0.52 | 0.72 | -0.73 | -0.42 |
| **Venezuela** | 0.49 | 6.80 | 2.50 | 8.30 | 11.12 | -0.02 | -0.03 | 0.92 | 0.16 | -0.01 | 4.08 | 2.61 | -0.02 | 1.59 | -0.03 | 0.23 | -0.02 | 0.27 | -0.01 | 0.45 | 0.26 | 1.52 | 0.05 | 0.37 |
| **Mexico** | 0.53 | 6.85 | 2.55 | 8.35 | 11.17 | 0.03 | 0.01 | 0.96 | 0.20 | 0.03 | 4.13 | 2.65 | 0.02 | 1.64 | 0.01 | 0.27 | 0.03 | 0.31 | 0.04 | 0.50 | 0.30 | 1.56 | 0.10 | 0.41 |
| **USA** | 0.52 | 6.84 | 2.54 | 8.34 | 11.16 | 0.02 | 0.00 | 0.95 | 0.19 | 0.02 | 4.12 | 2.64 | 0.01 | 1.63 | 0.00 | 0.26 | 0.02 | 0.30 | 0.03 | 0.49 | 0.29 | 1.55 | 0.09 | 0.40 |
| **Canada** | 0.50 | 6.81 | 2.51 | 8.31 | 11.14 | -0.01 | -0.03 | 0.92 | 0.16 | 0.00 | 4.09 | 2.62 | -0.01 | 1.60 | -0.02 | 0.24 | -0.01 | 0.28 | 0.00 | 0.46 | 0.27 | 1.53 | 0.06 | 0.38 |
| **Europe (28)** | 0.52 | 6.83 | 2.53 | 8.34 | 11.16 | 0.01 | 0.00 | 0.95 | 0.19 | 0.02 | 4.11 | 2.64 | 0.01 | 1.62 | 0.00 | 0.26 | 0.01 | 0.30 | 0.02 | 0.48 | 0.29 | 1.55 | 0.08 | 0.40 |
| **Russia** | 0.44 | 6.76 | 2.46 | 8.26 | 11.08 | -0.06 | -0.08 | 0.87 | 0.11 | -0.06 | 4.03 | 2.56 | -0.06 | 1.55 | -0.08 | 0.18 | -0.06 | 0.22 | -0.05 | 0.41 | 0.21 | 1.47 | 0.01 | 0.33 |
| **North Africa** | 0.52 | 6.83 | 2.53 | 8.34 | 11.16 | 0.01 | 0.00 | 0.95 | 0.19 | 0.02 | 4.11 | 2.64 | 0.01 | 1.62 | 0.00 | 0.26 | 0.01 | 0.30 | 0.02 | 0.48 | 0.29 | 1.55 | 0.08 | 0.40 |
| **Southern Africa** | 0.53 | 6.85 | 2.55 | 8.35 | 11.17 | 0.03 | 0.01 | 0.96 | 0.20 | 0.03 | 4.13 | 2.65 | 0.02 | 1.64 | 0.01 | 0.27 | 0.03 | 0.31 | 0.04 | 0.50 | 0.30 | 1.56 | 0.10 | 0.41 |
| **Western Asia** | 0.52 | 6.84 | 2.54 | 8.34 | 11.16 | 0.02 | 0.00 | 0.95 | 0.19 | 0.02 | 4.11 | 2.64 | 0.01 | 1.63 | 0.00 | 0.26 | 0.02 | 0.30 | 0.03 | 0.49 | 0.29 | 1.55 | 0.09 | 0.40 |
| **India** | 0.52 | 6.84 | 2.54 | 8.34 | 11.16 | 0.02 | 0.00 | 0.95 | 0.19 | 0.02 | 4.11 | 2.64 | 0.01 | 1.63 | 0.00 | 0.26 | 0.02 | 0.30 | 0.02 | 0.49 | 0.29 | 1.55 | 0.09 | 0.40 |
| **China, Hong Kong** | 0.53 | 6.84 | 2.54 | 8.34 | 11.17 | 0.02 | 0.00 | 0.95 | 0.19 | 0.03 | 4.12 | 2.65 | 0.02 | 1.63 | 0.01 | 0.26 | 0.02 | 0.30 | 0.03 | 0.49 | 0.29 | 1.56 | 0.09 | 0.41 |
| **Japan** | 0.53 | 6.85 | 2.55 | 8.35 | 11.17 | 0.03 | 0.01 | 0.96 | 0.20 | 0.03 | 4.13 | 2.65 | 0.03 | 1.64 | 0.01 | 0.27 | 0.03 | 0.31 | 0.04 | 0.50 | 0.30 | 1.56 | 0.10 | 0.41 |
| **South Asia** | 0.53 | 6.84 | 2.54 | 8.34 | 11.17 | 0.02 | 0.00 | 0.95 | 0.19 | 0.03 | 4.12 | 2.65 | 0.02 | 1.63 | 0.01 | 0.26 | 0.02 | 0.30 | 0.03 | 0.49 | 0.29 | 1.56 | 0.09 | 0.41 |
| **Australia** | 0.51 | 6.83 | 2.53 | 8.33 | 11.15 | 0.01 | -0.01 | 0.94 | 0.18 | 0.01 | 4.11 | 2.63 | 0.01 | 1.62 | -0.01 | 0.25 | 0.01 | 0.29 | 0.02 | 0.48 | 0.28 | 1.54 | 0.08 | 0.39 |
| **Rest of South America** | 0.51 | 6.83 | 2.53 | 8.33 | 11.15 | 0.01 | -0.01 | 0.94 | 0.18 | 0.01 | 4.11 | 2.63 | 0.01 | 1.62 | -0.01 | 0.25 | 0.01 | 0.29 | 0.02 | 0.48 | 0.28 | 1.54 | 0.08 | 0.39 |
| **Rest of Europe** | 0.46 | 6.78 | 2.48 | 8.28 | 11.10 | -0.04 | -0.06 | 0.89 | 0.13 | -0.04 | 4.06 | 2.58 | -0.04 | 1.57 | -0.06 | 0.20 | -0.04 | 0.24 | -0.03 | 0.43 | 0.23 | 1.49 | 0.03 | 0.35 |
| **Rest of Africa** | 0.51 | 6.82 | 2.52 | 8.33 | 11.15 | 0.00 | -0.01 | 0.94 | 0.18 | 0.01 | 4.10 | 2.63 | 0.00 | 1.61 | -0.01 | 0.25 | 0.00 | 0.29 | 0.01 | 0.47 | 0.28 | 1.54 | 0.07 | 0.39 |
| **Rest of Asia and Oceania** | 0.53 | 6.85 | 2.55 | 8.35 | 11.17 | 0.02 | 0.01 | 0.96 | 0.20 | 0.03 | 4.12 | 2.65 | 0.02 | 1.63 | 0.01 | 0.27 | 0.03 | 0.31 | 0.03 | 0.50 | 0.30 | 1.56 | 0.10 | 0.41 |
| **Rest of the world** | 0.51 | 6.83 | 2.53 | 8.33 | 11.15 | 0.01 | -0.01 | 0.94 | 0.18 | 0.01 | 4.11 | 2.63 | 0.01 | 1.62 | -0.01 | 0.25 | 0.01 | 0.29 | 0.02 | 0.48 | 0.28 | 1.54 | 0.08 | 0.39 |

Source: Authors' simulations

### 2.4.3. Welfare Changes

The aggregate and decomposed changes in national welfare are included in **Tables 11 and 12**. The welfare losses for Brazil are $132 million in Scenario I, with regionalization, and $271 million in Scenario II, without regionalization. The decrease in welfare in both scenarios is 67% attributable to the deterioration in terms of trade. The welfare losses in Scenario I and Scenario II correspond to 0.006% and 0.013% of Brazil's GDP, respectively. Although these values seem negligible at first sight, the welfare loss in Scenario I is equivalent to 3.5 times the annual expenditure on agricultural defense by the Ministry of Agriculture, Livestock and Supply[12]. In Scenario II, the welfare loss is equivalent to 7.2 times this government expenditure. In other words, the losses to the Brazilian economy in case of an FMD outbreak would be substantially greater than the total amount spent annually on the control and prevention of both animal and plant diseases (Brazil, 2022).

Countries that compete with Brazil in the international market for beef and pork are simulated to experience welfare gains in both scenarios. Increased welfare is expected for Uruguay ($5.1 – 12.6 million), China and Hong Kong ($8.5 – 15.2 million), India ($11.2 – 24.5 million), and the United States ($11.9 – 24.9 million) for Scenarios I and II, respectively. At the same time, most of the regions that highly depend on Brazilian beef and pork show a decrease in welfare in both scenarios, including Russia (decrease between $53.2 – 105 million), Venezuela (decrease between $48.2 – 127 million), Western Asia (decrease between $27.3 – 60.1 million), and the European Union (decrease between $7.2 – 17.9 million), for Scenarios I and II, respectively. The loss in global welfare is simulated to be $215.6 million in Scenario I, and more than doubles in Scenario II, totaling $462.9 million. Thus, the occurrence of an FMD outbreak in Brazil would have an amplified worldwide impact, with some countries benefiting and others being harmed in socioeconomic terms, with an aggregate loss of welfare globally.

Countryman and Hagerman (2017) estimated that the 2001 FMD outbreak in Brazil caused a decrease in welfare in the country equivalent to $56 million at 2001 prices. This amount corresponds to approximately $77.51 million, at 2017 prices, which is 41% lower than the Scenario I result and 71% lower than the Scenario II result from this study. However, it is important to emphasize that Brazil was a much smaller player in the global meat market in 2001 compared to 2014. In addition, the study by Countryman and Hargerman (2017) does not consider impacts of the outbreak on domestic demand and therefore is not directly comparable.

Prospective studies carried out to assess the economic impacts of FMD outbreaks in other countries show potential for much greater welfare losses than found in this study. Tozer and Marsh (2012) estimate that an outbreak in Australia could lead to a welfare loss of between $3 million and $1.7 billion depending on the size of the outbreak. Hagerman et al. (2012) estimate that there would be a decrease in welfare of between $2.7 billion and $21.9 billion in the event of an FMD outbreak in California, and a loss between $11.2 billion and $13.5 billion if the outbreak occurred in Texas. Schroeder et al. (2015) estimate a welfare loss of between $56 billion and $188 billion if an FMD outbreak happened in the Midwest region of the United States, comparing different disease control strategies and identification of cases in several states at the same time. Tozer et al. (2015) analyze the economic impacts of different strategies to contain hypothetical FMD outbreaks in Canada and estimate that the welfare loss could range from $662 million to $26 billion. While welfare effects from the aforementioned studies

[12] In 2017, the executed budget (total expenditure) on agricultural defense by the Ministry of Agriculture, Livestock and Supply was US$37.5 million (Brazil, 2022).

have much larger ranges and substantially higher upper bounds, it is important to note that each study applied a different methodology and assumed very different factors related to FMD, especially in relation to outbreak size, eradication strategies and bans on international trade.

**Table 11**. Contributions to Changes in Welfare (Equivalent Variation) Across the World ($US millions): Scenario I

| Country/Region | Aggregate Welfare Effect | Terms of Trade Contribution | Technological Change Contribution | Allocative Efficiency Contribution | Savings and Investment Contribution |
|---|---|---|---|---|---|
| Brazil | -132.0 | -88.4 | -2.1 | -20.6 | -20.8 |
| Russia | -53.2 | 3.3 | -28.5 | -20.6 | -7.4 |
| Venezuela | -48.2 | 2.8 | -48.5 | -4.1 | 1.5 |
| Western Asia | -27.3 | -8.0 | -18.2 | -1.2 | 0.1 |
| Europe (28) | -7.2 | 13.3 | -3.6 | -15.7 | -1.2 |
| North Africa | -5.5 | 1.4 | -8.8 | 1.2 | 0.8 |
| Rest of Africa | -5.0 | -0.6 | -3.9 | -0.8 | 0.3 |
| Chile | -3.8 | 1.5 | -4.6 | -0.8 | 0.0 |
| Mexico | -1.2 | -0.8 | 0.0 | -0.5 | 0.1 |
| Rest of Europe | -0.3 | 3.4 | -1.0 | -2.4 | -0.4 |
| Southern Africa | -0.1 | -0.1 | 0.0 | 0.0 | 0.1 |
| Rest of South America | 0.1 | 0.6 | -0.6 | -0.1 | 0.2 |
| Rest of the world | 0.8 | 2.0 | -0.8 | -0.3 | -0.1 |
| South Asia | 1.9 | 0.8 | 0.0 | 0.3 | 0.9 |
| Argentina | 2.1 | 5.0 | -1.6 | -1.5 | 0.2 |
| Paraguay | 2.3 | 6.1 | -4.9 | 0.5 | 0.6 |
| Australia | 2.9 | 2.4 | 0.0 | 0.0 | 0.4 |
| Canada | 4.2 | 3.9 | -0.2 | -0.2 | 0.6 |
| Japan | 4.5 | 4.6 | -0.2 | -0.3 | 0.4 |
| Uruguay | 5.1 | 4.4 | -1.3 | 1.3 | 0.7 |
| China, Hong Kong | 8.5 | 19.4 | -23.6 | 4.5 | 8.3 |
| India | 11.2 | 8.1 | 0.0 | -1.1 | 4.2 |
| United States of America | 11.9 | 7.9 | -4.0 | -1.0 | 9.0 |
| Rest of Asia and Oceania | 12.6 | 7.1 | -1.5 | 5.5 | 1.5 |

Source: Authors' simulations

**Table 12**. Contributions to Changes in Welfare (Equivalent Variation) Across the World ($US millions): Scenario II

| Country/Region | Aggregate Welfare Effect | Terms of Trade Contribution | Technological Change Contribution | Allocative Efficiency Contribution | Savings and Investment Contribution |
|---|---|---|---|---|---|
| Brazil | -271.0 | -184.0 | -2.0 | -42.1 | -43.3 |
| Venezuela | -127.0 | 5.3 | -128.0 | -9.2 | 5.3 |
| Russia | -105.0 | 6.9 | -56.9 | -40.5 | -15.0 |
| Western Asia | -60.1 | -15.8 | -41.3 | -2.6 | -0.3 |
| Europe (28) | -17.9 | 24.3 | -7.6 | -32.5 | -2.2 |
| North Africa | -12.1 | 3.2 | -19.8 | 2.7 | 1.8 |
| Rest of Africa | -9.4 | -0.9 | -7.5 | -1.6 | 0.6 |
| Chile | -8.5 | 3.1 | -9.8 | -1.7 | 0.1 |
| Mexico | -2.5 | -1.6 | 0.0 | -1.1 | 0.2 |
| Rest of Europe | -1.0 | 6.7 | -1.8 | -5.0 | -0.8 |
| Southern Africa | -0.2 | -0.3 | 0.0 | 0.0 | 0.2 |
| Rest of South America | 1.5 | 2.0 | -0.8 | -0.1 | 0.4 |
| Rest of the world | 2.8 | 5.1 | -1.3 | -0.6 | -0.4 |
| South Asia | 4.1 | 1.6 | 0.0 | 0.7 | 1.9 |
| Australia | 6.9 | 6.0 | 0.0 | 0.1 | 0.8 |
| Argentina | 6.9 | 11.2 | -1.8 | -2.8 | 0.3 |
| Canada | 7.0 | 6.6 | -0.3 | -0.4 | 1.1 |
| Japan | 8.8 | 9.0 | -0.3 | -0.6 | 0.7 |
| Paraguay | 10.8 | 13.3 | -5.8 | 1.7 | 1.7 |
| Uruguay | 12.6 | 9.7 | -2.1 | 3.2 | 1.7 |
| China, Hong Kong | 15.2 | 39.9 | -50.6 | 10.1 | 15.9 |
| India | 24.5 | 17.8 | 0.0 | -2.4 | 9.1 |
| United States of America | 24.9 | 16.0 | -6.7 | -2.0 | 17.7 |
| Rest of Asia and Oceania | 25.9 | 15.1 | -3.1 | 11.2 | 2.7 |

Source: Authors' simulations

### 2.4.4. Sensitivity Analysis

The SSA employed in this study tested the sensitivity of results to the magnitudes of the shocks to variables in both scenarios. The SSA established intervals for each variable, with a triangular, symmetric and independent distribution. **Table 13** shows the results of the SSA for variations in production losses, based on the epidemiological scenarios which included best, mean, and worst-case scenarios for an FMD outbreak. The production loss in the best case is expected to be half the loss of the mean case, so the production shocks were varied by 50% in relation to the initial shock for the sensitivity analysis. This means that in the SSA, the model was solved by varying the productivity loss live cattle within a range between -0.03% and -0.01%. The second SSA for the production loss considered the worst epidemiological scenario, which would be a variation of 150% compared to the production loss of the mean scenario. The SSA was then based on a production shock range between -0.05% and 0% for live cattle. The reported confidence intervals were obtained through the estimated mean and standard deviation of the SSA solutions, using Chebychev's inequality – which implies bounds of 4.47 standard deviations from the mean, for a 95% confidence interval.

