Journal of Agricultural and Resource Economics: Preprint
ISSN: 1068-5502 (Print); 2327-8285 (Online)

doi: 10.22004/ag.econ.342181

Economy-Wide Effects of Bovine Spongiform Encephalopathy in Brazil

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Bovine spongiform encephalopathy (BSE) has caused turbulence in international beef markets over the last 40 years and resulted in severe economic consequences for countries with identified BSE cases. Brazil's latest atypical BSE cases occurred in 2021 and 2023, and China banned Brazilian beef imports in each case. This study employs a computable general equilibrium model to assess the economy-wide impacts of BSE in Brazil due to negative domestic and international market reactions. Decreased beef exports lead to welfare losses for Brazil, while Brazil's most important competitors in the international market for beef benefit from trade diversion.

Key words: beef, BSE, computable general equilibrium model, economic impacts, international trade

Introduction

Global health safety is a major international concern, particularly in the wake of the COVID-19 pandemic. There are imminent threats to human and animal health with the emergence and resurgence of infectious diseases with epidemic potential. Countries are threatened by epidemics that may cause considerable health impacts and lead to substantial national and global economic losses. Zoonotic diseases, such as bovine spongiform encephalopathy (BSE) and the associated human variant Creutzfeldt-Jakob disease (vCJD), underline that human and animal health are interconnected (Tozer et al., 2010). Therefore, it is essential to have coordinated, collaborative, multidisciplinary, and intersectoral approaches to better understand and respond quickly to zoonotic disease events (Mackenzie et al., 2013).

BSE is a degenerative, neurological cattle disease with a long incubation period, and there is currently no treatment or vaccine against it. Unlike contagious viral or bacterial disease, BSE cannot be transferred from animal to animal or from animal to human via direct or indirect contact. This disease has two distinct forms: classical BSE occurs through consuming contaminated feed or additives containing the abnormal prion[1] protein agent. On the other hand, atypical BSE refers

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This research did not receive any funding. The authors declare no conflicts of interest.

Review coordinated by Jeffrey J. Reimer.

[1] Prions are abnormal, transmissible pathogenic agents and can cause neurodegenerative diseases in mammals, including BSE in cattle. Unlike bacteria, viruses, and fungi, prions do not contain nucleic acids (DNA or RNA). Instead, a prion is a misfolded version of a normal protein that can be found in the brain.

to naturally and sporadically occurring forms believed to appear in all cattle populations at a very low rate and have only been identified in older cattle when conducting surveillance. BSE is a mandatory notification disease and must be reported to the World Organization for Animal Health (WOAH) when detected.

Classical BSE was first diagnosed in the United Kingdom (UK) in 1986, being subsequently reported in 25 countries, mainly in Europe, Asia, the Middle East, and North America (Adkin et al., 2016; Corona et al., 2017; WOAH, 2021a). The infectious BSE prion is resistant to commercial inactivation procedures such as heat, which means that it may not be destroyed in the rendering process after slaughter. Commercial beef processing has been adapted to remove specified risk materials, such as the brain and spinal cord, to reduce the risk that BSE prions could be passed to humans. Epidemiological and pathological studies support that consuming food containing high-risk products from BSE-infected cattle puts a person at increased risk of vCJD, negatively affecting beef demand (Mangen and Burrel, 2001; Almas et al., 2005; Lloyd et al., 2006; WOAH, 2021a).

In the early 2000s, prions that cause atypical BSE were discovered through enhanced surveillance for transmissible spongiform encephalopathies. Atypical BSE presents different neuropathological and molecular features from classical BSE, occurring naturally, particularly among cattle eight years of age or older (Costassa et al., 2016; Kumagai et al., 2019). The occurrence of atypical BSE is not considered for official BSE risk status recognition due to its natural occurrence (Casalone and Hope, 2018). Although the yearly incidence of atypical BSE is considered negligible, the possibility of transmission through recycling of the agent cannot be ruled out. Actions to manage exposure risk to atypical BSE in the feed supply chain are recommended as a precautionary measure. Countries must provide evidence to WOAH that any cattle detected with atypical BSE have been destroyed to prevent potential contamination entry into the feed or food supply chain (WOAH, 2021b).

BSE outbreaks cause severe economic consequences for the beef sector, especially for international trade (Lloyd et al., 2006; Wick and Holland, 2010; Mathews and Adkin, 2011; Webb et al., 2018). Adverse impacts on international trade were highlighted after BSE cases were identified in Japan, Canada, and the United States (U.S.) in the early 2000s. Japan suffered from bans on beef exports to South Korea, Singapore, China, Malaysia, and the Philippines (Jin and Koo, 2003; Jin, 2006; Kumagai et al., 2019). Canada faced import bans on cattle and beef from 34 countries, including the U.S. and Mexico (Loppacher et al., 2004; Le Roy et al., 2006; Weerahewa et al., 2008; Klein and Le Roy, 2010; Jones and Davidson, 2014). Fifty-three countries imposed bans on imports of U.S. beef, and markets such as Japan, South Korea, Taiwan, and China remained closed for years. China's market only reopened to U.S. beef in 2016 (Coffey et al., 2005; Mathews et al., 2006; Peterson et al., 2017). Trade restrictions related to BSE for cattle and beef originating from Canada and the U.S. led to a shortage in the global beef market between 2003 and 2006. As a result, countries capable of exporting, notably Australia and Brazil, increased their export market shares while Canada and the U.S. saw a decline in their export market shares. (Mathews et al., 2006; Mutondo et al., 2009; Jordan, 2016; Soon and Thompson, 2020).

In addition to international trade restrictions, BSE reduces domestic beef consumption in affected countries. Japan, Canada, and the U.S. experienced sharp decreases in domestic beef consumption in the short term after the identification of BSE cases in the early 2000s because of consumer concerns about food safety (Jin et al., 2004; Almas et al., 2005; Klein and Le Roy, 2010; Klein and Le Roy, 2010; Muringai and Goddard, 2011; Yang and Goddard, 2011; Myae and

These misfolded proteins can induce other normal proteins also to misfold, leading to a cascade of amplification that results in the accumulation of prion proteins in the brain. This accumulation disrupts typical tissue structure, leading to the characteristic spongy degeneration of the brain tissues and associated fatal neurological symptoms. The disease caused by prions can be transmitted between animals and, in some cases, to humans through the consumption of infected tissue (Zerr et al., 2024).

Goddard, 2011; Muringai and Goddard, 2016; Coffey et al., 2005; Yeboah et al., 2007). The experiences of BSE outbreaks, especially in Canada and the U.S., underline the importance of considering food risks in terms of direct impacts on animal health and food safety and the broader economic impacts on domestic and global markets.

Beef is a substantial component of world agricultural trade value, contributing USD 57 billion to global agricultural trade value in 2020 (FAO, 2022). Understanding the effects of diseases on the beef market is a crucial food policy concern. The impact of BSE on trade can look quite different from viral diseases like African swine fever or foot-and-mouth disease (FMD), which are often large-scale outbreaks. BSE is more commonly restricted to a single identified animal or a very small number of identified animals, causing negligible production losses, yet leading to trade bans that usually cover a wide geographic area. The effects of a BSE outbreak on market access may persist long after the outbreak ends, as in the case of China and the U.S., increasing the relevance of this issue for exporting countries (Pereira et al., 2011). A country that has identified a case of BSE is about 12% less likely to export to a market that has not detected BSE, and the value of trade that does take place is decreased by 20-30% (Webb et al., 2018). Outbreak-related policies affect both food security and market access issues (Jones and Davidson, 2014).

Livestock production is one of the main economic activities in Brazil. The Brazilian cattle herd is the largest in the world, with 224.6 million heads, representing 14.3% of the world herd (FAO, 2023). In 2022, Brazil exported 1.99 million tons of beef, corresponding to approximately 15% of total exports on the international market (MDIC, 2023; FAO, 2023). Although Brazil has never had a case of classical BSE, sporadic atypical BSE cases have been identified in 2012, 2014, 2019, 2021, and 2023. The most recent cases were detected in September 2021 and February 2023. Brazil's BSE status within WOAH remained the same, yet the international market response included restrictions on imports of Brazilian beef. In 2021, Egypt and Saudi Arabia halted beef imports from Brazil for ten days. China and Hong Kong, which accounted for about 64% of Brazil's beef exports, suspended beef imports for 100 days (MAPA, 2021a). In 2023, China imposed a total ban on Brazilian-originated beef for 30 days. As there is nothing a country can do to prevent the sporadic occurrence of atypical BSE, it is important to study the potential impacts of BSE in Brazil to inform potential policy formulation related to animal disease events.

This research applies a computable general equilibrium (CGE) model to capture the effects of reduced demand for Brazilian beef due to an **atypical** BSE case. This work simulates prices, output, welfare, and trade changes arising from decreased international demand for Brazilian cattle and beef. This study contributes to the literature on the impacts of sanitary measures in the global market. Furthermore, the simulation of potential economic impacts informs policymakers on the magnitude of estimated economic losses and trade impacts of the occurrence of an atypical BSE case in Brazil.