In this sense, varying the cattle production loss shock by 50%, results show with 95% confidence that the total impact of an FMD outbreak on welfare in Brazil would be between -$137.05 and -$126.77 million for the scenario with regionalization, and between -$276.43 and -$266.23 million for the scenario without regionalization (**Table 13**). Increasing the variation of the shock on cattle production to 150%, the range of the impacts on welfare would be between -$147.38 and -$116.44 million if regionalization was applied by the international market, and between -$287.65 and -$255.01 million if regionalization was not implemented. Although the variations in production losses are substantial compared to the mean epidemiological scenario, they remain relatively small.

**Table 13.** SSA with Variation in Shocks to Production and Exports, 95% Confidence Interval

| **Shocked Variable** | **Variation in Shocks** | **Affected Variable** | **SI - Regionalization** | | | **SII - No Regionalization** | | |
|---|---|---|---|---|---|---|---|---|
| | | | **Model Result** | **Lower Limit** | **Upper Limit** | **Model Result** | **Lower Limit** | **Upper Limit** |
| Cattle Production | 50% | Welfare ($ millions) | -131.91 | -137.05 | -126.77 | -271.33 | -276.43 | -266.23 |
| | 150% | Welfare ($ millions) | -131.91 | -147.38 | -116.44 | -271.33 | -287.65 | -255.01 |
| Cattle, Hog, Beef, and Pork Exports | 50% | Welfare ($ millions) | -131.91 | -169.18 | -94.08 | -271.33 | -348.17 | -192.25 |
| | | Output Cattle (%) | -0.96 | -1.27 | -0.65 | -2.17 | -2.88 | -1.44 |
| | | Output Hog (%) | -0.38 | -0.55 | -0.19 | -0.59 | -0.80 | -0.36 |
| | | Output Beef (%) | -1.03 | -1.43 | -0.63 | -2.30 | -3.18 | -1.40 |
| | | Output Pork (%) | -4.87 | -6.77 | -2.93 | -7.88 | -10.79 | -4.89 |

Source: Authors' simulations

The effects of government expenditure variations were also analyzed based on the best and worst-case epidemiological scenarios. Two SSAs were implemented, one with a variation of 50% and the other with a variation of 150% in government expenditure. However, even with substantial variations compared to the mean scenario considered for the initial simulations, the impact of government expenditure variation was negligible, and results from the SSA did not demonstrate noteworthy differences in model results. The same is true for the SSA for beef and pork domestic demand variations, considering that the impact of -0.42% could vary 100% or 150%.

Sensitivity analysis was also considered for Brazilian changes in exports restrictions for cattle, hogs, beef, and pork from Brazil. Considering 50% variation in Brazilian exports reductions in both scenarios, no impacts on producer prices were observed. However, varying exports restrictions for the SSA showed variations in output and welfare effects. **Table 13** shows that pork output varies between -6.77% and -2.93% in Scenario I, and between -10,79% and -4.89% in Scenario II, with 95% confidence. Furthermore, the SSA results in **Table 13** indicate that the total welfare impact in Brazil could be in the range of -$169.2 and -$94.1 million if regionalization is applied, or between -348.2 and -$192.3 million with no regionalization.

## 2.5. Conclusion and Policy Implications

Brazil's livestock and meat sectors are highly integrated in the international market and are important both domestically and globally. The persistent risk of emerging infectious disease threatens the stability of the

Brazilian animal agriculture industry and food security. This economic analysis shows the dimension of the impacts of a highly contagious animal disease (FMD) in Brazil and the spillover effects on other countries. The occurrence of an FMD outbreak in Brazil could cause direct production and demand impacts, as well as trade losses for the country. Direct economic losses are estimated and inputted as exogenous shocks into a multiregional CGE model based on results from a new epidemiological model for FMD spread in Brazil. This is the first study for Brazil using epidemiological results and estimates of direct losses based on observed data on livestock inventories and prices in Brazil. Furthermore, the applied CGE framework combines an advanced economic modeling approach for FMD analysis and the unique benefit of considering the impacts of an FMD outbreak in Brazil on different countries and regions.

Unlike other studies from the international literature that focus on alternate FMD mitigation strategies, this research focuses on the measures and goals stablished in the Contingency Plan for FMD by the Brazilian Ministry of Agriculture, Livestock and Supply. This means that the results of this study are based on a control and eradication strategy that combines stamping-out and emergency vaccination and a goal of eradicating a foot-and-mouth disease outbreak within a 30-day period. Differences in the distribution of economic consequences arise between the application and non-application of the Principle of Regionalization by the international market. The total welfare impact from a simulated FMD outbreak ranges from $132 million to $271 million in Brazil when considering the mean case from the epidemiological model.

Other countries are also negatively affected by an FMD outbreak in Brazil, especially Venezuela, Russia and the Western Asia region, which all suffer welfare losses due to reliance on Brazilian meat to satisfy domestic demand. On the other hand, Brazil's major competitors in the global meat market are expected to benefit from an FMD-related crisis in Brazil, including Uruguay, China, India, and the United States. The results of the present study show that the United States would be the country with the greatest welfare gain, between $12 million and $25 million, as a result of an FMD outbreak in Brazil. This is complementary to the result found by Boisvert et al. (2012), which used the GTAP model to assess the impacts of a hypothetical FMD disease outbreak in the United States and found a welfare gain in South American countries, especially Brazil.

The welfare loss estimates of this study are much smaller than in many other studies mainly because the focus is on a short-run localized FMD outbreak that only lasts 30 days. Although relatively small, the $132 million decrease in welfare in Brazil corresponds to 3.5 times the annual expenditure of the Ministry of Agriculture for the prevention of animal and plant diseases. In Scenario II, in which Brazil's export markets do not apply the Regionalization Principle, the $271 million loss corresponds to 7.2 times the expenditure on health programs. This means that every $1 spent on animal health services by the federal government could be avoiding a potential FMD-related loss of between $3.50 and $7.20, assuming that the official animal health service is effective in preventing the introduction of the disease into Brazil.

Several limitations of this research are noteworthy. First, the epidemiological and economic modeling employed in this study are based on simulations and assumptions. The simulated FMD outbreak is hypothetical because the disease has been eradicated from Brazil and there have been no outbreaks in free areas in the country for over 15 years. Thus, there is no way to predict where the disease may be introduced and how its spread may occur. The mitigation strategies assumed in this study are fixed and the simulation of disease spread is stochastic. Furthermore, the duration of the outbreak and the assumed impacts on domestic and export market demand are extremely important for assessing the economic impacts of FMD. The lack of publicly available information on public costs and production losses means that the production loss and cost of eradication presented are highly stylized. There is also little published information on how domestic or import markets would react to an FMD outbreak, because there have been no recent FMD outbreaks in major beef or pork export countries withing the last decade. Therefore, there is not robust information to fully anticipate demand shocks related to such an event. Although the CGE model used makes it possible to evaluate results on welfare and bilateral trade for different countries and regions, this advantage comes at the cost of lost detail and sensitivity at the production level when compared to a country-level model. As in the CGE model applied by Oladosu et al. (2013), the present study uses a static model, which does not capture the future impacts of increased government spending to eradicate the FMD outbreak, nor the impacts of the delay in resuming exports to some more restrictive import markets. It is important to consider these limitations when analyzing the results of this study.

In addition to the loss of access to export markets, there are considerable costs in controlling FMD, in addition to the payment of indemnities, loss of production and losses in livestock-related industries. Despite the economic importance of outbreaks of this disease, there are relatively few studies that combine robust epidemiological models with rigorous economic analyses. The results of this research demonstrate the importance of promoting investments on animal disease preparedness, to prevent the entry and spread of animal diseases in Brazil given the costs that may arise in the case of an FMD outbreak. Ensuring a disease-free status of several animal diseases is essential for Brazil to maintain access to the international market and maintain its position as an important meat exporter to the rest of the world.

This study raises questions for future research. First, diversified FMD epidemiological scenarios must be considered for economic analysis of impacts. Second, additional research is warranted to investigate different control and eradication measures and varied capacity constraints to respond to animal health emergencies. Finally, scenarios of different trade sanctions can be further explored through the application of a dynamic model that allows an analysis over time. Overall, this study shows that the impacts of an FMD outbreak in Brazil, although relatively small given the size of the Brazilian economy, can lead to economic damages domestically and in countries that highly depend on Brazilian exports. Key findings from this work are relevant for informing public policy related to animal health and highlight the global impacts of animal disease events on agricultural markets.

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## APPENDIX

**Table A1.** Agricultural Sectors Aggregation Description

| N. | Code | Aggregated Sector | Description |
|---|---|---|---|
| 1 | gro | Grains | Rice; Wheat; Maize (corn); Sorghum; Barley; Rye; Oats; Millets; Other cereals |
| 2 | ocr | Other agricultural products | Vegetables; Fruit and nuts; Edible roots and tubers with high starch or inulin content; Pulses (dried leguminous vegetables); Oil seeds and oleaginous fruit; Sugar crops; Fibre crops; Stimulant, spice and aromatic crops; Forage products; Plants and parts of plants used primarily in perfumery, in pharmacy, or for insecticidal, fungicidal or similar purposes; Beet seeds (excluding sugar beet seeds) and seeds of forage plants; Natural rubber in primary forms or in plates, sheets or strip; Living plants,cut flowers and flower buds, flower seeds; Unmanufactured tobacco; Other raw vegetable materials n.e.c.; Raw animal materials used in textiles; Forestry and logging products. |
| 3 | clt | Cattle | Bovine animals, live; Other ruminants; Bovine semen; Horses and other equines |
| 4 | hog | Hogs | Swine/pigs |
| 5 | oap | Poultry and other animals | Poultry; Other live animals; Eggs of hens or other birds in shell, fresh; Semen, n.e.c; Natural honey; Snails, fresh, chilled, frozen, dried, salted or in brine, except sea snails; Edible products of animal origin n.e.c.; Hides, skins and furskins, raw; Insect waxes and spermaceti, whether or not refined or coloured. |
| 6 | cmt | Beef | Meat of cattle, fresh or chilled; Meat of buffalo, fresh or chilled; Edible offal of cattle, fresh, chilled or frozen; Meat of horses and other equines, fresh or chilled; Meat of sheep, fresh or chilled; Meat of goat, fresh or chilled; Meat of camels and camelids, fresh or chilled; Other meat of mammals, fresh or chilled; Meat of mammals, frozen; Edible offal of mammals, fresh, chilled or frozen. |
| 7 | pmt | Pork | Meat of pigs, fresh or chilled |
| 8 | omt | Other meat | Meat of rabbits and hares, fresh or chilled; Meat of poultry, fresh or chilled; Meat of poultry, frozen; Edible offal of poultry, fresh, chilled or frozen; Other meat and edible offal, fresh, chilled or frozen; Preserves and preparations of meat, meat offal or blood; Flours, meals and pellets of meat or meat offal, inedible, greaves. |
| 9 | dyp | Dairy products | Raw milk; Dairy products |

| | | | |
|---|---|---|---|
| 10 | ofd | Other processed foods | Animal fats; Vegetable oils; Margarine and similar preparations; Cotton linters; Oil-cake and other residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits, except those of mustard; vegetable waxes, except triglycerides; degras; residues resulting from the treatment of fatty substances or animal or vegetable waxes; Rice, semi- or wholly milled, or husked; Sugar and molasses; Prepared and preserved fish, crustaceans, molluscs and other aquatic invertebrates; Prepared and preserved vegetables, pulses and potatoes; Prepared and preserved fruits and nuts; Wheat and meslin flour; Other cereal flours; Groats, meal and pellets of wheat and other cereals; Other cereal grain products (including corn flakes); Other vegetable flours and meals; Mixes and doughs for the preparation of bakers' wares; Starches and starch products; sugars and sugar syrups n.e.c.; Preparations used in animal feeding; lucerne (alfalfa) meal and pellets; Bakery products; Cocoa, chocolate and sugar confectionery; Macaroni, noodles, couscous and similar farinaceous products; Food products n.e.c.; Beverages; Tobacco products. |

Source: Authors’ aggregation using GTAP V10 Database

**Table A2.** Other Sectors Aggregation Description

| N. | Code | Aggregated Sector | Description |
|---|---|---|---|
| 1 | opp | Other primary products | Fishing and aquaculture; Hunting, trapping and related service activities; Mining of coal and lignite; Extraction of crude petroleum; Support activities for petroleum and natural gas extraction (petroleum part); Extraction of natural gas; Support activities for petroleum and natural gas extraction (natural gas part); Mining of metal ores; Other mining and quarrying; Support activities for other mining and quarrying. |
| 2 | mfg | Manufacturing | Manufacture of textiles; Manufacture of wearing apparel; Manufacture of leather and related products; Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials; Manufacture of paper and paper products; Printing and reproduction of record media; Manufacture of coke and refined petroleum products; Manufacture of chemicals and chemical products; Manufacture of pharmaceuticals, medicinal chemical and botanical products; Manufacture of rubber and plastics products; Manufacture of other non-metallic mineral products; Manufacture of basic iron and steel; Casting of iron and steel; Manufacture of basic precious and other non-ferrous metals; Casting of non-ferrous metals; Manufacture of fabricated metal products, except machinery and equipment; Manufacture of computer, electronic and optical products; Manufacture of electrical equipment; Manufacture of machinery and equipment n.e.c.; Manufacture of motor vehicles, trailers and semi-trailers; Manufacture of other transport equipment; Manufacture of furniture; Other manufacturing; Repair and installation of machinery and equipment; Production, collection and distribution of electricity; Steam and hot water supply; Manufacture of gas; distribution of gaseous fuels through mains. |
| 3 | ser | Services | Collection, purification and distribution of water, water collection, treatment and supply; Sewerage; Waste collection, treatment and disposal activities; materials recovery; Remediation activities and other waste management services; Construction of buildings; Civil engineering; Specialized construction activities; Wholesale and retail trade and repair of motor vehicles and motorcycles; Wholesale trade, except of motor vehicles and motorcycles; Retail trade, except of motor vehicles and motorcycles; Accommodation; Food and beverage service activities; Land transport and transport via pipelines; Water transport; Air transport; Warehousing and support activities for transportation; Postal and courier activities; Publishing activities; Motion picture, video and television program production, sound recording and music publishing activities; Programming and broadcasting activities; Telecommunications; Computer programming, consultancy and related activities; Information service activities; Financial service activities, except insurance and pension funding; Activities auxiliary to financial service activities, except insurance and pension funding; Fund management activities; Insurance, reinsurance and pension funding, except compulsory social security; Activities auxiliary to insurance and pension funding; Real estate activities; Professional, scientific and technical activities and Administrative and support service activities; Arts, entertainment and recreation; Other service activities; Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use; Public administration and defense; compulsory social security; Activities of extraterritorial organizations and bodies; Education; Human health and social work activities; n.a. |

Source: Authors' aggregation using GTAP V10 Database

**Table A3.** Regional Aggregation Description

| N. | Code | Region | Countries |
|---|---|---|---|
| 1 | aus | Australia | Australia |
| 2 | chk | China, Hong Kong | China, Hong Kong |
| 3 | jpn | Japan | Japan |
| 4 | ind | India | India |
| 5 | osa | South Asia | Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia |
| 6 | oao | Rest of Asia and Oceania | Korea, Taiwan, Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia, New Zealand, Rest of Oceania |
| 7 | can | Canada | Canada |
| 8 | usa | United States of America | United States of America |
| 9 | mex | Mexico | Mexico |
| 10 | arg | Argentina | Argentina |
| 11 | bra | Brazil | Brazil |
| 12 | chl | Chile | Chile |
| 13 | pry | Paraguay | Paraguay |
| 14 | ury | Uruguay | Uruguay |
| 15 | vem | Venezuela | Venezuela |
| 16 | osm | Rest of South America | Colombia, Bolivia, Ecuador, Peru, Rest of South America |
| 17 | eu28 | Europe | Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom |
| 18 | oeu | Rest of Europe | Switzerland, Norway, Rest of EFTA, Albania, Belarus, Ukraine, Rest of Eastern Europe, Rest of Europe |
| 19 | rus | Russian Federation | Russian Federation |
| 20 | wna | Western Asia | Armenia, Azerbaijan, Georgia, Bahrain, Iran, Israel, Kuwait, Jordan, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Rest of Western Asia |
| 21 | noa | North Africa | Egypt, Morocco, Tunisia, Rest of North Africa |
| 22 | sna | Southern Africa | Botswana, Namibia, South Africa, Rest of South African Customs Union |
| 23 | oaf | Rest of Africa | Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa |

| | | | |
|---|---|---|---|
| 24 | row | Rest of the world | Mongolia, Rest of East Asia, Rest of North America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean, Kazakhstan, Kyrgyzstan, Taijikistan, Rest of Former Soviet Union, Rest of the World |