Existing research on BSE primarily concentrates on classical cases that occurred in the early 2000s (Philippidis and Hubbard, 2005; Devadoss et al., 2006; Wigle et al., 2007; Tsigas et al., 2008; Wieck and Holland, 2010; Peterson et al., 2017). This research stands out for examining the effects of an atypical BSE case, highlighting that while the economic consequences might not be substantial relative to other animal diseases, identifying just one affected animal can pose a risk to international trade and domestic demand. This finding holds crucial significance for major beef-exporting countries like Brazil. In addition, this paper's findings can be contrasted with those of Menezes et al. (2022), which assesses the effects of a highly contagious disease (FMD) on global trade. Unlike FMD, atypical BSE does not directly affect cattle production. Historically, restrictions on international trade due to FMD have been more severe than those related to atypical BSE. As a result, these two papers complement each other in examining the impacts of highly contagious diseases versus non-infectious diseases on international trade.

The next section describes Brazil’s national program for the prevention and surveillance of BSE, including recent occurrences of atypical BSE cases. The subsequent section shows Brazil’s heavy reliance on beef exports to China while concurrently observing China’s efforts to broaden its beef sources and reduce its dependence on beef imports from Brazil. The fourth section details

the modeling framework employed, introduces the external shocks to simulate changes in domestic beef demand and exports from Brazil, and outlines four policy scenarios considered in the analysis. Findings reveal that an atypical BSE case in Brazil has a minimal impact on local supply chains. However, restrictions on export flows lead to adverse effects, particularly affecting overall welfare in Brazil. Simultaneously, Brazil's major competitors in the global beef market benefit from trade diversion away from Brazil. Consequently, although the domestic effects are relatively modest, trade restrictions due to BSE burden the affected country despite atypical BSE not altering the country's risk status within the WOAH. This research provides a basis for evaluating the effects of potential classical BSE cases in Brazil or other countries, which could result in more severe economic repercussions.

BSE in Brazil

Brazil has never had a case of classical BSE but still implements measures to prevent the introduction of the disease. The Ministry of Agriculture and Livestock (Mapa) keeps updated regulatory measures and applies sanitary requirements throughout the beef supply chain, from import controls to final domestic products. Strict inspections and monitoring are carried out in slaughterhouses, feed suppliers, and farm properties to ensure the health and safety of the Brazilian livestock sector and consumers (Vaz and Sena, 2017). Sanitary measures to prevent BSE in Brazil were established in 1990 and are continuously improved. At first, BSE-related policies were included in the National Program for the Control of Rabies in Herbivores. However, Normative Instruction No. 44 of September 17, 2013, established the National Program for the Prevention and Surveillance of BSE (MAPA, 2021b). The main objectives of the BSE Program are i) to prevent the entry of the BSE agent into the national territory, ii) to apply risk mitigation measures to avoid possible recycling and dissemination of the BSE agent in the country, and iii) to maintain a surveillance system for the detection of infected animals. Preventive health measures are harmonized with the provisions of WOAH, which considers risk management for the occurrence of BSE. WOAH currently classifies Brazil in the insignificant risk category (WOAH, 2021b), demonstrating the current measures' effectiveness and the lack of classical BSE in Brazil.

Although Brazil has never had a case of classical BSE, six cases of atypical BSE have been identified in the country: one in the years 2012, 2014, and 2019, two cases in 2021, and one case in 2023. All cases occurred in older animals, which were considered low-risk by WOAH. Nevertheless, identifying atypical cases reinforces the need for strict maintenance of BSE surveillance and prevention measures to avoid the introduction of BSE in the territory.

Brazil's BSE status within WOAH did not change when the atypical cases were identified, yet the international market reacted by imposing bans on Brazilian cattle and beef. After confirmation of the first case of atypical BSE in Brazil in 2012, imports from Brazil were suspended by South Africa, China, Japan, South Korea, Egypt, Saudi Arabia, Lebanon, and Iraq (Globo Rural, 2012). Japan and South Korea did not import substantial volumes from Brazil, but Egypt and Lebanon were among the main markets for Brazilian beef then (ComexStat, 2023). Most countries eliminated the bans in less than a month, but Iraq, South Africa, Saudi Arabia, and China maintained bans for three years. With the confirmation of a new case of BSE in 2014, Egypt, Iran, and Peru temporarily closed their markets to Brazilian beef (Globo Rural, 2014). In 2019, only China closed its market for ten days (Exame, 2019). It is important to highlight that when China reopened the market for Brazilian beef in 2015, an agreement was signed by both countries stating that if a BSE case is confirmed in Brazil, beef exports to China automatically stop as a preventive measure until the case is considered resolved by WOAH (Sindicarne, 2015).