Source: Authors' aggregation using GTAP V10 Database

**Table A4.** Changes in Regional Bilateral Beef Exports (%): Scenario II

| Exporting Regions | Importing Regions | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Brazil | Argentina | Chile | Paraguay | Uruguay | Venezuela | Mexico | USA | Canada | Europe (28) | Russia | North Africa | Southern Africa | Western Asia | India | China, Hong Kong | Japan | South Asia | Australia | Rest of South America | Rest of Europe | Rest of Africa | Rest of Asia and Oceania | Rest of the world |
| **Brazil** | -28.00 | -26.01 | -22.29 | -12.40 | -19.63 | -12.21 | -26.30 | -26.25 | -26.25 | -26.18 | -22.21 | -22.78 | -26.28 | -25.04 | -26.23 | -23.99 | -26.28 | -26.22 | -26.16 | -26.00 | -25.82 | -25.36 | -26.20 | -26.15 |
| **Argentina** | 0.13 | 0.05 | 5.12 | 18.48 | 8.71 | 18.76 | -0.35 | -0.28 | -0.28 | -0.17 | 5.23 | 4.45 | -0.29 | 1.40 | -0.27 | 2.82 | -0.29 | -0.22 | -0.16 | 0.11 | 0.34 | 0.96 | -0.17 | -0.11 |
| **Chile** | -0.29 | -0.38 | 4.66 | 17.97 | 8.25 | 18.24 | -0.75 | -0.68 | -0.69 | -0.58 | 4.79 | 4.01 | -0.73 | 0.98 | -0.69 | 2.39 | -0.71 | -0.64 | -0.58 | -0.31 | -0.08 | 0.53 | -0.59 | -0.52 |
| **Paraguay** | -1.48 | -1.57 | 3.43 | 16.51 | 6.91 | 16.78 | -2.00 | -1.93 | -1.93 | -1.80 | 3.54 | 2.78 | -1.92 | -0.23 | -1.92 | 1.15 | -1.95 | -1.81 | -1.82 | -1.50 | -1.27 | -0.66 | -1.77 | -1.71 |
| **Uruguay** | -0.95 | -1.04 | 3.99 | 17.22 | 7.50 | 17.48 | -1.42 | -1.34 | -1.34 | -1.25 | 4.10 | 3.33 | -1.37 | 0.31 | -1.37 | 1.71 | -1.41 | -1.30 | -1.27 | -0.97 | -0.74 | -0.13 | -1.24 | -1.18 |
| **Venezuela** | -9.40 | -9.46 | -4.88 | 7.21 | -1.63 | 7.46 | -9.82 | -9.76 | -9.76 | -9.67 | -4.78 | -5.40 | -9.78 | -8.25 | -9.74 | -6.96 | -9.78 | -9.70 | -9.65 | -9.42 | -9.17 | -8.65 | -9.66 | -9.57 |
| **Mexico** | 0.52 | 0.45 | 5.53 | 18.95 | 9.14 | 19.22 | 0.04 | 0.12 | 0.12 | 0.22 | 5.64 | 4.86 | 0.09 | 1.79 | 0.13 | 3.22 | 0.10 | 0.18 | 0.24 | 0.50 | 0.73 | 1.35 | 0.22 | 0.28 |
| **USA** | 0.51 | 0.44 | 5.52 | 18.93 | 9.13 | 19.21 | 0.03 | 0.11 | 0.11 | 0.21 | 5.62 | 4.84 | 0.08 | 1.78 | 0.12 | 3.20 | 0.08 | 0.17 | 0.22 | 0.49 | 0.72 | 1.34 | 0.21 | 0.27 |
| **Canada** | 0.49 | 0.42 | 5.50 | 18.92 | 9.11 | 19.19 | 0.02 | 0.10 | 0.10 | 0.20 | 5.61 | 4.83 | 0.07 | 1.77 | 0.11 | 3.19 | 0.07 | 0.16 | 0.21 | 0.47 | 0.71 | 1.32 | 0.20 | 0.26 |
| **Europe (28)** | 0.50 | 0.43 | 5.51 | 18.93 | 9.12 | 19.20 | 0.03 | 0.10 | 0.10 | 0.20 | 5.62 | 4.84 | 0.08 | 1.78 | 0.12 | 3.20 | 0.08 | 0.17 | 0.22 | 0.48 | 0.71 | 1.33 | 0.20 | 0.27 |
| **Russia** | 0.12 | 0.05 | 5.11 | 18.47 | 8.70 | 18.74 | -0.36 | -0.28 | -0.28 | -0.18 | 5.21 | 4.44 | -0.31 | 1.39 | -0.27 | 2.80 | -0.31 | -0.22 | -0.17 | 0.10 | 0.33 | 0.94 | -0.18 | -0.11 |
| **North Africa** | 0.46 | 0.39 | 5.47 | 18.88 | 9.08 | 19.15 | -0.01 | 0.06 | 0.06 | 0.16 | 5.58 | 4.80 | 0.04 | 1.74 | 0.07 | 3.16 | 0.04 | 0.12 | 0.18 | 0.44 | 0.67 | 1.29 | 0.16 | 0.22 |
| **Southern Africa** | 0.53 | 0.46 | 5.53 | 18.95 | 9.15 | 19.23 | 0.05 | 0.13 | 0.13 | 0.23 | 5.64 | 4.86 | 0.10 | 1.80 | 0.14 | 3.22 | 0.10 | 0.19 | 0.24 | 0.50 | 0.74 | 1.35 | 0.23 | 0.29 |
| **Western Asia** | -0.21 | -0.28 | 4.76 | 18.10 | 8.34 | 18.35 | -0.68 | -0.61 | -0.61 | -0.50 | 4.87 | 4.11 | -0.63 | 1.07 | -0.60 | 2.47 | -0.63 | -0.53 | -0.49 | -0.23 | 0.00 | 0.63 | -0.50 | -0.44 |
| **India** | 0.50 | 0.43 | 5.50 | 18.92 | 9.11 | 19.19 | 0.02 | 0.10 | 0.10 | 0.20 | 5.61 | 4.84 | 0.07 | 1.77 | 0.11 | 3.19 | 0.07 | 0.16 | 0.21 | 0.48 | 0.71 | 1.33 | 0.20 | 0.26 |
| **China, Hong Kong** | 0.27 | 0.20 | 5.27 | 18.65 | 8.87 | 18.92 | -0.20 | -0.13 | -0.13 | -0.03 | 5.37 | 4.60 | -0.15 | 1.55 | -0.12 | 2.97 | -0.15 | -0.06 | -0.01 | 0.25 | 0.48 | 1.10 | -0.03 | 0.04 |
| **Japan** | 0.53 | 0.46 | 5.54 | 18.96 | 9.15 | 19.23 | 0.05 | 0.13 | 0.13 | 0.23 | 5.65 | 4.87 | 0.10 | 1.80 | 0.14 | 3.23 | 0.10 | 0.19 | 0.24 | 0.51 | 0.74 | 1.36 | 0.23 | 0.29 |
| **South Asia** | 0.52 | 0.45 | 5.53 | 18.95 | 9.14 | 19.23 | 0.05 | 0.12 | 0.12 | 0.22 | 5.64 | 4.86 | 0.10 | 1.80 | 0.14 | 3.22 | 0.10 | 0.18 | 0.24 | 0.50 | 0.73 | 1.35 | 0.22 | 0.29 |
| **Australia** | 0.27 | 0.19 | 5.26 | 18.64 | 8.86 | 18.91 | -0.21 | -0.13 | -0.13 | -0.03 | 5.37 | 4.60 | -0.16 | 1.54 | -0.12 | 2.96 | -0.16 | -0.07 | -0.02 | 0.25 | 0.48 | 1.09 | -0.03 | 0.03 |
| **Rest of South America** | 0.32 | 0.25 | 5.31 | 18.70 | 8.92 | 18.99 | -0.16 | -0.08 | -0.08 | 0.02 | 5.43 | 4.65 | -0.11 | 1.59 | -0.07 | 3.01 | -0.11 | -0.02 | 0.03 | 0.30 | 0.53 | 1.15 | 0.02 | 0.08 |
| **Rest of Europe** | 0.34 | 0.27 | 5.34 | 18.74 | 8.95 | 19.01 | -0.13 | -0.05 | -0.05 | 0.05 | 5.46 | 4.68 | -0.08 | 1.62 | -0.04 | 3.04 | -0.08 | 0.01 | 0.06 | 0.32 | 0.56 | 1.17 | 0.05 | 0.11 |
| **Rest of Africa** | 0.47 | 0.40 | 5.47 | 18.88 | 9.08 | 19.16 | -0.01 | 0.07 | 0.07 | 0.17 | 5.58 | 4.80 | 0.04 | 1.74 | 0.08 | 3.16 | 0.04 | 0.13 | 0.18 | 0.44 | 0.68 | 1.30 | 0.17 | 0.23 |
| **Rest of Asia and Oceania** | 0.39 | 0.32 | 5.40 | 18.80 | 9.00 | 19.07 | -0.08 | 0.00 | 0.00 | 0.10 | 5.51 | 4.73 | -0.03 | 1.67 | 0.01 | 3.09 | -0.03 | 0.06 | 0.11 | 0.37 | 0.61 | 1.23 | 0.10 | 0.16 |
| **Rest of the world** | 0.44 | 0.38 | 5.45 | 18.86 | 9.06 | 19.14 | -0.03 | 0.05 | 0.05 | 0.15 | 5.56 | 4.78 | 0.02 | 1.72 | 0.06 | 3.14 | 0.02 | 0.11 | 0.16 | 0.42 | 0.65 | 1.28 | 0.15 | 0.21 |

Source: Authors' simulations

**Table A5.** Changes in Regional Bilateral Pork Exports (%): Scenario II

| Exporting Regions | Importing Regions | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Brazil | Argentina | Chile | Paraguay | Uruguay | Venezuela | Mexico | USA | Canada | Europe (28) | Russia | North Africa | Southern Africa | Western Asia | India | China, Hong Kong | Japan | South Asia | Australia | Rest of South America | Rest of Europe | Rest of Africa | Rest of Asia and Oceania | Rest of the world |
| **Brazil** | -32.77 | -22.79 | -27.94 | -20.92 | -17.39 | -30.75 | -30.81 | -29.74 | -30.59 | -30.77 | -26.12 | -27.83 | -30.79 | -28.99 | -30.78 | -30.52 | -30.79 | -30.48 | -30.77 | -30.27 | -30.48 | -29.07 | -30.71 | -30.35 |
| **Argentina** | 0.35 | 11.57 | 4.12 | 14.27 | 19.38 | 0.06 | -0.02 | 1.51 | 0.29 | 0.02 | 6.76 | 4.28 | 0.00 | 2.61 | -0.01 | 0.40 | 0.01 | 0.46 | 0.02 | 0.77 | 0.45 | 2.49 | 0.12 | 0.63 |
| **Chile** | 0.13 | 11.32 | 3.89 | 14.01 | 19.12 | -0.16 | -0.24 | 1.29 | 0.07 | -0.20 | 6.53 | 4.04 | -0.22 | 2.38 | -0.24 | 0.18 | -0.21 | 0.23 | -0.20 | 0.54 | 0.23 | 2.27 | -0.10 | 0.41 |
| **Paraguay** | -1.65 | 9.35 | 2.05 | 11.99 | 17.00 | -1.93 | -2.01 | -0.51 | -1.71 | -1.98 | 4.71 | 2.20 | -1.99 | 0.57 | -2.00 | -1.57 | -1.98 | -1.54 | -1.97 | -1.22 | -1.55 | 0.48 | -1.87 | -1.37 |
| **Uruguay** | -1.36 | 9.67 | 2.38 | 12.30 | 17.32 | -1.61 | -1.74 | -0.21 | -1.42 | -1.70 | 4.96 | 2.52 | -1.72 | 0.84 | -1.73 | -1.31 | -1.67 | -1.26 | -1.70 | -0.97 | -1.27 | 0.73 | -1.60 | -1.10 |
| **Venezuela** | 0.17 | 11.37 | 3.94 | 14.06 | 19.17 | -0.11 | -0.20 | 1.33 | 0.11 | -0.16 | 6.57 | 4.10 | -0.17 | 2.43 | -0.19 | 0.22 | -0.17 | 0.28 | -0.15 | 0.59 | 0.27 | 2.31 | -0.05 | 0.45 |
| **Mexico** | 0.38 | 11.61 | 4.16 | 14.31 | 19.42 | 0.10 | 0.02 | 1.55 | 0.33 | 0.05 | 6.80 | 4.32 | 0.04 | 2.65 | 0.02 | 0.44 | 0.05 | 0.50 | 0.06 | 0.80 | 0.49 | 2.53 | 0.16 | 0.67 |
| **United States of America** | 0.36 | 11.59 | 4.14 | 14.29 | 19.40 | 0.08 | 0.00 | 1.53 | 0.31 | 0.03 | 6.78 | 4.30 | 0.02 | 2.63 | 0.01 | 0.42 | 0.03 | 0.48 | 0.04 | 0.78 | 0.47 | 2.51 | 0.14 | 0.65 |
| **Canada** | 0.32 | 11.54 | 4.10 | 14.24 | 19.35 | 0.04 | -0.04 | 1.49 | 0.27 | -0.01 | 6.74 | 4.26 | -0.02 | 2.59 | -0.04 | 0.38 | -0.01 | 0.44 | 0.00 | 0.75 | 0.43 | 2.47 | 0.10 | 0.61 |
| **Europe (28)** | 0.36 | 11.58 | 4.14 | 14.28 | 19.39 | 0.08 | -0.01 | 1.53 | 0.30 | 0.03 | 6.77 | 4.29 | 0.02 | 2.62 | 0.00 | 0.41 | 0.02 | 0.47 | 0.04 | 0.78 | 0.46 | 2.51 | 0.14 | 0.65 |
| **Russian Federation** | 0.22 | 11.43 | 3.99 | 14.12 | 19.23 | -0.06 | -0.14 | 1.39 | 0.17 | -0.11 | 6.63 | 4.15 | -0.12 | 2.48 | -0.14 | 0.28 | -0.11 | 0.34 | -0.10 | 0.64 | 0.33 | 2.37 | 0.00 | 0.51 |
| **North Africa** | 0.35 | 11.57 | 4.13 | 14.27 | 19.38 | 0.07 | -0.02 | 1.52 | 0.29 | 0.02 | 6.76 | 4.28 | 0.01 | 2.61 | -0.01 | 0.40 | 0.01 | 0.47 | 0.03 | 0.77 | 0.45 | 2.50 | 0.13 | 0.64 |
| **Southern Africa** | 0.38 | 11.61 | 4.16 | 14.31 | 19.42 | 0.10 | 0.02 | 1.55 | 0.33 | 0.05 | 6.80 | 4.32 | 0.04 | 2.65 | 0.02 | 0.44 | 0.05 | 0.50 | 0.06 | 0.80 | 0.49 | 2.53 | 0.16 | 0.67 |
| **Western Asia** | 0.37 | 11.59 | 4.14 | 14.29 | 19.40 | 0.08 | 0.00 | 1.53 | 0.31 | 0.03 | 6.78 | 4.30 | 0.02 | 2.63 | 0.01 | 0.42 | 0.03 | 0.48 | 0.04 | 0.79 | 0.47 | 2.51 | 0.14 | 0.65 |
| **India** | 0.36 | 11.58 | 4.13 | 14.28 | 19.39 | 0.08 | -0.01 | 1.52 | 0.30 | 0.03 | 6.77 | 4.29 | 0.01 | 2.62 | 0.00 | 0.41 | 0.02 | 0.47 | 0.04 | 0.78 | 0.46 | 2.50 | 0.13 | 0.64 |
| **China, Hong Kong** | 0.37 | 11.60 | 4.15 | 14.30 | 19.41 | 0.09 | 0.01 | 1.54 | 0.32 | 0.04 | 6.79 | 4.31 | 0.03 | 2.64 | 0.01 | 0.43 | 0.04 | 0.49 | 0.05 | 0.79 | 0.48 | 2.52 | 0.15 | 0.66 |
| **Japan** | 0.38 | 11.61 | 4.16 | 14.31 | 19.43 | 0.10 | 0.02 | 1.55 | 0.33 | 0.05 | 6.80 | 4.32 | 0.04 | 2.65 | 0.03 | 0.44 | 0.05 | 0.50 | 0.06 | 0.81 | 0.49 | 2.53 | 0.16 | 0.67 |
| **South Asia** | 0.37 | 11.59 | 4.15 | 14.29 | 19.41 | 0.09 | 0.00 | 1.54 | 0.31 | 0.04 | 6.78 | 4.30 | 0.03 | 2.63 | 0.01 | 0.42 | 0.03 | 0.48 | 0.05 | 0.79 | 0.47 | 2.52 | 0.15 | 0.66 |
| **Australia** | 0.34 | 11.56 | 4.12 | 14.26 | 19.37 | 0.06 | -0.02 | 1.51 | 0.29 | 0.01 | 6.76 | 4.28 | 0.00 | 2.61 | -0.02 | 0.40 | 0.01 | 0.46 | 0.02 | 0.76 | 0.45 | 2.49 | 0.12 | 0.63 |
| **Rest of South America** | 0.35 | 11.58 | 4.13 | 14.28 | 19.39 | 0.07 | -0.01 | 1.52 | 0.30 | 0.02 | 6.77 | 4.29 | 0.01 | 2.62 | -0.01 | 0.41 | 0.02 | 0.47 | 0.03 | 0.77 | 0.46 | 2.50 | 0.13 | 0.64 |
| **Rest of Europe** | 0.27 | 11.48 | 4.04 | 14.18 | 19.29 | -0.01 | -0.10 | 1.43 | 0.21 | -0.06 | 6.68 | 4.20 | -0.07 | 2.53 | -0.09 | 0.32 | -0.07 | 0.38 | -0.05 | 0.69 | 0.37 | 2.41 | 0.04 | 0.56 |
| **Rest of Africa** | 0.34 | 11.56 | 4.11 | 14.26 | 19.37 | 0.06 | -0.03 | 1.50 | 0.28 | 0.01 | 6.75 | 4.27 | 0.00 | 2.60 | -0.02 | 0.39 | 0.00 | 0.45 | 0.02 | 0.76 | 0.44 | 2.49 | 0.11 | 0.63 |
| **Rest of Asia and Oceania** | 0.38 | 11.61 | 4.16 | 14.30 | 19.42 | 0.10 | 0.01 | 1.55 | 0.32 | 0.05 | 6.79 | 4.31 | 0.04 | 2.64 | 0.02 | 0.43 | 0.04 | 0.49 | 0.06 | 0.80 | 0.48 | 2.53 | 0.16 | 0.67 |
| **Rest of the world** | 0.34 | 11.57 | 4.12 | 14.26 | 19.37 | 0.06 | -0.02 | 1.51 | 0.29 | 0.01 | 6.76 | 4.28 | 0.00 | 2.61 | -0.02 | 0.40 | 0.01 | 0.46 | 0.02 | 0.76 | 0.45 | 2.49 | 0.12 | 0.63 |

Source: Authors' simulations

# 3. ECONOMIC IMPACTS OF POTENTIAL FOOT-AND-MOUTH DISEASE OUTBREAKS IN BRAZIL: A DYNAMIC COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS

**Abstract:** One of the most economically important animal diseases in the world, foot-and-mouth disease (FMD) has always been a major concern for Brazil, one of the largest suppliers of beef and pork in the international market. Seeking to improve the country's FMD status, the suspension of vaccination in Brazil was initiated in 2020 and an FMD-emergency response plan was developed. To provide more information around this policy change, this study estimates the potential economic impacts of FMD in Brazil, based on the results of two models, an epidemiological model, and a computable general equilibrium model. The absence and need for estimates of the economic effects that outbreaks of this disease can cause on the Brazilian livestock-related sectors motivated this research. Two scenarios were simulated employing a regional, dynamic general equilibrium model, called TERM-BR. The results show that outbreaks located in specific states have a high impact on other regions of Brazil, demonstrating a spillover effect of economic losses beyond the region directly affected by FMD. Also, the results highlight the distributive effects of FMD outbreaks on Brazilian society, with most of the negative impacts falling predominantly on workers - and consequently families - with lower incomes. From the combination of two robust models that provide important epidemiological and economic results, this study shows the relevance of animal disease control and surveillance in Brazil.

**Keywords:** Foot-and-Mouth Disease, Economic Impacts, Computable General Equilibrium Model, Brazil.

## 3.1. Introduction

Foot-and-mouth disease (FMD) is a highly infectious animal disease that affects cloven-hoofed animals, such as cattle, hogs and buffalos. Although not a disease with a high mortality rate, FMD is considered one of the most important animal diseases in the world because of its substantial impacts on the economy of the affected country and on international trade of animals and meat (Knight-Jones et al., 2017). FMD outbreak simulation modeling is widely used as a decision support tool in contingency plans for awareness and preparedness for potential outbreaks in several countries (Halasa et al., 2015). The economic incentives for the control of FMD are complex, responding to factors such as implications for poverty, technical feasibility and political convenience, in addition to efforts to reopen import markets (Perry and Rich, 2007; Perry and Grace, 2009; Rich and Perry, 2011; Countryman and Hagerman, 2017).

In Brazil, the National Program for the Eradication and Prevention of FMD (PNEFA) was the first and largest consolidated animal health program of the Ministry of Agriculture, Livestock and Supply (MAPA). After more than 50 years implementing measures to eradicate and prevent FMD, on May 24, 2018, Brazil received the certification of FMD-free country with vaccination from the World Organization for Animal Health (OIE). Currently, Brazilian policies related to control and surveillance of FMD are being modified to achieve a higher FMD status. In 2020, Brazil began the suspension of vaccination against FMD in six geographical zones: Paraná, Rio Grande do Sul, Acre, Rondônia, part of Amazonas and part of Mato Grosso. On May 27, 2021, these areas were recognized by OIE as new FMD-free zones without vaccination (MAPA, 2021a). According to PNEFA 2017-2026 Strategic Plan, all Brazilian states will suspend FMD vaccination until 2023 (MAPA, 2019).

Schroeder et al. (2015) state that changes in sanitary guidelines for FMD, combined with the formulation of contingency plans for emergencies related to the disease, must be accompanied by an economic assessment of the potential impacts of the disease in the country that is making these changes, so that the measures implemented are at the same time efficient and economically viable. While effective surveillance and rapid disease control are the main objective, it is equally essential in developing FMD management plans to understand the economic impacts of mitigation strategies. Given the scarcity of funding for surveillance and prevention, an assessment of the extent of the economic costs of FMD outbreaks is fundamental for policy makers, who face resource allocation constraints. Hagerman et al. (2010) and Knight-Jones et al. (2017) emphasize that understanding the FMD-related impacts is essential to guide control policies. The importance of promoting studies that help in the formulation of strategies and policies for monitoring, controlling and eradicating FMD outbreaks in Brazil is highlighted.

This study estimates the regional economic impacts of hypothetical FMD outbreaks in Brazil using a Computable General Equilibrium (CGE) model called TERM-BR, which allows for a disaggregated analysis for different Brazilian regions (Ferreira Filho and Horridge, 2006a; Ferreira Filho and Horridge, 2006b). For this purpose, results of an epidemiological model are used as basis for the analysis of FMD economic consequences in two states: Paraná and Mato Grosso. Both states are located on the international border, that can be considered a risk for FMD introduction in Brazil. Furthermore, Paraná and Mato Grosso are major meat producers, representing an important share of the country's beef and pork production and exports. Although this study is based on production losses in the cattle sector, in the event of an FMD outbreak, domestic and international demand for hogs and pork is also impacted, given that swine are also susceptible to the disease. Considering the states that have started the suspension of vaccination against FMD in Brazil, Mato Grosso was chosen for being the largest producer of cattle and beef, and Paraná for being one of the largest producers of hogs and pork.

The research developed in this paper contributes to the existing literature in two main aspects. First, this study is based on results from a FMD epidemiological model, created specifically for Brazil, to generate disease spread scenarios. Second, the outputs of this model are used as an input for the comprehensive inter-regional CGE model, which allows the estimation of the potential FMD socioeconomic costs. To the best of our knowledge this is the first time this methodological approach is used to estimate FMD impacts in Brazil. The results of this research can be informative to policies and strategies to minimize the socioeconomic losses of potential FMD outbreaks in the country. Additionally, the methodology developed in this research may also contribute to the formulation of strategies aimed at other animal diseases that are still present in Brazil.

## 3.2. Production and Exports in Paraná and Mato Grosso

Paraná is located in the Southern region of Brazil, while Mato Grosso is part of the Midwest region (**Figure 1**). Livestock is an important economic activity in both states, and they represent a large portion of meat production in Brazil. Mato Grosso’s cattle herd represents 15% of the national herd, while the hog herd of Paraná represents 17% of Brazil's herd. The distribution of livestock properties is different between the two states. Paraná has more properties in a considerably smaller geographic space than Mato Grosso, which in turn has larger and more spaced properties (**Table 1**).


**Figure 1.** Location of Paraná and Mato Grosso
Source: Author’s elaboration

**Table 1.** Livestock Production Characteristics in Paraná and Mato Grosso

| Production Characteristics | | Brazil | Paraná | Mato Grosso |
|---|---|---|---|---|
| Total Area of Livestock Properties (hectares) | | 223,711,017 | 4,893,678 | 35,109,656 |
| Number of Livestock Properties | Cattle | 2,522,487 | 169,212 | 92,338 |
| | Pig | 1,445,901 | 114,416 | 45,806 |
| Herd | Cattle | 218,150,298 | 8,584,939 | 32,702,525 |
| | Pig | 41,124,233 | 6,944,541 | 2,601,292 |

Source: Author’s elaboration based on the Agricultural Census 2017 (IBGE, 2019) and Municipal Livestock Research (IBGE, 2022a)

Brazil has the largest commercial cattle herd in the world according to data from the Food and Agriculture Organization of the United Nations (FAO, 2022). In addition, the country is the second largest producer of beef, and the largest exporter of this product, representing 15% of total world exports (FAO, 2022; UN Comtrade, 2022). In 2020, Brazil produced 7.8 million tons of beef. Mato Grosso was responsible for 18.1% of this production, while Paraná corresponded to 4.6%. In the same year, Brazilian beef exports represented 22% of beef production, and the revenue from these exports was approximately US$ 7.4 billion (**Table 2**). Mato Grosso and Paraná corresponded to 22.0% and 1.2% of the exported volume, respectively. Mato Grosso is the Brazilian state with the largest cattle herd, and which produces and exports the largest volume of beef.

**Table 2.** Production and Exports of Beef in Paraná and Mato Grosso, 2020

| State/Country | Beef production (tons) | Exports (tons) | Exports (US$ 1,000) |
|---|---|---|---|
| Paraná | 359,618 | 20,909 | 91,129 |
| Mato Grosso | 1,419,369 | 380,011 | 1,631,323 |
| Brazil | 7,824,888 | 1,724,404 | 7,446,886 |

Source: Author's elaboration based on the Quarterly Animal Slaughter Survey (IBGE, 2022b) and ComexStat exports data (MDIC, 2022)

In addition, Brazil has the fourth largest swine herd in the world, being the fifth largest producer of pork, and the seventh largest exporter of this product (FAO, 2022; UN Comtrade, 2022). Brazilian pork production totaled 4.5 million tons in 2020, with 21% being produced by Paraná, and 6% by Mato Grosso. Brazil exported 20% of the produced volume, with a total revenue equal to US$ 2.1 billion (**Table 3**). Paraná exported 12% of its pork production, representing 12.7% of the total exported volume of the country. Mato Grosso exported 10.7% of its pork production, which was equivalent to 3.1% of national exports. Paraná is the Brazilian state with the largest hog herd, the second largest pork production and the third largest pork exports.

**Table 3.** Production and Exports of Pork in Paraná and Mato Grosso, 2020

| State/Country | Pork production (tons) | Exports (tons) | Exports (US$ 1,000) |
|---|---|---|---|
| Paraná | 936,475 | 114,642 | 273,087 |
| Mato Grosso | 264,371 | 28,216 | 49,514 |
| Brazil | 4,482,048 | 901,102 | 2,120,464 |

Source: Author's elaboration based on the Quarterly Animal Slaughter Survey (IBGE, 2022b) and ComexStat exports data (MDIC, 2022)

The data presented above show Brazil's important role as one of the main producers and suppliers of beef and pork in the international market. At the same time, the data also demonstrate the substantial contribution of the states of Mato Grosso and Paraná to maintain this prominent position of the Brazilian meat production and exports. In this way, the preservation of herd health in Brazil is extremely important for the maintenance of meat production and for food security in the country and worldwide.

## 3.3. Methodological Approach, Data and Simulation Strategy

This study links supply shocks from a FMD spread model with a computable general equilibrium (CGE) model to assess the economic impacts of hypothetical FMD outbreaks in Brazil. Additional economic shocks include domestic and international markets, which are discussed in detail below. Government costs associated with controlling and eradicating an FMD outbreak are also estimated and applied as exogenous shocks to the CGE model. A CGE model consists of a system of equations that describe an economy as a whole and the interactions between its parts, considering the behavior of all consumers and firms. The equations of this system are derived directly from economic theory and include exogenous variables, endogenous variables and market restrictions. All equations in the model are solved simultaneously to find an equilibrium for the entire economy, so that, under a set of prices, the supply and demand quantities are equal in all sectors (Burfisher, 2017). The CGE model database provides the values of all exogenous variables and parameters and the initial equilibrium values of all endogenous variables. This database is divided into two components. The first is the Social Accounting Matrix (SAM), which describes the circular flow of income and expenditure in a country's economy over a given period of time, usually a year. The second component presents different parameters, which describe the responses of producers and consumers to changes in prices and income. Industries are aggregated into representative industry groups. Household transactions are often added to those of a single representative family or a small number of family types. Goods and services consumed in the economy are also aggregated into broad categories of commodities and services (Oladosu et al., 2013). CGE models are commonly used to quantify and analyze the economic impacts of FMD outbreaks in several countries, being applied both to the situation of outbreaks that have already occurred and to the assessment of hypothetical outbreaks (Dent et al., 2002; O'Toole et al., 2002; Smorfitt et al., 2005; Hsu et al., 2005; Randolph et al., 2005; Rich et al., 2005; Junker et al., 2009; Boisvert et al., 2012; Buetre et al., 2013; Oladosu et al., 2013; Gohin and Hault, 2013; MPI, 2014; Countryman and Hagerman, 2017; Miller et al., 2019).

### 3.3.1. TERM-BR

The CGE model used in this study is called TERM-BR, consisting in a dynamic, inter-regional, bottom-up model that divides the Brazilian economy into 122 productive sectors and 27 regions. The model's bottom-up structure allows for regional modeling of agents' behavior through an interdependent system, treating each region of the country as a separate economy. In this way, the model allows the assessment of the regional impacts derived from shocks that occurred in a specific region, based on the integration between these economies through interregional transport and trade flows, and through the factor market. Results at the national level are then determined by the weighted aggregation of regional results. Equations are described in linear form and results are expressed as a growth rate, in percentage change (Facchinelo, 2008; Diniz, 2019).

This framework is an adaptation of the Australian model called The Enormous Regional Model (TERM). Initially, TERM-BR was presented by Ferreira Filho and Horridge (2006a), and Ferreira Filho and Horridge (2006b). Further details on the model can be found in Fachinello (2008), Horridge (2011), Ferreira Filho and Horridge (2014) and Ferreira Filho et al. (2015). The TERM-BR version used in this study is calibrated for 2015 with data from Brazil's Input-Output Matrix, and from various auxiliary data sources, such as the National Household Sample Survey (Pesquisa Nacional de Amostra de Domicílios - PNAD) and the Household Expenditure Survey (Pesquisa de Orçamentos Familiares - POF). The production structure of the model is illustrated in **Figure 2**.

The TERM-BR structure, like most CGE models, represents a competitive economy derived from Walrasian models, with an empirical implementation that identifies the individual behavior of agents and the technological and institutional constraints they face. This model presents a set of equations and identities that reproduce a competitive equilibrium. The maximization of the utility function of households subject to budget constraints is obtained at the same time as the minimization of firms' costs for a given function and level of production, given the availability of factors. Likewise, the concept of conditioned optimization is included to represent the behavior of all other agents (government, rest of the world, etc.). The determination of equilibrium involves prices and the interaction between supply and demand (Dixon and Jorgenson, 2013).

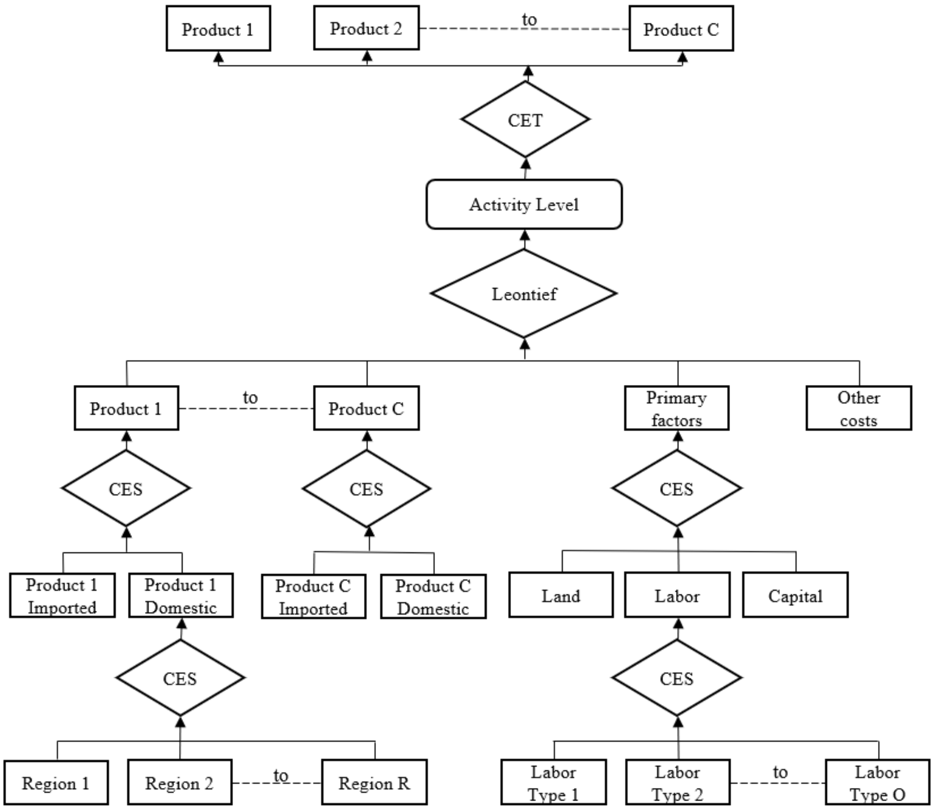


**Figure 2.** Production structure of TERM-BR
Source: Author's elaboration

TERM-BR captures the interaction between producers, 10 family income groups[13], federal government, state governments and the rest of the world. The production technology defines that each industry can produce only one product, representing a diagonal production matrix. For this, industries combine intermediate composite inputs, primary factors and other production costs in a fixed proportion, based on a Leontief function. The allocation of intermediate inputs is defined by Constant Elasticity of Substitution (CES) functions, which determine the proportion of use of domestic or imported inputs, guided by relative prices and product specific substitution elasticities. Domestic inputs are also domestic regional composites. And, finally, the composite primary factor is disaggregated into land, labor, and capital, with labor being further disaggregated into 10 different labor types. Regarding the final demand components, the demand for exports in each region is determined by relative prices and export demand elasticities of each product. Households maximize their utility, subject to a budget constraint. Household demand is modeled through the Linear Expenditure System (LES). It is important to highlight some relevant hypotheses of the TERM-BR model. The framework allows for the possibility of trade deficits between the Brazilian regions and assumes free trade between regions, considering a common external tariff for all regions. The model also allows free movement of workforce between regions based on wage differentials. Finally, the regional household consumption is assumed to follow regional income.