The fourth and fifth cases of atypical BSE in Brazil were confirmed on September 3, 2021. The next day, China, Hong Kong, Egypt, and Saudi Arabia suspended imports of Brazilian beef. After ten days, Saudi Arabia and Egypt reopened markets when WOAH confirmed that Brazil's BSE status would not change (Regional Council of Veterinary Medicine of the State of São Paulo – CRMVSP, 2021). China and Hong Kong, which account for approximately 64% of Brazilian

beef exports, kept the suspension in place for 100 days. Japan was still maintaining a BSE-related ban on Brazilian beef that had been in place since 2012. The continued suspension of beef shipments to China after September 3, 2021, limited the domestic demand for animals for slaughter. As a result, cattle prices in Brazil briefly decreased by 7% in September and 11.8% in October before recovering to pre-BSE projections in November 2021 (Cepea, 2021a; Cepea, 2021b; Cepea, 2021c). On February 22, 2023, another BSE case was identified in Brazil, and exports to China were automatically suspended. Five days later, WOAH confirmed it was an atypical case, but China kept the market closed for 30 days. Although there is no evidence that BSE cases in Brazil affected production and exports from other sectors, the consequences of atypical cases for the Brazilian beef supply chain highlight the importance of economic studies to assess the potential economic damage caused by animal disease cases.

Brazilian Beef Trade and the Importance of China

Brazilian beef exports gained greater relevance in the international market during the 2000s. Brazil began to export more with increased commodity prices, becoming one of the world's largest beef suppliers, especially frozen beef (see Figure S1 in the Supplementary Material). In 2022, Brazil was the second largest beef producer, accounting for 17.4% of global beef production. In the same year, Brazil exported 22% of its domestic output and was the largest beef exporter, supplying 15% of global export volumes. Brazilian revenue from beef exports reached a record of $11.8 billion in 2022. Approximately 64% of exports went to China and Hong Kong, 7% to the U.S., 3.1% to Chile, and 2.8% to Egypt (see Figure S2 in the Supplementary Material). However, China only recently emerged as a primary importer of Brazilian beef. Between 2000 and 2004, the largest buyers were the United Kingdom, the Netherlands, Chile, the U.S., and Egypt, comprising approximately 50% of Brazilian exports. In 2005, Russia became the largest buyer of beef from Brazil and led export shares until 2012, accounting for 20% to 30% of annual exports.

Chinese imports of Brazilian beef were negligible from 2000 to 2007, and only about 4% of Brazilian exports were destined for Hong Kong during this period. However, Hong Kong later began importing more Brazilian beef, representing 7% of Brazilian exports in 2008 and 12% in 2009. In 2013, the share of exports destined for Hong Kong (19.8%) exceeded the share of Russia (18.9%). Still, the Chinese market remained closed to Brazilian beef because of the atypical BSE case in 2012, as mentioned previously. China increased beef imports from Brazil in 2015, together with Hong Kong, representing about 24% of Brazilian beef exports (see Figure S3 in the Supplementary Material). Chinese imports increased over time, reaching a record in 2022, with China and Hong Kong accounting for 64% of Brazilian beef exports. China banned Brazilian beef imports from September to December 2021, culminating in a decrease in beef exports destinated to China and a reduction in the volume of Brazilian beef exports in 2021 (8.3% lower compared to 2020), which had a relatively small effect on the domestic prices, as previously described. The full impacts of the Chinese market closure in 2023 due to the latest atypical BSE case in Brazil are still unknown as of the time this paper was written.

The 2000s were marked by the gradual opening of the Chinese market to beef imports, especially due to China's entry into the World Trade Organization in 2001 (WTO, 2023). Between 2000 and 2012, the U.S. was the largest beef importer in the world, which changed in 2013 once the combined imports from Hong Kong and China surpassed US imports. China and Hong Kong previously represented approximately 2% of world imports, but in 2013 this share increased to 9%. The Chinese import share in the world beef market increased over time, reaching 23.1% and 19.1% of world imports in 2020 and 2021, respectively (United Nations Statistics Division, 2023). Between 2000 and 2011, Chinese beef imports were mainly offal, a pattern that changed from 2012 onwards, with an increase in the imported volume of frozen beef (see Figure S4 in the Supplementary Material). Cheng et al. (2015) show that China's share of global meat imports is expected to increase along with the country's economic growth in the coming decades.

Luo and Tian (2018) state that the combination of rising demand with constrained domestic production in China led the country to increase imports of meat products from the international market. The study shows that China's meat imports have become more diversified and sustainable over the last two decades, mainly because China increased beef imports from different trade partners. China imported beef from 47 countries in 2000 and 69 countries in 2020. The U.S. accounted for between 40% and 50% of China's annual beef imports from the 1990s until 2003, when the identification of BSE in the U.S. caused exports to China to fall to 11%. Subsequently, Brazil and Australia became the largest suppliers to China, representing 30% and 20% of total Chinese beef imports, respectively, in 2004 (United Nations Statistics Division, 2023). Brazil's share of Chinese beef imports reached a record 49.4% in 2008 (see Figure S5 in the Supplementary Material). The U.S. share of Chinese beef imports increased in 2010, reaching 17% that year. Nevertheless, Brazil remained the leading beef supplier to China despite increases in market shares gained by Australia, New Zealand, Argentina, and Canada between 2013 and 2021. The diversification of beef import sourcing highlights China's decreased dependence on Brazilian beef.

Modeling Framework and Data

This research investigates the impacts of an atypical BSE case on the Brazilian economy. This work simulates an atypical BSE case by imposing exogenous shocks to domestic production and trade in a CGE model. CGE models have been used widely to assess animal health-related issues and sanitary barriers to international trade (Beckman and Arita, 2017; Miller et al., 2019; Maliszewska et al., 2020). The advantages of using this type of framework are that constraints ensure commodity and factor markets balance, and macroeconomic identities hold. Equilibrium prices, such as commodity and factor prices, are endogenously determined. Shocks in any sector have repercussions throughout the economy and impact other sectors because of interlinkages within the economy. The economy-wide nature of CGE models creates an ideal framework to assess the economic impacts of BSE (McDonald and Roberts, 1998; Hubbard and Philippidis, 2001; Philippidis and Hubbard, 2005; Devadoss et al., 2006; Wigle et al., 2007; Tsigas et al., 2008; Wieck and Holland, 2010).

The analytical framework of this study consists of simulations employed with the standard Global Trade Analysis Project (GTAP) model and database (Hertel, 1997; Aguiar et al., 2019). This work follows the standard approach of using macroeconomic shocks to update version 10 of the GTAP database from 2014 to 2019. This method simulates actual gross domestic product (GDP) changes and population (Beckman et al., 2012). The GTAP model is a multi-region, multi-commodity, general equilibrium framework with a structure representing 141 regions and 65 products based on annual data. Models such as GTAP have emerged as increasingly important tools in analyzing economic issues by accounting for relevant linkages among agents and sectors across regions in the global economy (Boisvert et al., 2012). This research assumes a standard GTAP model closure with mobile capital and labor and sluggish land mobility across sectors. GTAP is a static model in that it provides estimates of economic impacts for a one-time shock.

Producers are assumed to be perfectly competitive cost minimizers in the model, with technology defined as a nested production function. Producers demand intermediate inputs based on the prices of inputs and outputs, subject to a Leontief intermediate production function. In addition, primary factors are substituted by producers as their relative prices change. Consumer demand is described by a constant difference in the elasticity demand system, which allows income growth to affect consumer preferences (Beckman et al., 2021). Each region's representative household is assumed to maximize utility derived from the consumption of market goods and savings subject to a regional income constraint. Cobb-Douglas functions describe government and investment demand. Finally, import demand is defined by the Armington specification, which allows for the substitution of domestics and imports and product differentiation by import source (Armington, 1969). Generally, the Armington specification

allows for cross-hauling, where a product can be imported and exported, and explicitly tracks bilateral trade flows (Hertel, 1997). Commodity markets are comprised of both domestic demand and supply plus international trade.

The GTAP framework is commonly used to assess the effects of economic shocks on the international trading system, including international trade flows and transport margins, global savings and investment, and a comprehensive consumer demand system that accounts for price and income responsiveness across countries (Countryman and Hagerman, 2017). The most significant advantage of this model for the present analysis is that it allows the assessment of bilateral trade between Brazil and its trade partners in the international beef market. There is strong precedent in the literature to employ the GTAP framework to assess the potential impacts of BSE in the global beef market (Hubbard and Philippidis, 2001; Philippidis and Hubbard, 2005; Wigle et al., 2007; Tsigas et al., 2008).