Because this research focuses on the impact of FMD outbreaks on Brazil's agriculture, the aggregation retained detail for the agri-food industry by keeping 11 agricultural sectors disaggregated: corn, soybean, other

[13] TERM-BR has 10 types of labor and 10 types of representative families. For the types of labor, the classification is based on salary ranges that represent an approximation of the qualification of the workforce. Families are also classified according to income ranges. The classification table is presented in the **Appendix Table A1**.

agricultural products, cattle, raw milk, hogs, poultry and eggs, beef, pork, poultry meat, and milk and dairy. The pharmaceutical products sector was also kept disaggregated because of a specific exogenous shock for the simulation. The remaining sectors were combined into eight aggregate sectors: forestry products, mining, other food products, other fuels, gas-alcohol, ethanol, manufacturing and services (see **Appendix Table A2**). Thus, the 122 products, 122 industries and 126 users of the original database were aggregated into 20 products, 20 industries and 24 users. The 27 Federative Units of Brazil were aggregated into eight regions, including the two states of interest for the simulations: Paraná and Mato Grosso (**Table 4**). The state of São Paulo was kept separated from the rest of the Southeast region due to the economic importance of this state in Brazil.

**Table 4.** Regional Aggregation Description

| Region | Federative Units |
|---|---|
| Paraná (PR) | Paraná |
| Rest of South (RoS) | Rio Grande do Sul, Santa Catarina |
| Mato Grosso (MT) | Mato Grosso |
| Rest of Midwest (RoM) | Goiás, Mato Grosso do Sul, Distrito Federal |
| São Paulo (SP) | São Paulo |
| Rest of Southeast (RoSE) | Rio de Janeiro, São Paulo, Minas Gerais, Espírito Santo |
| Northeast (NE) | Alagoas, Bahia, Ceará, Maranhão, Paraíba, Pernambuco, Piauí, Sergipe, Rio Grande do Norte |
| North (N) | Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins |

Source: Authors' aggregation using TERM-BR15 Database

To create the model baseline, the model database was updated based on observed data and projections of macroeconomic variables from 2015 onwards. From 2016 to 2018, the update was elaborated from observed data in Brazil for population, gross domestic product (GDP), investment, exports, imports etc. From 2019 to 2025, World Bank projections for Brazil's GDP and the Brazilian Institute of Geography and Statistics (IBGE) projections for population were considered. This projection of the model data allows the implementation of future events simulations and the analysis of prospective effects caused by potential FMD outbreaks.

### 3.3.2. Epidemiological Data

The epidemiological data used in this study was generated by a FMD spread model for Brazil[14]. The model consists in a spatial, stochastic simulation framework that simulates the stages of FMD virus infection in cattle in Brazil. As cattle move substantially more than hogs in Brazil, and hogs usually remain in the same property until slaughter, the risk of FMD infection and transmission in cattle farms is considerably higher. Then, the epidemiological model simulations only consider virus spread among cattle. This type of structure has been used in several studies in order to support assessments of the economic impacts of highly contagious animal diseases in different countries (Schoenbaum and Disney, 2003; Pendell et al., 2007; Paarlberg et al., 2008; Schroeder et al., 2015; Pendell et al., 2015). The outbreak simulation framework requires extensive parameterization, including

[14] Personal communication with Dr. Fernando Ferreira from the Epidemiology and Biostatistics Laboratory of the University of Sao Paulo, Brazil, on June 23, 2021.

information on animal population (e.g., location, production type, size of herd), disease manifestation, disease transmission (by proximity or movement), disease detection, surveillance, and control (e.g., animal movement control, traceability, vaccination). The model's animal movement data was based on Animal Transit Guides, which are official control data of animal movement throughout the Brazilian territory. Since the results of the epidemiological model are used as exogenous shocks in the economic model, and are not the focus of this paper, the reader should consult the complete documentation of the parameter values used in the model with Dr. Fernando Ferreira.

The epidemiological model generated a distribution of disease spread outcomes after performing a hundred simulations. In addition to the uncertainty resulting from the stochastic disease spread model, different starting locations for infection were incorporated to better reflect uncertainty, although the different possibilities for virus introduction were all located close to the international border of Brazil. Outbreak simulations were carried out for both Paraná and Mato Grosso. The epidemiological model results provided the number of infected farms, the number of infected animals, and the number of farms and animals within a 15-kilometer radius of distance from infected sites (which were called contacting properties and contacting animals). The model assumes that all infected animals would be slaughtered and all contacting animals, vaccinated. In other words, the framework assumes that the FMD outbreak control and eradication strategy would combine stamping-out with emergency vaccination. The model also assumes that the outbreak would be eradicated in 30 days, according to policy goals stablished by the Brazilian Ministry of Agriculture, Livestock and Supply. The epidemiological results are presented in **Table 5**.

**Table 5.** Results of the Epidemiological Model

| State | Scenario | Infected properties | Infected animals | Contacting properties | Contacting animals |
|---|---|---|---|---|---|
| Paraná | Best case | 668 | 19,287 | 5,376 | 181,441 |
| | Mean | 1,298 | 42,670 | 9,515 | 395,643 |
| | Worst case | 2,482 | 114,425 | 26,955 | 1,466,085 |
| Mato Grosso | Best case | 1 | 5,055 | 163 | 52,946 |
| | Mean | 31 | 16,067 | 815 | 210,595 |
| | Worst case | 288 | 75,317 | 2,891 | 710,698 |

Source: Epidemiological model

Note: The best and worst-case scenarios were defined based on the minimum and maximum number of infected animals.

### 3.3.3. Initial Shocks Associated with FMD Outbreaks

Four main direct shocks associated with FMD outbreaks are computed in the simulations: production loss, domestic consumer response, government expenditure related to outbreak control, and international demand response. These shocks are detailed below. The economic shocks and scenarios are based on the **mean case** of the epidemiological data for the feasibility of economic simulations and evaluation of the several results provided by the CGE model.

#### 3.3.3.1. Production Loss

Estimates of shocks on cattle production are based on the results of the epidemiological model. Specifically, the total number of animals slaughtered is used to calculate the percentage decrease in supply. Productivity losses of recovered animals are not included, as the epidemiological model assumes that all infected animals and at high risk of infection are slaughtered, and their carcasses destroyed. To calculate the cattle production loss, this study considers the number of infected bovine animals and, consequently, slaughtered, as well as the average price per head in the affected state (**Table 6**). In 2015, the average price of cattle for slaughter in Paraná was R$4,377.14 per head, and in Mato Grosso, R$3.905,30 per head (Cepea, 2021). Due to the lack of data on the type of animals affected by the outbreak and cattle prices, other types of cattle[15] besides beef cattle are not considered in the estimation of prices per head.

**Table 6.** Value of Production Loss

| Data/State | Paraná | Mato Grosso |
|---|---|---|
| Infected herd | 42,670 | 16,067 |
| Loss due to culling (R$)† | 186,772,706.96 | 62,745,123.06 |
| % State Production Value | 6.43% | 0.74% |

Source: Authors' calculations
† Note: 2015 values

The economic simulations assume that the production loss happens beyond the year of the outbreak. As the slaughter of animals impacts the production for years ahead, the loss of animals leads to changes in herd structure, since more animals are needed for replacement (Knight-Jones and Rushton, 2013). Some studies attempt to model this continued impact by applying production shocks for a few years following the FMD outbreak (Tozer and Marsh, 2012; Buetre et al., 2013). This research assumes that the shock on production would last three years after the outbreak, with a recovery of a quarter of the loss each year, and a full recovery of the pre-outbreak production level four years after the outbreak (see **Tables 8 and 9**). It is important to highlight that the average price per head considered in this work accounts for animals ready for slaughter, which can lead to an overestimation of losses, as outbreaks can affect animals of all ages and for different production purposes. In addition to the difficulties of pricing young animals, the epidemiological model does not provide details about the age of infected animals. Furthermore, the average price does not consider the devaluation of animals due to the FMD outbreak, which may also overestimate the losses.

#### 3.3.3.2. Adverse Reaction from the Domestic Market

Although FMD is not a concern for human health, as it is not a zoonosis, a decrease in consumer demand during an outbreak can be assumed due to variations in the level of consumer perception of food safety (Pendell et al., 2015). Several studies show the negative impacts of animal diseases on consumer demand for livestock products (Piggott and Marsh, 2004; Coffey et al., 2005; Schlenk and Villas-Boas, 2009). As the impact of FMD on demand is complex to be quantitatively estimated, some studies assume an arbitrary 5% decrease in domestic

[15] In addition to animals ready for slaughter, properties can have animals in the fattening stage, cattle for breeding and dairy cattle.

demand for beef and pork in countries affected by the disease (Zhao et al., 2006; Nogueira et al., 2011; Tozer and Marsh, 2012; Pendell et al., 2015; Schroeder et al., 2015). However, the domestic demand shock due to an FMD outbreak in the present study is based on the estimate of Mu et al. (2015) for the United States domestic market reaction to a hypothetical bovine spongiform encephalopathy (BSE) outbreak. Mu et al. (2015) estimates that the American demand for beef would decrease in 0.42% following an announcement of an BSE outbreak. This research assumes that the consumer market reaction to news about an FMD outbreak in Brazil would be similar to the case presented by Mu et al. (2015), and the Brazilian market would react in the same way as the United States market. The simulations assume that domestic demand for beef and pork would decrease by 0.42% in Brazil after the announcement of an FMD outbreak, recovering in the following year. This shock in domestic demand represents the portion of the Brazilian population that would reduce the consumption of final goods and provides a policy instrument for managing the impacts on final demand resulting from FMD outbreaks.

#### 3.3.3.3. Consequences of FMD outbreaks on Government Costs

Direct operating costs related to FMD outbreaks were estimated based on simulated epidemiological scenarios (**Table 7**). This estimation is important to determine the change in government expenditure to control and eradicate outbreaks (Boisvert et al., 2012; Oladosu et al., 2013). The types of costs listed below are analyzed in other studies for FMD, such as in Elbakidze et al. (2009) and Pendell et al. (2015). The official animal health service of Paraná[16] provided some estimates for the costs of FMD outbreak contention. In the absence of information for Mato Grosso, the costs provided for Paraná are used as a proxy to estimate impacts in both states.

The first estimated public cost is related to depopulation of infected animals. As the results of the epidemiological model indicate a substantial number of infected animals in all scenarios, the most viable form of slaughter used by Brazilian health authorities is sanitary rifle. In this case, the cost to slaughter FMD-infected animals is the cost of the ammunition used by the army to proceed with depopulation. After the infected animals are slaughtered, their carcasses are eliminated, which in Brazil is usually done by burying the carcasses, using excavators for trenching. This study considers the excavator hourly cost and the machine operator’s daily wage to estimate the cost of carcass disposal for both affected states.

Brazilian law states that producers who had FMD-infected animals slaughtered by the government must be compensated. According to the “Contingency Plan for FMD” (MAPA, 2020), the Brazilian government must indemnify 50% of the price of the culled animal. Pricing animals for indemnity purposes is complex and generates many discussions (Hagerman et al., 2010). In this study, the average price of cattle for slaughter from Cepea (2021) is considered to calculate the cost of compensation. It is important to emphasize that there may be an overestimation of this cost because animals of different ages and at different stages of the breeding process can be infected by the FMD virus.

The fourth estimated cost is the cost of laboratory tests. Tests for FMD in Brazil are carried out in a Federal Agricultural Defense Laboratory and, therefore, there is no exact cost to process the samples. The

[16] The costs of animal slaughter, carcass disposal, laboratory tests and visits of agricultural inspectors to properties were obtained in a personal communication with the Animal Health Manager of the Agricultural Defense Agency of Paraná (ADAPAR), Rafael Gonçalves Dias, on January 27, 2021.

Agricultural Defense Agency of Paraná provided estimates of the cost of inputs for the collection and processing of samples and the cost of sending samples to the laboratory. From this information and the results of the epidemiological model, the total cost of FMD tests is estimated, considering the testing of animals to prove the FMD infection and the testing of vaccinated animals, since all the vaccinated animals would have to be tested for recovery of the FMD-free status in the area affected by the outbreak.

This analysis also assumes that all contacting animals from the epidemiological results would be vaccinated against FMD. The cost of FMD vaccine per head from Miranda et al. (2018), which considers both the price of the vaccine dose and the labor cost per head for its application, is used for the estimation of the emergency vaccination cost. The cost per dose is R$1.29 for Paraná, and R$1.21 for Mato Grosso at 2015 prices (Miranda et al, 2018). Then, the government spending on emergency vaccination is estimated by multiplying the cost per dose by the number of contacting animals in each epidemiological scenario.

The last estimated public cost is the cost of agricultural inspectors' visits to infected and contacting properties. The estimation assumes ten visits to infected properties and two visits to contacting properties according to information from the official animal health service. In addition, it is considered that the cost per visit to properties in Mato Grosso would be double the cost per visit to properties in Paraná due to the greater dispersion of farms in Mato Grosso, as mentioned in section 3.2.

**Table 7.** Public Costs for Outbreak Control and Eradication, in R$†

| Cost Category | Paraná | Mato Grosso |
|---|---|---|
| Slaughter | 85,340.00 | 32,133.31 |
| Carcass Disposal | 226,151.00 | 85,153.26 |
| Laboratory Tests | 5,003,736.00 | 2,623,544.82 |
| Indemnification | 93,386,353.48 | 31,372,561.53 |
| Emergency Vaccination | 508,549.67 | 255,550.37 |
| Visits of Agricultural Inspectors | 3,841,200.00 | 465,800.82 |
| **Total Government Cost** | **103,051,330.15** | **34,834,744.10** |

Source: Authors' calculations
† Note: 2015 values

#### 3.3.3.4. Export Market Loss

The magnitude and duration of trade shocks assumed in this study are based on observations of previous events around the world and on the OIE Terrestrial Animal Health Code (OIE, 2021). Although the actual duration of export restrictions depends on several factors, such as product types, outbreak size, trade agreements, and countries involved, the literature provides valuable information on trade sanctions related to FMD. According to the OIE Terrestrial Animal Health Code (OIE, 2021), when emergency vaccination is implemented in tandem with stamping-out, the recovery of FMD-free status takes at least six months after the last animal is vaccinated, considering that vaccinated animals are not slaughtered later (OIE, 2021). Thus, during the first year after the outbreak notification, the impacts on exports may be more substantial due to the continued suspension of the FMD-free status.

Different assumptions are made about international market bans on a country affected by FMD in prospective studies that analyze hypothetical FMD outbreaks in several countries. For Australia, Dent et al. (2002) assume a closure of beef and livestock import markets for six years, while Tozer and Marsh (2012) consider that the restrictions would only last for one year. Carpenter et al. (2011), Hagerman et al. (2012), and Boisvert et al. (2012) assume that exports of animal products from the United States would be totally banned from the international market for one year after the outbreak eradication, whereas Ekboir et al. (2003) consider that bans would last for two years, and Zhao et al. (2006) presume that it would take three years for full recovery of exports. For a hypothetical FMD outbreak in Canada, Tozer et al. (2015) assume that exports would be reduced to 5% of their pre-outbreak level, with a full recovery only three years after the outbreak. In a study of hypothetical FMD outbreaks in Mexico, Nogueira et al. (2011) consider restrictions on meat exports between one and two years after the eradication of the outbreak. Similar assumptions are made by Feng et al. (2017) and Porphyre et al. (2018) for the United Kingdom, and by Rich and Winter-Nelson (2007) for countries from South America.

Considering all the information listed previously, this study assumes that the international demand for cattle, hogs, beef and pork exported by the affected Brazilian state (Paraná or Mato Grosso) reduces by 90% in the year of the outbreak. In the following year, the state recovers 25% of the lost exports, two years later, 50%, and three years later, 75% (see **Tables 8 and 9**)[17]. Exports return to pre-outbreak levels only in the fourth year after the outbreak. This assumption is based on the idea that the Principle of Regionalization would be respected by the international market. Brazilian states not affected by the outbreak continue to export, and only the affected state suffers sanctions from other countries, which is not guaranteed in the event of an animal health emergency related to FMD. Consequently, this assumption can lead to an underestimation of FMD outbreaks total impact on Brazilian exports.