Version 10 of the GTAP database includes 141 regions, which aggregate 244 countries, and 65 sectors of economic activity that can be described more generally by three broad categories: agriculture and food processing, manufacturing, and services. As this study focuses on the impact of BSE, sectors related to cattle and beef markets were kept disaggregated, including eight agricultural sectors: grains; other agricultural products; cattle; poultry and other animals; beef; other meat; dairy products; and other processed foods. The remaining sectors were combined into three aggregate sectors: other primary products, manufacturing, and services (see Table S1 in the Supplementary Material). Furthermore, the GTAP regional data was aggregated, keeping detail on the major players in the international beef market and the importers that imposed bans on beef from Brazil after the BSE cases were identified. The aggregated data is divided into 19 regions: Brazil, Argentina, Chile, Uruguay, Paraguay, U.S., Mexico, Canada, European Union and United Kingdom, Russia, Egypt, Saudi Arabia, India, China and Hong Kong, Japan, South Korea, Australia, New Zealand, and rest of the world (see Table S2 in the Supplementary Material).

Scenario Design

This research simulates four BSE-related policy scenarios to understand the economy-wide effects of an atypical case of BSE in Brazil. The scenarios comprise exogenous shocks on Brazilian beef domestic demand and exports, detailed below. This research follows the literature by considering changes in domestic and international demand for beef because of the nature of country responses to the identification of BSE in a trade partner (Devadoss et al., 2006; Yeboah et al., 2007; Wigle et al., 2007; Tsigas et al., 2008; Tozer et al., 2010; Wieck and Holland, 2010). The simulations also include scenarios related to observed behavior associated with the atypical BSE cases identified in Brazil in 2021. It is important to note that the main four scenarios consider atypical BSE cases, which imply different impacts on demand compared to classical BSE outbreaks (WOAH, 2023).

Four policy scenarios are employed to simulate the economic implications of an atypical BSE case in Brazil. Scenarios include import bans on Brazilian cattle and beef imposed by China, Egypt, and Saudi Arabia and decreased domestic beef demand in two policy scenarios. These countries were chosen based on historical data on bans of Brazilian beef due to atypical BSE cases. Domestic beef demand is not altered in Scenarios I and II. Scenarios III and IV consider a negative consumer response simulated by a 0.42% decrease in domestic demand, following Mu et al. (2015). All scenarios assume that Egypt and Saudi Arabia ban Brazilian cattle and beef imports for one month; however, the time China restricts cattle and beef imports from Brazil varies across scenarios. Scenario I simulates a three-month ban on Brazilian cattle and beef imports in China, which is the length of China's restrictions imposed in 2021 after identifying two atypical

Table 1. Scenarios for Changes in Domestic Demand for Beef and Restrictions on Brazilian Cattle and Beef Exports

Scenario	Ban on Cattle and Beef Exports from Brazil (months)			Domestic Demand for Beef (%)
	China	Egypt	Saudi Arabia	
I	3	1	1	0.00
II	1	1	1	0.00
III	3	1	1	-0.42
IV	6	1	1	-0.42

Note: Scenario I considers bans on Brazilian imports into China for 3 months, Egypt for 1 month, and Saudi Arabia for 1 month. Scenario II assumes bans on Brazilian imports into all the countries for 1 month. Scenario III assumes the same import bans from Scenario I with an additional decrease in domestic demand for beef in Brazil of 0.42%. Scenario IV represents the worst-case scenario, with bans on Brazilian imports into China for 6 months, Egypt for 1 month, and Saudi Arabia for 1 month, in addition to a 0.42% decrease in Brazilian domestic demand for beef.
Source: Authors' design

BSE cases in Brazil (**Table 1**). Scenario II is the most optimistic since domestic demand is not affected, and the bans on Brazilian cattle and beef exports into China last for one month. Scenario III is an intermediate scenario with a relatively small impact on domestic demand and bans on Brazilian exports, similar to 2021. Scenario IV is the most pessimistic, combining a 0.42% decrease in domestic demand with a Chinese ban on Brazilian cattle and beef for six months. The last scenario incorporates the possibility of longer-lasting restrictions based on historic bans imposed by China in the face of other BSE events in Brazil and other countries. An additional scenario is presented in the supplementary material, considering trade restrictions on Brazilian cattle and beef from seven regions: Canada, China, and Hong Kong, the European Union and United Kingdom, Japan, Korea, Mexico, and the U.S. This additional scenario simulates a situation closer to what could happen if a case of classical BSE was identified in Brazil, which is like what happened in Europe in the early 2000.s. Because the GTAP database is annual, the shocks were implemented in the model considering a portion of the year. For example, if the ban imposed by China lasted six months, a 50% decrease in Chinese imports of cattle and beef from Brazil was simulated. Menezes et al. (2023), Menezes et al. (2022), and Maliszewska et al. (2020) present similar types of simulations using CGE models.

Domestic Demand for Beef

The literature shows the relevance of non-price and non-income determinants in explaining consumer behavior, particularly those related to human health and food safety issues. Among these determinants, consumer information on food contamination significantly influences purchase decisions (Piggott and Marsh, 2004; Schlenker and Villas-Boas, 2009; Taylor et al., 2016). The BSE crisis of March 1996 in the UK triggered a panic reaction against beef (McDonald and Roberts, 1998). According to Mangen and Burrell (2001), preference shifts due to the BSE scare in March 1996 decreased expenditure shares of beef, minced meat, and meat products by 2.5, 3.3, and 7.9 percentage points, respectively, in the Netherlands. The BSE crisis in 2000 caused a decline in beef demand and price in Spain (Serra, 2011). Kuchler and Tegene (2006) found that beef demand in Canada was negatively affected for two weeks after the announcement of BSE detection in 2003. Mu et al. (2015) estimate that the BSE case in the U.S. resulted in a 0.42% short-run decrease in domestic beef demand.

Brazil is the fourth largest beef-consuming country in the world, accounting for approximately 13% of beef global consumption. Brazilian beef consumption totaled 5.9 million tons in 2021, highlighting beef's importance in the domestic market (Conab, 2023). The U.S. is the largest beef consumer in the world and consumed 13.6 million tons in 2021, representing 21% of total global beef consumption (Shahbandeh, 2023). In the absence of studies on Brazilian consumer responses to a domestic BSE case, this research employs the results of Mu et al. (2015) to simulate changes in domestic demand for beef in Brazil. Scenarios I and II do not consider a shock in domestic demand, while Scenarios III and IV apply a -0.42% decrease in domestic demand for beef in Brazil.

Domestic demand for beef is endogenous in the GTAP model. Swapping domestic demand with an exogenous variable is necessary to apply exogenous shocks to domestic demand directly. The exogenous variable for the change in taxes on imports of commodity i into region r ($tm_{i,r}$) from the standard GTAP closure was swapped with private household demand for domestic commodity i in region r ($qpd_{i,r}$), which then became an exogenous variable. Generally, $qpd_{i,r}$ directly affects domestic commodity prices for households, household tax payments, and welfare (measured by equivalent variation). Variable $qpd_{i,r}$ is determined in the model by equation (1):

$$qpd_{i,r} = qp_{i,r} + ESUBD_i \times \left(pp_{i,r} - ppd_{i,r}\right) \quad (1)$$

where: $qpd_{i,r}$ = private household demand for domestic commodity i in region r; $qp_{i,r}$ = private household demand for domestic commodity i in region r; $ESUBD_i$ = elasticity of substitution between domestic and imported commodities i for all agents; $pp_{i,r}$ = private consumption price for commodity i in region r; and $ppd_{i,r}$ = private household's demand price for domestic commodity i in region r.

Brazilian Beef Exports

Trade regulations can be decisive measures to prevent or postpone the spread of contagious animal diseases and to protect animal and human health. However, a policy can also unnecessarily restrict trade. International agreements on standards have been created to protect animal, plant, and human health in the least trade-restrictive manner, as designated by the Technical Barriers to Trade (TBT) Agreement within the World Trade Organization (WTO). However, the norm has been for regulations to be far more restrictive than previously agreed-upon measures when dealing with BSE. The major impact of atypical BSE will be through market closures, given the minor production effects associated with atypical BSE cases. The identification of a BSE case happens when cattle exhibit neurological symptoms or are excluded from slaughter due to neurological symptoms, so the direct herd impacts and production losses from BSE are minimal (Tozer et al., 2010).