It is important to emphasize that the TERM-BR database computes exports by port of departure and not by state of origin, so the shocks on exports were applied at national level. Therefore, the share of exports from Mato Grosso and Paraná in total Brazilian exports is estimated from export data by state of origin from ComexStat (MDIC, 2022)[18]. Mato Grosso does not export live cattle or hogs, but Paraná exports live hogs, so the scenario of economic shocks for Paraná considers an additional shock in exports (see **Tables 8 and 9**). As highlighted in section 3.2, beef exports from Mato Grosso represent a greater share of national exports in relation to beef exports from Paraná. For pork exports, this relationship is inverse: exports from Paraná have a greater share than exports from Mato Grosso in national exports. This implies different shocks on national exports depending on the state considered in the elaboration of the economic scenario, as observed in the next section.

### 3.3.4. Model Closure and Simulation Scenarios

CGE models typically have more variables than equations. Closing the model means choosing a set of variables as exogenous so the system can be solved for the set of endogenous variables. The closure determines a

[17] Although large percentage shocks are applied to cattle and hog exports, these shocks are not so substantial in level, given that Brazil only exports approximately 2% of the cattle production, and 0.1% of the hog production.
[18] For the calculation of shares, the following Harmonized System (HS) 4-digit codes were considered: 0102 - live bovine animals; 0103 - live swine animals; 0201 - meat of bovine animals, fresh or chilled; 0202 - meat of bovine animals, frozen; 0203 - meat of swine, fresh, chilled or frozen.

particular way by which an equilibrium is reached, and the choice depends on the modeler's overview of the structure of the analyzed economy and on how to approach the problem in question. In this research, considering the use of a dynamic model, the closure is defined explicitly according to the number of years of extension of direct shocks to the model: 4 years, since the baseline goes from 2022 to 2025.

Direct shocks related to FMD outbreaks are added to the baseline. The simulation strategy adopted in this study allows for the analysis of how each shock would affect the trajectory of the Brazilian economy represented in the model from 2022 to 2025, considering two different scenarios: I) FMD outbreak in Paraná, and II) FMD outbreak in Mato Grosso (**Figure 3**). With this strategy, it is possible to isolate the specific socioeconomic effects of each shock. **Tables 8 and 9** present the value and timeline of the shocks applied to the model. All procedures are performed within the GEMPACK software platform (Horridge, 2011).

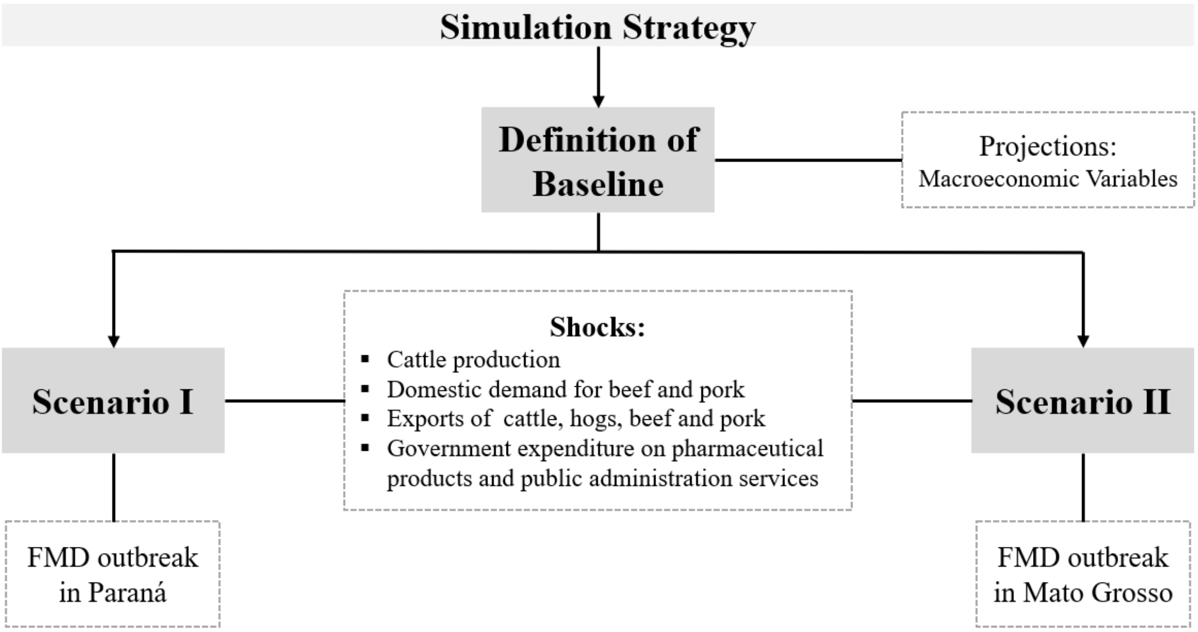


**Figure 3.** Production structure of TERM-BR
Source: Author's elaboration

**Table 8.** Scenario I: FMD Outbreak in Paraná

| Variable | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|
| Cattle production | -6.43% | -4.82% | -3.22% | -1.61% |
| Beef domestic demand | -0.42% | - | - | - |
| Pork domestic demand | -0.42% | - | - | - |
| Hog Exports | -3.31% | -2.48% | -1.65% | -0.83% |
| Beef exports | -1.12% | -0.84% | -0.56% | -0.28% |
| Pork exports | -10.20% | -7.65% | -5.10% | -2.55% |
| Government expenditure on pharmaceutical products | 1.17% | - | - | - |
| Government expenditure on public administration services | 0.25% | - | - | - |

Source: Authors' calculations

**Table 9.** Scenario II: FMD Outbreak in Mato Grosso

| Variable | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|
| Cattle production | -0.74% | -0.56% | -0.37% | -0.19% |
| Beef domestic demand | -0.42% | - | - | - |
| Pork domestic demand | -0.42% | - | - | - |
| Beef exports | -20.07% | -15.06% | -10.04% | -5.02% |
| Pork exports | -3.64% | -2.73% | -1.82% | -0.91% |
| Government expenditure on pharmaceutical products | 3.50% | - | - | - |
| Government expenditure on public administration services | 0.39% | - | - | - |

Source: Authors' calculations

## 3.4. Results

Results of the scenarios developed to represent the occurrence of FMD outbreaks in Brazil are presented in this section. The first general effect of direct impacts of an FMD outbreak is the decrease in the country's domestic income. This effect can be observed in **Table 10** in terms of reduction in real household consumption, as well as real GDP, in both simulated scenarios. Analyzing the effects of each shock separately, it is evident that the shocks on exports are the ones that most affected the macroeconomic variables, compared to the effects of other shocks (reduced production and domestic demand, increased government expenditure).

Real GDP is 0.008% lower than the baseline in Scenario I (FMD outbreak in Paraná, in 2025. For Scenario II, with an outbreak in Mato Grosso, the Brazilian real GDP in 2025 is 0.018% lower than the baseline (**Table 10**). To put this impact into perspective, the decrease in real GDP corresponds to R$526.74 million for Scenario I and R$1.19 billion for Scenario II at 2015 prices. The losses in terms of GDP in Scenario I are approximately 12 times the annual expenditure on agricultural defense by the Brazilian federal government[19]. In Scenario II, the economic loss in terms of GDP corresponds to 28 times that expenditure on disease prevention in agriculture. This GDP result illustrates the importance of investments in animal health programs and disease prevention in agriculture. **Table 10** also shows a decrease in household consumption. As a result, there is an increase in aggregate exports, while imports fall. In particular, the decrease in beef and exports as a result of FMD outbreaks leads to a devaluation of the Brazilian currency, making it more advantageous to export products and more expensive to import. It is noteworthy that the variations in macroeconomic variables are small mainly because the scenarios assume an outbreak duration of only 30 days.

[19] Between 2018 and 2021, the average expenditure in agricultural defense by the Ministry of Agriculture, Livestock and Supply was 0.0006% of Brazil's annual GDP (Brazil, 2022). This proportion in relation to GDP is used to contextualize the results of the present study.

**Table 10.** Contribution of Shocks to Macroeconomic Variables Changes, % Change from Baseline, Accumulated in 2025

| Outbreak Location | Shocks | Household Consumption | Real Investment | Exports (volume) | Imports (volume) | Real GDP | Real Wage |
|---|---|---|---|---|---|---|---|
| **Paraná (Scenario I)** | 1. Production + Government Expenditure | -0.003 | -0.008 | -0.005 | -0.001 | -0.003 | -0.003 |
| | 2. Domestic Demand | 0.000 | -0.009 | 0.006 | 0.000 | 0.000 | -0.001 |
| | 3. Exports | -0.014 | -0.098 | 0.059 | -0.067 | -0.005 | -0.020 |
| | 4. All shocks (Scenario I) | -0.016 | -0.106 | 0.054 | -0.061 | -0.008 | -0.022 |
| **Mato Grosso (Scenario II)** | 1. Production + Government Expenditure | -0.002 | -0.004 | -0.001 | 0.000 | -0.001 | -0.002 |
| | 2. Domestic Demand | 0.000 | -0.009 | 0.006 | 0.000 | 0.000 | -0.001 |
| | 3. Exports | -0.068 | -0.447 | 0.255 | -0.343 | -0.023 | -0.102 |
| | 4. All shocks (Scenario II) | -0.062 | -0.452 | 0.253 | -0.343 | -0.018 | -0.098 |

Source: TERM-BR model results

The regional results (**Table 11**) vary across the country as a consequence of differential effects of the shocks caused by FMD outbreaks in each of the eight regions analyzed. In Scenario I, real GDP decreases only in Paraná (-0.05%), where the outbreak occurs, and in Paraná's geographical region, Rest of South (-0.02%). On the other hand, in Scenario II, the GDP of the region affected by the FMD outbreak (Mato Grosso) increases (0.22%), while the GDP of Rest of Midwest, Paraná, Rest of South, Northeast and North falls. This increase in Mato Grosso's GDP is explained by the 1.85% increase in the state's total exports, which is justified by the devaluation of the exchange rate, mainly due to the increase in corn and soybean exports. Mato Grosso is responsible for the production of 26.5% of the total soybean and 19.2% of corn in Brazil in 2015. Soybean represents 15.4% of the total value of all activities in Mato Grosso, and corn 3%. Paraná is also an important producer of soybean and corn, representing 18.2% and 18.6% of national production, respectively. However, the importance of corn and soybean in the total activities of Paraná is relatively smaller, with soybeans representing 2.7% of the total produced by the state, and corn 0.7%. That is why the exchange devaluation raises the GDP of Mato Grosso, even with the negative shock in meat exports. Although the impacts on states' GDP are not substantial, there is a decrease in household consumption, real investment and real wage. The outbreak in Paraná has the greatest impact on the affected region, while the outbreak in Mato Grosso impacts other regions of Brazil, especially the North and Northeast regions.

**Table 11.** Regional Macroeconomic Variables, % Change from Baseline, Accumulated in 2025

| Region | Household Consumption | | Real Investment | | Exports (volume) | | Imports (volume) | | Real GDP | | Real Wage | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SI | SII | SI | SII | SI | SII | SI | SII | SI | SII | SI | SII |
| PR | -0.06 | -0.12 | -0.24 | -0.84 | 0.16 | -0.01 | -0.13 | -0.52 | -0.05 | -0.05 | -0.08 | -0.21 |
| RoS | -0.05 | -0.09 | -0.33 | -0.89 | -0.39 | -0.98 | -0.14 | -0.44 | -0.02 | -0.05 | -0.07 | -0.20 |
| MT | -0.03 | -0.09 | -0.05 | -0.32 | 0.30 | 1.85 | -0.06 | -0.35 | 0.00 | 0.22 | -0.02 | -0.09 |
| RoM | -0.01 | -0.08 | -0.07 | -1.63 | 0.24 | 1.88 | -0.06 | -0.48 | 0.00 | -0.03 | -0.01 | -0.16 |
| SP | -0.01 | 0.04 | -0.03 | -0.11 | 0.10 | -0.33 | -0.04 | -0.23 | 0.00 | 0.00 | -0.01 | -0.02 |
| RoSE | 0.00 | 0.04 | 0.01 | 0.09 | 0.17 | 1.05 | -0.04 | -0.24 | 0.00 | 0.00 | -0.01 | -0.01 |
| NE | -0.01 | -0.23 | -0.05 | -1.87 | 0.20 | 1.71 | -0.05 | -0.54 | 0.00 | -0.05 | -0.01 | -0.16 |
| N | -0.02 | -0.47 | -0.04 | -3.34 | 0.21 | 1.64 | -0.05 | -0.62 | 0.00 | -0.09 | -0.02 | -0.36 |

Source: TERM-BR model results

Note 1: SI = Scenario I; SII = Scenario II

Note 2: PR = Paraná; RoS = Rest of South; MT = Mato Grosso; RoM = Rest of Midwest; SP = São Paulo; RoSE = Rest of Southeast; NE = Northeast; N = North

More specifically, aggregate national exports of hogs and pork in 2025 are substantially affected by an FMD outbreak in Paraná (**Table 12**), presenting a decrease of 8.37% and 23.30%, respectively. For the outbreak scenario in Mato Grosso, pork exports also decrease (-8.81%), but the most significant impact is on domestic beef exports, which are 42% lower three years after the outbreak, compared to the baseline. It is important to note that there is no substitution of beef and pork exports for exports of poultry meat.

**Table 12.** National Exports of Agricultural Products, % Change from Baseline, Accumulated in 2025

| Sector | Scenario I | Scenario II |
|---|---|---|
| Corn | 0.26 | 1.64 |
| Soybean | 0.20 | 1.20 |
| Other agricultural products | 0.23 | 1.54 |
| Cattle | 0.12 | 11.90 |
| Raw milk | 0.00 | 0.00 |
| Hogs | -8.37 | 0.00 |
| Poultry and eggs | 0.46 | 2.49 |
| Beef | -2.77 | -42.00 |
| Pork | -23.30 | -8.81 |
| Poultry meat | 0.43 | 2.10 |
| Milk and dairy | 0.00 | 0.00 |

Source: TERM-BR model results

As a result of the strong decrease in beef and pork exports, live animals and meat production are negatively affected in all Brazilian regions (**Table 13**). In Scenario I, hog and pork production are most affected in Paraná and the Rest of South region, which is expected, since the Southern region of Brazil concentrates most of the production of these sectors. Cattle production in Paraná is also substantially affected, with a decrease of 15.20%. Livestock-related production in other regions such as Mato Grosso, Rest of Midwest and São Paulo is negatively impacted by the FMD outbreak in Paraná. The results of national aggregate production for Scenario I show that hog and pork production are 9.0% and 9.4% lower, respectively, compared to the baseline in 2025.

**Table 13.** Regional Production of Agricultural Sectors, % Change from Baseline, Accumulated in 2025: Scenario I

| Sector | PR | RoS | MT | RoM | SP | RoSE | NE | N |
|---|---|---|---|---|---|---|---|---|
| Corn | 0.20 | 0.20 | 0.11 | 0.07 | 0.09 | 0.06 | 0.03 | 0.11 |
| Soybean | 0.26 | 0.28 | 0.12 | 0.09 | 0.10 | 0.07 | 0.06 | 0.13 |
| Other agricultural products | 0.18 | 0.19 | 0.05 | 0.02 | 0.04 | 0.03 | 0.02 | 0.06 |
| Cattle | -15.20 | -0.02 | -0.29 | -0.23 | -0.19 | -0.35 | -0.33 | -0.29 |
| Raw milk | 0.00 | 0.19 | 0.07 | 0.05 | 0.04 | 0.01 | 0.01 | 0.04 |
| Hogs | -9.66 | -16.60 | -5.42 | -3.90 | -2.83 | -1.73 | -1.54 | -1.95 |
| Poultry and eggs | 0.38 | 0.33 | 0.13 | 0.06 | -0.02 | -0.01 | 0.01 | 0.03 |
| Beef | -0.98 | -1.23 | -0.44 | -0.47 | -1.03 | -0.51 | -0.41 | -0.58 |
| Pork | -9.84 | -17.20 | -5.54 | -3.93 | -3.79 | -1.69 | -1.52 | -2.01 |
| Poultry meat | 0.42 | 0.40 | 0.15 | 0.08 | 0.07 | 0.04 | 0.03 | 0.06 |
| Milk and dairy | 0.06 | 0.08 | 0.02 | -0.01 | -0.03 | -0.03 | -0.01 | -0.01 |

Source: TERM-BR model results

Note: PR = Paraná; RoS = Rest of South; MT = Mato Grosso; RoM = Rest of Midwest; SP = São Paulo; RoSE = Rest of Southeast; NE = Northeast; N = North

On the other hand, in Scenario II, the cattle sector is most heavily impacted in all regions of Brazil other than the region affected by the outbreak, Mato Grosso (**Table 14**). However, the production of the beef sector is most impacted in Mato Grosso, being almost 15% lower than the baseline in 2025. Beef production in Paraná and São Paulo is also approximately 11% lower. At the aggregate national level, production of cattle and beef would be 8% and 10% lower, respectively, in 2025. While both scenarios show a substantial decrease in beef and pork production, the results do not present a shift in land use towards other agricultural products.

**Table 14.** Regional Production of Agricultural Sectors, % Change from Baseline, Accumulated in 2025: Scenario II

| Sector | PR | RoS | MT | RoM | SP | RoSE | NE | N |
|---|---|---|---|---|---|---|---|---|
| Corn | 0.99 | 0.93 | 0.54 | 0.66 | 0.62 | 0.36 | 0.22 | 1.32 |
| Soybean | 1.07 | 1.26 | 0.77 | 0.86 | 0.71 | 0.53 | 0.54 | 1.62 |
| Other agricultural products | 0.64 | 0.77 | 0.29 | 0.20 | 0.28 | 0.25 | 0.32 | 0.93 |
| Cattle | -11.90 | -12.30 | -1.85 | -7.75 | -7.21 | -6.74 | -9.39 | -8.41 |
| Raw milk | 0.53 | 0.65 | 0.00 | 1.24 | 1.23 | -0.15 | 0.19 | 0.85 |
| Hogs | -3.58 | -6.23 | -2.24 | -1.56 | -1.53 | -1.08 | -0.74 | -0.38 |
| Poultry and eggs | 1.54 | 1.43 | 0.73 | 0.72 | 0.16 | 0.06 | 0.12 | 0.62 |
| Beef | -11.30 | -14.60 | -1.93 | -3.70 | -10.80 | -4.37 | -2.55 | -5.19 |
| Pork | -3.66 | -6.45 | -2.30 | -1.59 | -1.86 | -1.05 | -0.76 | -0.46 |
| Poultry meat | 1.82 | 1.80 | 0.93 | 0.90 | 0.39 | 0.27 | 0.23 | 0.85 |
| Milk and dairy | 0.23 | 0.16 | -0.05 | 0.15 | -0.08 | -0.24 | -0.06 | 0.11 |

Source: TERM-BR model results

Note: PR = Paraná; RoS = Rest of South; MT = Mato Grosso; RoM = Rest of Midwest; SP = São Paulo; RoSE = Rest of Southeast; NE = Northeast; N = North

As previously noted in **Tables 10 and 11**, aggregate household consumption in the Brazilian economy declines in real terms. A more detailed analysis of household consumption, stratified by income levels, reveals a more complex picture. In **Tables 15 and 16**, families (consumption units) are stratified by family income level. Each income level has a particular consumption basket, which may also vary according to the region. **Table 15** shows that the households with lower levels of income are the most affected, especially in Paraná, where the FMD outbreak is simulated. Mato Grosso and the North region present similar effects as the ones observed in Paraná. The consumption of households with higher income levels is practically unaffected in almost all regions of Brazil, except for Paraná, where the consumption of households with the highest income level slightly increases (0.07%). At national aggregate level, the real consumption of households of groups POF1 to POF4 shows a stronger reduction than the other levels. The real consumer bundle price index increases between 0.007% and 0.011% for different income levels, with the greatest increase occurring for POF1 families (see **Appendix Table A3**).

The results for Scenario II show a greater reduction in household consumption (**Table 16**). Unlike Scenario I, household consumption falls more in regions other than the one where the outbreak is simulated. In the Northeast and North regions, consumption of families with the lowest income level is 2.86% and 1.75% lower, respectively, compared to the baseline for 2025. In Mato Grosso, where the hypothetical outbreak happens, consumption at the lowest income level is 1.11% lower than the baseline. At the same time, consumption of higher-income households increases. As in Scenario I, household consumption is less affected in the regions of São Paulo and Rest of the Southeast. Consumption of lower-income households (POF1) is the most affected, being 1.3% lower than the baseline at the national aggregate level. Consumption is higher than the baseline for higher income levels. The real consumption index decreases slightly for families at POF1 and POF2 levels and increases for other income levels (see **Appendix Table A3**).

**Table 15.** Regional Real Household Consumption, % Change from Baseline, Accumulated in 2025, Scenario I

| Household Income Group | PR | RoS | MT | RoM | SP | RoSE | NE | N |
|---|---|---|---|---|---|---|---|---|
| POF1 (poorest) | -0.14 | -0.05 | -0.10 | -0.02 | -0.03 | -0.03 | -0.07 | -0.11 |
| POF2 | -0.25 | -0.18 | -0.12 | -0.03 | -0.02 | -0.02 | -0.03 | -0.05 |
| POF3 | -0.20 | -0.16 | -0.07 | -0.03 | -0.02 | -0.02 | -0.02 | -0.04 |
| POF4 | -0.18 | -0.13 | -0.04 | -0.02 | -0.02 | -0.02 | -0.02 | -0.03 |
| POF5 | -0.14 | -0.11 | -0.02 | -0.02 | -0.01 | -0.01 | -0.02 | -0.03 |
| POF6 | -0.10 | -0.09 | 0.00 | -0.02 | -0.01 | -0.01 | -0.01 | -0.02 |
| POF7 | -0.07 | -0.07 | 0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 |
| POF8 | -0.05 | -0.05 | 0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 |
| POF9 | -0.01 | -0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| POF10 (richest) | 0.07 | 0.02 | 0.02 | 0.00 | 0.00 | 0.02 | 0.01 | 0.02 |

Source: TERM-BR model results

Note: PR = Paraná; RoS = Rest of South; MT = Mato Grosso; RoM = Rest of Midwest; SP = São Paulo; RoSE = Rest of Southeast; NE = Northeast; N = North

Even though prices fall slightly for the poorest families, their consumption is still lower than the rest of the households with higher income levels. This happens because consumption is not only determined by the prices of the basket, but also by the variation in family income. The decline in consumption of the poorest households is explained by the fact that livestock production is particularly intensive in the use of the economy's least skilled workers, who are mostly represented in the income levels of the poorest households. Workers classified as OCC1 (the least skilled, or the lowest paid in the economy) make up approximately 10% of the payroll of the cattle sector, which is directly affected by FMD outbreaks. Among the agricultural sectors, this sector (cattle) is also the one that employs the most OCC1 workers (5%). Workers in this category (OCC1) make up most of the income of the poorest families (POF1) (see **Appendix Tables A4 and A5**).

**Table 16.** Regional Real Household Consumption, % Change from Baseline, Accumulated in 2025, Scenario II

| Household Income Group | PR | RoS | MT | RoM | SP | RoSE | NE | N |
|---|---|---|---|---|---|---|---|---|
| POF1 (poorest) | -0.35 | -0.11 | -1.11 | -0.56 | -0.23 | -0.43 | -2.86 | -1.75 |
| POF2 | -0.58 | -0.60 | -0.58 | -0.51 | -0.13 | -0.19 | -1.12 | -0.53 |
| POF3 | -0.44 | -0.46 | -0.38 | -0.46 | -0.08 | -0.14 | -0.94 | -0.39 |
| POF4 | -0.37 | -0.38 | -0.21 | -0.38 | -0.05 | -0.10 | -0.77 | -0.29 |
| POF5 | -0.27 | -0.28 | -0.06 | -0.31 | -0.03 | -0.05 | -0.60 | -0.21 |
| POF6 | -0.21 | -0.21 | 0.02 | -0.23 | -0.01 | -0.03 | -0.44 | -0.14 |
| POF7 | -0.14 | -0.11 | 0.12 | -0.11 | 0.02 | 0.00 | -0.27 | -0.06 |
| POF8 | -0.09 | -0.06 | 0.16 | -0.07 | 0.06 | 0.03 | -0.16 | -0.03 |
| POF9 | -0.02 | 0.01 | 0.22 | 0.01 | 0.06 | 0.05 | 0.03 | 0.05 |
| POF10 (richest) | 0.13 | 0.13 | 0.19 | 0.23 | 0.09 | 0.19 | 0.45 | 0.23 |

Source: TERM-BR model results

Note: PR = Paraná; RoS = Rest of South; MT = Mato Grosso; RoM = Rest of Midwest; SP = São Paulo; RoSE = Rest of Southeast; NE = Northeast; N = North

In this way, reduced production in the livestock and meat sectors affects the demand for primary factors, particularly the factor in which the activity is intensive, that is, labor, reducing the demand for it. **Table 17** shows that, in Scenario I, employment in hogs and pork sectors is 9.71% and 11.50% lower than the baseline in 2025, respectively. In Scenario II, employment in cattle and beef sectors decreases by 8.8% and 12.60%, respectively. This explains the greater decrease in consumption of lower-income families when an FMD outbreak occurs in Mato Grosso (Scenario II), compared to consumption when Paraná is affected (Scenario I).

This observation can also be complemented with the results for regional average wages. In Scenario I, wages of the three lowest pay levels (OCC1 to OCC3) fall slightly in Paraná. Wages of other levels of labor and other regions are practically unaffected (see **Appendix Table A6**). In Scenario II, in turn, the wages of OCC1 level fall more, reducing 1.19% in Mato Grosso, 1.73% in the Northeast and 2.83% in the North. At the same time, higher wages increase more (see **Appendix Table A7**). This shows the distributive effects of FMD outbreaks on Brazilian society, because the negative impacts fall predominantly on workers – and consequently families – with lower incomes.

**Table 17.** Average National Employment in Agricultural Sectors, % Change from Baseline, Accumulated in 2025

| Sector | Scenario I | Scenario II |
|---|---|---|
| Corn | 0.13 | 0.79 |
| Soybean | 0.19 | 1.07 |
| Other agricultural products | 0.08 | 0.51 |
| Cattle | -0.69 | -8.80 |
| Raw milk | 0.10 | 0.16 |
| Hogs | -9.71 | -3.73 |
| Poultry and eggs | 0.21 | 0.98 |
| Beef | -1.15 | -12.60 |
| Pork | -11.50 | -4.40 |
| Poultry meat | 0.32 | 1.52 |
| Milk and dairy | 0.02 | 0.04 |

Source: TERM-BR model results

## 3.5. Policy Implications

An FMD outbreak in Brazil can result in large costs to both producers and the government, and loss of income for livestock workers. How outbreaks are managed from detection to eradication has a substantial impact on the economic outcome. In this study, the economic impacts are directly related to the Ministry of Agriculture's objective of eradicating an FMD outbreak within 30 days, combining stamping-out and emergency vaccination strategies. This response plan implies that the Brazilian government would have to spend a substantial amount within a month to contain the outbreak.

On the export side, this study considers the timetable provided by the OIE Terrestrial Animal Health Code (OIE, 2021) for the re-establishment of FMD-free status in the affected zone. Nevertheless, the reopening of markets could take much longer than that, because there is no guarantee that countries would strictly follow OIE guidelines to resume trade with Brazil. Political negotiations in the event of animal disease outbreaks are a crucial factor in international trade. This was highlighted during 2021, when Brazil had two atypical cases of bovine spongiform encephalopathy (BSE) and China banned imports of Brazilian beef for more than three months (MAPA, 2021b). In addition, negotiations are important to ensure the application of the Principle of

Regionalization by importers, as it assures lower losses in exports of live animals and animal products, as demonstrated in the study of Hafi et al. (2022) for Australia.

Brazil's position as one of the main suppliers of beef and pork in the international market leads to trade-related economic losses that exceed the costs of government response, according to the estimates based on information from the official animal health service of Paraná. However, additional government costs would be involved in measures to enhance surveillance to support the disease freedom status of other Brazilian states and to enhance inspections of lives animals and products traded between regions and at export ports. Enhanced biosecurity along the entire beef and pork supply chain in Brazil would also result in high costs as a result of an FMD outbreak.

Due to the scarcity of funds for animal disease prevention, an understanding of the extent of the economic costs of FMD, as demonstrated in this research, is critical information for policymakers facing difficult decisions about where to allocate these scarce resources. Furthermore, it is important to consider that investments in FMD prevention benefit different sectors and agents of the economy. The negative impact of FMD on the availability and distribution of animal products directly affects producers, entrepreneurs and rural families, in addition to having a negative impact on the commercial activities of the agricultural sector, harming the consumer market and society in general (Smith et al., 2014).

Finally, the results of the economic model show the importance of considering all the social effects in emergency response plans related to animal diseases. Workers and families of lower income levels are the most affected, as they are largely employed in livestock sectors. Thus, it is necessary to formulate social policies aimed at the population most negatively affected by outbreaks of animal diseases, such as FMD.

The results of this study can help policymakers in two important ways. First, this information could be used to assist in the preparation of response and control plans, as the results show the main sectors and regions affected in the event of an FMD-related emergency. Second, the results demonstrate the importance of identifying and eradicating outbreaks as quickly as possible, given the extent of economic losses for Brazil when considering a conservative eradication scenario (30 days). The estimated economic impacts show the importance of early detection of the disease and timely implementation of control measures. Therefore, the results of this study can be used to inform policy decisions when mobilizing resources to prepare and respond to sanitary events related to FMD.

The simulation approach presented in this study can be used for future research involving prospective simulations of the potential impacts of FMD and other animal diseases. Alternative control and eradication measures can be considered as a basis for economic estimates. In addition, other types of costs and improvement of direct cost estimates can also be implemented in the analytical strategy proposed in this study. The simulation results show the importance of putting into perspective the role of livestock sectors and considering other economic factors, such as household consumption and labor market, in the formulation of agricultural policies. Given the vulnerability of Brazil's food system to sanitary crisis related to animal diseases, the policy significance of ensuring and maintaining FMD-free states to support meat production and exports in Brazil is highlighted. Both Brazilian industry and government can secure lower losses by applying response plans that reduce the time to eradicate FMD outbreaks.

## 3.6. Final Remarks

This paper presents the results of simulations to estimate the socioeconomic consequences of FMD outbreaks in Brazil, with two scenarios that consider different affected regions. A CGE model is employed for the analysis. This approach enables the estimation of economic consequences of FMD in tandem with the implications of domestic and international demand reactions. Due to the lack of historical experience with FMD outbreaks in the last decade, it was necessary to make assumptions, specially about demand shocks.

Although the results are robust to basic conditions, future research would benefit from the validation of estimates of the direct impacts of FMD outbreaks, consumer aversion to beef and pork, eradication costs and international bans to Brazilian exports. For example, the size of the FMD outbreak could substantially diverge from the epidemiological model results used in this study, what would implicate in different costs of control and eradication and different reactions from the domestic and international markets. In addition, it is necessary to improve the estimations on the process of recovery of the most affected sectors of the economy in the long run.

The results indicate that an FMD outbreak would have significant but not devastating impacts on the Brazilian economy. The impacts are not so substantial compared to the size of the economy because of the limited animal population affected, given the assumption that the outbreak would be eradicated in 30 days and the Principle of Regionalization would be applied by importers of beef and pork from Brazil. The simulations results give a range of the expected magnitude of the economic impacts of an FMD outbreak in Brazil.

Future research must consider the possibility of disease spread to more than one state at the same time. Furthermore, the results of this study are based on regional cost specification and estimates that vary substantially between Brazilian regions, so these costs and consequent effects could be larger for other regions in Brazil. Moreover, the assumption in the epidemiological model (that based all the analysis) that herds with clinical signs could be immediately identified, euthanized and discarded probably overestimated the effectiveness of depopulation control. Future research could also consider different types of affected cattle, not just beef cattle.

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# APPENDIX

**Table A1.** Classification of Representative Families and Labor

| Classification of Families | Classification of Labor | Income Range (R$ 2015) | Income Range (minimum wages) |
|---|---|---|---|
| FAM1 | OCC1 | [0-788) | [0-1) |
| FAM2 | OCC2 | [788-1,576) | [1-2) |
| FAM3 | OCC3 | [1,576-2,364) | [2-3) |
| FAM4 | OCC4 | [2,364-3,152) | [3-4) |
| FAM5 | OCC5 | [3,152-3,940) | [4-5) |
| FAM6 | OCC6 | [3,940-4,728) | [5-6) |
| FAM7 | OCC7 | [4,728-5,516) | [6-7) |
| FAM8 | OCC8 | [5,516-6,304) | [7-8) |
| FAM9 | OCC9 | [6,304-7,880) | [8-10) |
| FAM10 | OCC10 | ≥7,880 | ≥10 |

Source: TERM-BR15 Database

**Table A2.** Sectors Aggregation Description

| Sectors TERM-BR15 | | Description | Aggregation | |
|---|---|---|---|---|
| 1 | ArrozTrigOut | Rice, wheat and other cereals | 3 | Other agricultural products |
| 2 | MilhoGrao | Corn | 1 | Corn |
| 3 | AlgodHerb | Cotton, other fibers from the temporary crop | 3 | Other agricultural products |
| 4 | CanaDeAcucar | Sugar cane | 3 | Other agricultural products |
| 5 | SojaGrao | Soybean | 2 | Soybean |
| 6 | OutPrLavTemp | Other products and services from temporary agriculture | 3 | Other agricultural products |
| 7 | Laranja | Orange | 3 | Other agricultural products |
| 8 | CafeGrao | Coffee | 3 | Other agricultural products |
| 9 | OutPrLavPerm | Other permanent agriculture products | 3 | Other agricultural products |
| 10 | BovOutrAnim | Cattle and other live animals, hunting and services | 4 | Cattle |
| 11 | LeitVacOuAni | Milk from cows and other animals | 5 | Raw Milk |
| 12 | Suinos | Hogs | 6 | Hogs |
| 13 | AvesOvos | Poultry and eggs | 7 | Poultry and eggs |
| 14 | ExplFlorSilv | Forestry products | 8 | Forestry products |
| 15 | PescaAcq | Fishing and aquaculture (fish, crustaceans and molluscs) | 3 | Other agricultural products |
| 16 | CarvMiner | Mineral coal | 9 | Mining |
| 17 | MinNaoMetal | Non-metallic minerals | 9 | Mining |
| 18 | PetroGasNat | Oil, natural gas and support services | 9 | Mining |
| 19 | MinFerro | Iron ore | 9 | Mining |
| 20 | MinMetNaoFer | Non-ferrous metallic minerals | 9 | Mining |
| 21 | AbateCarne | Beef and other cattle products | 10 | Beef |
| 22 | CarneSuino | Pork | 11 | Pork |
| 23 | CarneAves | Poultry meat | 12 | Poultry meat |
| 24 | PescadoInd | Industrialized fish | 14 | Other food products |
| 25 | LeiteResfr | Cold, sterilized and pasteurized milk | 13 | Milk and dairy |
| 26 | OutLaticinio | Other dairy products | 13 | Milk and dairy |
| 27 | Acucar | Sugar | 14 | Other food products |
| 28 | ConservFrut | Canned fruits, vegetables and fruit juices | 14 | Other food products |

| | | | | |
|---|---|---|---|---|
| 29 | OleoGordura | Vegetable and animal oils and fats | 14 | Other food products |
| 30 | Cafe | Processed coffee | 14 | Other food products |
| 31 | ArrozBenef | Processed rice and rice products | 14 | Other food products |
| 32 | PrTrigManMil | Products derived from wheat, cassava or corn | 14 | Other food products |
| 33 | Racao | Animal feed | 14 | Other food products |
| 34 | OutProdAlim | Other food products | 14 | Other food products |
| 35 | Bebidas | Beverage | 17 | Manufacturing |
| 36 | ProdFumo | Tobacco products | 17 | Manufacturing |
| 37 | FioFibraText | Processed textile fibers | 17 | Manufacturing |
| 38 | Tecelagem | Fabrics | 17 | Manufacturing |
| 39 | FabOutPText | Textiles for household use and other textiles | 17 | Manufacturing |
| 40 | ArtVestAc | Clothing and Accessories | 17 | Manufacturing |
| 41 | CalcadArtCou | Footwear and leather goods | 17 | Manufacturing |
| 42 | ProdMadeira | Wood products, excluding furniture | 17 | Manufacturing |
| 43 | Celulose | Cellulose | 17 | Manufacturing |
| 44 | PapPapel | Paper, cardboard, packaging and paper artifacts | 17 | Manufacturing |
| 45 | SevImpreRep | Printing and reproduction services | 17 | Manufacturing |
| 46 | CombAviacao | Aviation fuels | 15 | Other fuels |
| 47 | Gasoalcool | Gas-alcohol | 16 | Gas-alcohol |
| 48 | Nafta | Naphthas for petrochemicals | 15 | Other fuels |
| 49 | OleoComb | Fuel oil | 15 | Other fuels |
| 50 | DieselBiodis | Diesel - biodiesel | 15 | Other fuels |
| 51 | OutProRefPet | Other petroleum refining products | 15 | Other fuels |
| 52 | EtanolCombus | Ethanol and other biofuels | 18 | Ethanol |
| 53 | ProdQuimInor | Inorganic Chemicals | 17 | Manufacturing |
| 54 | AduboFert | Fertilizers | 17 | Manufacturing |
| 55 | ProdQuimOrg | Organic chemicals | 17 | Manufacturing |
| 56 | FabResina | Resins, elastomers and artificial and synthetic fibers | 17 | Manufacturing |
| 57 | DefAgricol | Pesticides | 17 | Manufacturing |
| 58 | ProdQuimDiv | Chemical products | 17 | Manufacturing |
| 59 | TintasVerniz | Paints, varnishes, enamels and lacquers | 17 | Manufacturing |
| 60 | PerfSabLimp | Perfumery, soaps and cleaning items | 17 | Manufacturing |
| 61 | ProdFarmac | Pharmaceutical products | 19 | Pharmaceutical products |
| 62 | ArtBorrac | Rubber products | 17 | Manufacturing |
| 63 | ArtPlastico | Plastic products | 17 | Manufacturing |
| 64 | Cimento | Cement | 17 | Manufacturing |
| 65 | ArtCimGesso | Cement and plaster products | 17 | Manufacturing |
| 66 | VidroCerOut | Glass, ceramic and other non-metallic mineral products | 17 | Manufacturing |
| 67 | GusaFerLig | Iron | 17 | Manufacturing |
| 68 | Laminados | Laminates | 17 | Manufacturing |
| 69 | ProdMetMNF | Non-ferrous metal metallurgy products | 17 | Manufacturing |
| 70 | FundidosAco | Steel and non-ferrous metal products | 17 | Manufacturing |
| 71 | ProduMetal | Metal products, excluding machinery and equipment | 17 | Manufacturing |
| 72 | CompEletron | Electronic components | 17 | Manufacturing |
| 73 | MaqEscEquInf | Office machinery and computer equipment | 17 | Manufacturing |

| | | | | |
|---|---|---|---|---|
| 74 | MatEletrCom | Electronic material and communications equipment | 17 | Manufacturing |
| 75 | EqMedContOpt | Measurement, test and control, optical and electromedical equipment | 17 | Manufacturing |
| 76 | MaqApaEquEle | Electrical machines, appliances and materials | 17 | Manufacturing |
| 77 | Eletrodome | Home appliances | 17 | Manufacturing |
| 78 | TratMaqAgric | Tractors and other agricultural machinery | 17 | Manufacturing |
| 79 | MaqExtConst | Machines for mineral extraction and construction | 17 | Manufacturing |
| 80 | OutMaqEquip | Other mechanical machinery and equipment | 17 | Manufacturing |
| 81 | Automoveis | Cars, vans and others | 17 | Manufacturing |
| 82 | CaminhOnib | Trucks and buses | 17 | Manufacturing |
| 83 | PecasVeicAut | Motor vehicle parts and accessories | 17 | Manufacturing |
| 84 | OutrEquTran | Aircraft, boats and other transport equipment | 17 | Manufacturing |
| 85 | Moveis | Furniture | 17 | Manufacturing |
| 86 | OutAtivIndst | Products from various industries | 17 | Manufacturing |
| 87 | ManRepMaqEqp | Maintenance, repair and installation of machinery and equipment | 20 | Services |
| 88 | EletricidGas | Electricity, gas and other utilities | 20 | Services |
| 89 | AguaEsgRes | Water, sewage, recycling and waste management | 20 | Services |
| 90 | ConstEdif | Construction | 20 | Services |
| 91 | ConstInfra | Infrastructure construction | 20 | Services |
| 92 | SevEspConst | Specialized services for construction | 20 | Services |
| 93 | Comercio | Wholesale and retail trade | 20 | Services |
| 94 | Transporte | Inland freight transport, inland passenger transport, waterway transport, air transport, storage and auxiliary services to transport, mail and other delivery services | 20 | Services |
| 95 | SevAlojament | Accommodation services in hotels and similar | 20 | Services |
| 96 | SevAliment | Food services | 20 | Services |
| 97 | LivroJornRev | Books, newspapers and magazines | 20 | Services |
| 98 | CineMusRadTV | Film, music, radio and television services | 20 | Services |
| 99 | TelecomOuts | Telecommunications, paid TV and other related services | 20 | Services |
| 100 | DesenSistOut | Systems development and other information services | 20 | Services |
| 101 | IntFinancSeg | Financial intermediation, insurance and supplementary pension | 20 | Services |
| 102 | AlugEftSvImb | Effective rental and real estate services | 20 | Services |
| 103 | AluguelImput | Imputed rent | 20 | Services |
| 104 | SevJurCont | Legal services, accounting and consulting | 20 | Services |
| 105 | SevPesqDesn | Research and Development | 20 | Services |
| 106 | SevArquiEng | Architectural and engineering services | 20 | Services |
| 107 | PublicidOut | Advertising and other technical services | 20 | Services |
| 108 | AluguelNimb | Non-real estate rentals and intellectual property asset management | 20 | Services |
| 109 | CondomSevEdf | Condominiums and building services | 20 | Services |
| 110 | OutServAdm | Other administrative services | 20 | Services |
| 111 | VigilSegInv | Surveillance, security and investigation services | 20 | Services |
| 112 | ServAdmPub | Public administration collective services | 20 | Services |
| 113 | PrevAssisSoc | Welfare and social assistance services | 20 | Services |
| 114 | EducPublica | Public education | 20 | Services |
| 115 | EducPrivada | Private education | 20 | Services |
| 116 | SaudePublica | Public health | 20 | Services |

| | | | | |
|---|---|---|---|---|
| 117 | SaudePrivada | Private health | 20 | Services |
| 118 | ArteCultEsp | Arts, culture, sport and recreation services | 20 | Services |
| 119 | OrgPatrSind | Employers, unions and other associative services | 20 | Services |
| 120 | ManutRepPC | Maintenance of computers, telephones and household items | 20 | Services |
| 121 | ServPessoais | Personal services | 20 | Services |
| 122 | ServDomest | Household services | 20 | Services |

Source: Authors' aggregation using TERM-BR15 Database

**Table A3.** Real Household Consumption and Prices, % Change from Baseline, Accumulated in 2025

| Household Income Group | Scenario I | | Scenario II | |
|---|---|---|---|---|
| | Real Consumption | Real Consumer Basket Price Index | Real Consumption | Real Consumer Basket Price Index |
| POF1 (poorest) | -0.066 | 0.011 | -1.290 | -0.022 |
| POF2 | -0.054 | 0.011 | -0.475 | -0.003 |
| POF3 | -0.049 | 0.009 | -0.328 | 0.010 |
| POF4 | -0.047 | 0.008 | -0.247 | 0.018 |
| POF5 | -0.036 | 0.008 | -0.157 | 0.030 |
| POF6 | -0.030 | 0.007 | -0.103 | 0.045 |
| POF7 | -0.021 | 0.007 | -0.043 | 0.044 |
| POF8 | -0.015 | 0.009 | 0.001 | 0.044 |
| POF9 | -0.007 | 0.007 | 0.042 | 0.051 |
| POF10 (richest) | 0.011 | 0.009 | 0.153 | 0.069 |

Source: TERM-BR model results

**Table A4.** Participation of each Type of Labor in the Sector Payroll

| Sector | OCC 1 | OCC 2 | OCC 3 | OCC 4 | OCC 5 | OCC 6 | OCC 7 | OCC 8 | OCC 9 | OCC1 0 | Tota l |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Corn | 0.03 | 0.44 | 0.27 | 0.11 | 0.05 | 0.03 | 0.01 | 0.01 | 0.02 | 0.04 | 1.00 |
| Soybean | 0.02 | 0.33 | 0.31 | 0.15 | 0.07 | 0.04 | 0.02 | 0.01 | 0.02 | 0.05 | 1.00 |
| Other agricultural products | 0.06 | 0.45 | 0.22 | 0.11 | 0.05 | 0.03 | 0.02 | 0.01 | 0.02 | 0.05 | 1.00 |
| Cattle | 0.10 | 0.54 | 0.21 | 0.06 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.03 | 1.00 |
| Raw milk | 0.09 | 0.58 | 0.20 | 0.05 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 1.00 |
| Hogs | 0.04 | 0.56 | 0.23 | 0.06 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 1.00 |
| Poultry and eggs | 0.03 | 0.59 | 0.17 | 0.06 | 0.04 | 0.02 | 0.02 | 0.01 | 0.02 | 0.04 | 1.00 |
| Forestry products | 0.04 | 0.46 | 0.17 | 0.10 | 0.07 | 0.04 | 0.03 | 0.02 | 0.02 | 0.06 | 1.00 |
| Mining | 0.00 | 0.05 | 0.06 | 0.06 | 0.05 | 0.03 | 0.03 | 0.02 | 0.05 | 0.66 | 1.00 |
| Beef | 0.02 | 0.52 | 0.23 | 0.07 | 0.04 | 0.03 | 0.02 | 0.01 | 0.02 | 0.05 | 1.00 |
| Pork | 0.02 | 0.53 | 0.22 | 0.07 | 0.04 | 0.02 | 0.02 | 0.01 | 0.02 | 0.04 | 1.00 |
| Poultry meat | 0.02 | 0.53 | 0.22 | 0.07 | 0.04 | 0.03 | 0.02 | 0.01 | 0.02 | 0.04 | 1.00 |
| Milk and dairy | 0.03 | 0.39 | 0.21 | 0.10 | 0.06 | 0.05 | 0.04 | 0.02 | 0.02 | 0.08 | 1.00 |
| Other food products | 0.02 | 0.35 | 0.18 | 0.10 | 0.06 | 0.04 | 0.03 | 0.02 | 0.04 | 0.15 | 1.00 |
| Other fuels | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.92 | 1.00 |
| Gas-alcohol | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.95 | 1.00 |
| Manufacturing | 0.02 | 0.27 | 0.16 | 0.10 | 0.07 | 0.05 | 0.04 | 0.03 | 0.05 | 0.21 | 1.00 |
| Ethanol | 0.01 | 0.16 | 0.27 | 0.22 | 0.10 | 0.05 | 0.03 | 0.02 | 0.03 | 0.12 | 1.00 |
| Pharmaceutical products | 0.00 | 0.09 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.10 | 0.48 | 1.00 |
| Services | 0.02 | 0.29 | 0.15 | 0.09 | 0.06 | 0.05 | 0.04 | 0.03 | 0.05 | 0.23 | 1.00 |

Source: TERM-BR15 Database

**Table A5.** Participation of the Sectors in the Payroll of each Type of Labor

| Sector | OCC1 | OCC2 | OCC3 | OCC4 | OCC5 | OCC6 | OCC7 | OCC8 | OCC9 | OCC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Corn | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Soybean | 0.01 | 0.02 | 0.03 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| Other agricultural products | 0.05 | 0.03 | 0.03 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| Cattle | 0.05 | 0.02 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Raw milk | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hogs | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Poultry and eggs | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Forestry products | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mining | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 |
| Beef | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pork | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Poultry meat | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Milk and dairy | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other food products | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 |
| Other fuels | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Gas-alcohol | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Manufacturing | 0.07 | 0.09 | 0.10 | 0.10 | 0.11 | 0.10 | 0.10 | 0.10 | 0.10 | 0.09 |
| Ethanol | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pharmaceutical products | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Services | 0.78 | 0.78 | 0.76 | 0.78 | 0.81 | 0.83 | 0.83 | 0.84 | 0.85 | 0.83 |
| Total | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Source: TERM-BR15 Database

**Table A6.** Average Real Wages, % Change from Baseline, Accumulated in 2025: Scenario I

| Type of Work | PR | RoS | MT | RoM | SP | RoSE | NE | N |
|---|---|---|---|---|---|---|---|---|
| OCC1 | -0.14 | -0.06 | -0.10 | -0.03 | -0.03 | -0.03 | -0.07 | -0.11 |
| OCC2 | -0.25 | -0.19 | -0.13 | -0.04 | -0.02 | -0.03 | -0.02 | -0.04 |
| OCC3 | -0.11 | -0.12 | -0.01 | -0.02 | -0.02 | -0.02 | -0.02 | -0.03 |
| OCC4 | 0.01 | 0.00 | 0.07 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| OCC5 | 0.05 | 0.02 | 0.07 | 0.01 | 0.00 | 0.00 | 0.01 | 0.02 |
| OCC6 | 0.06 | 0.01 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 |
| OCC7 | 0.06 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| OCC8 | 0.06 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 |
| OCC9 | 0.08 | 0.04 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.02 |
| OCC10 | 0.11 | 0.04 | 0.00 | 0.01 | 0.00 | 0.02 | 0.02 | 0.03 |

Source: TERM-BR model results

Note: PR = Paraná; RoS = Rest of South; MT = Mato Grosso; RoM = Rest of Midwest; SP = São Paulo; RoSE = Rest of Southeast; NE = Northeast; N = North

**Table A7.** Average Real Wages, % Change from Baseline, Accumulated in 2025: Scenario II

| Type of Work | PR | RoS | MT | RoM | SP | RoSE | NE | N |
|---|---|---|---|---|---|---|---|---|
| OCC1 | -0.45 | -0.20 | -1.19 | -0.67 | -0.37 | -0.50 | -1.73 | -2.83 |
| OCC2 | -0.65 | -0.69 | -0.62 | -0.56 | -0.19 | -0.22 | -0.38 | -0.95 |
| OCC3 | -0.22 | -0.29 | -0.19 | -0.38 | -0.09 | -0.09 | -0.11 | -0.49 |
| OCC4 | 0.05 | 0.11 | 0.43 | 0.08 | 0.04 | 0.05 | 0.07 | 0.06 |
| OCC5 | 0.11 | 0.16 | 0.57 | 0.19 | 0.05 | 0.08 | 0.16 | 0.32 |
| OCC6 | 0.10 | 0.14 | 0.45 | 0.18 | 0.05 | 0.07 | 0.12 | 0.37 |
| OCC7 | 0.09 | 0.12 | 0.19 | 0.18 | 0.06 | 0.07 | 0.15 | 0.34 |
| OCC8 | 0.12 | 0.13 | 0.26 | 0.21 | 0.07 | 0.10 | 0.18 | 0.41 |
| OCC9 | 0.14 | 0.13 | 0.08 | 0.23 | 0.07 | 0.09 | 0.19 | 0.55 |
| OCC10 | 0.18 | 0.16 | 0.10 | 0.28 | 0.08 | 0.22 | 0.31 | 0.66 |

Source: TERM-BR model results

Note: PR = Paraná; RoS = Rest of South; MT = Mato Grosso; RoM = Rest of Midwest; SP = São Paulo; RoSE = Rest of Southeast; NE = Northeast; N = North