Examples of BSE-related trade policy studies are prevalent in the literature (Wigle et al., 2007; Tsigas et al., 2008; Wieck and Holland, 2010). Devadoss et al. (2006) simulate three possible export ban scenarios due to BSE in the U.S.: i) 90% decline in foreign demand and 0% decline in U.S. domestic demand; ii) 90% decline in foreign demand and 10% decline in U.S. domestic demand; iii) 90% decline in foreign demand and 25% decline in U.S. domestic demand. The first scenario isolates the effects of the import ban by foreign countries on U.S. beef and cattle markets. According to the authors, the second scenario is similar to what happened in 2004 after the BSE case in the U.S. The third scenario, though pessimistic, is consistent with the losses in the first few weeks of the BSE outbreak in the U.S. Similarly, Tozer et al. (2010) assess the potential impacts of a hypothetical BSE outbreak on the Australian beef industry and assume that a total ban on beef exports from Australia could last one to three years.

Considering the different simulation approaches presented in the international trade literature and the BSE-related bans observed in Brazil during the last decade, this study simulates alternative export ban scenarios for Brazilian cattle and beef ranging from one to six months due to an atypical

case of BSE. The simulations consider a total ban of Brazilian cattle and beef exports to Egypt and Saudi Arabia for one month for all scenarios and a total ban of Brazilian cattle and beef exports to China for one, three, and six months. An additional scenario (presented in the supplementary material) comprises a six-month ban on Brazilian cattle and beef exports imposed by seven regions: Canada, China and Hong Kong, the European Union and UK, Japan, Korea, Mexico, and the U.S.

Export quantities are endogenous in the GTAP model. Swapping export quantity from Brazil to other regions with an exogenous variable is necessary to apply exogenous shocks to exports. The exogenous variable for technological change for imports of commodity i from region r into region s ($ams_{i,r,s}$) from the standard GTAP closure was swapped with the quantity of exports of i from source r to destination s ($qxs_{i,r,s}$), which then became an exogenous variable. Generally, $qxs_{i,r,s}$ directly affects the value of exports and imports, domestic commodity prices, world commodity prices, export tax payments, bilateral demand for transport services, gross domestic product (GDP), and welfare. Variable $qxs_{i,r,s}$ is determined in the model by equation (2):

$$qxs_{i,r,s} = -ams_{i,r,s} + qim_{i,s} - ESUBM_{i,r,s} \times \left(pms_{i,r,s} - ams_{i,r,s} - pim_{i,s}\right) \quad (2)$$

where: $qxs_{i,r,s}$ = quantity of exports of i from source r to destination s; $ams_{i,r,s}$ = commodity i imports from region r augmenting technological change in region s; $qim_{i,s}$ = quantity of aggregate imports of commodity i demanded by region s; $ESUBM_{i,r,s}$ = elasticity of substitution among imports of commodity i from region r into region s in the Armington import demand structure; $pms_{i,r,s}$ = domestic price for commodity i supplied from region r to region s; and $pim_{i,s}$ = market price of aggregate imports of commodity i in region r.

Results

The occurrence of an atypical BSE case in Brazil leads to negative impacts concentrated in the cattle and beef sectors, as expected. In addition to decreasing Brazilian output, producer prices, and exports, import bans on cattle and beef from Brazil impact other countries, especially countries that highly depend on Brazilian products and major competitors in the international beef market. Changes in Brazilian output are more substantial in Scenario IV compared to the other scenarios, as expected, because it is the most pessimistic scenario. The cattle and beef sectors are the only negatively affected sectors, with a decrease in output of approximately 3% and 3.5%, respectively, in Scenario IV. Other sectors of the Brazilian economy show a relatively small positive increase in output. Considerable substitution effects between cattle and poultry or beef and other meat are not observed in output results (**Table 2**). Output changes were expected to be smaller in Scenario II compared to the other simulation scenarios since it considers a short-term ban on Brazilian exports to China. The difference in shocks between Scenarios I and III is the inclusion of the decrease in domestic demand for beef. Cattle and beef output decreased by approximately 20% more in Scenario III than in Scenario I. Therefore, the addition of domestic market responses leads to larger negative effects on the economy compared to the impacts caused by export bans alone. The decrease in cattle and beef output would more than double if China's ban on Brazilian beef lasted six months (Scenario IV) instead of three (Scenario I).

The decreases in producer prices caused by the cattle and beef export bans are not substantial, ranging from -0.07% to -0.42% in the beef sector. The cattle sector is the most negatively affected, with a decrease in producer price between 0.11% and 0.59%, depending on how long the bans last. Other sectors are marginally affected, with negligible decreases in producer prices (**Table 3**). Similar to output results, the decrease in cattle and beef producer prices would more than double if China's ban on Brazilian beef lasted six months (Scenario IV) instead of three months (Scenario I). Changes in land use are minor across scenarios, as described in the **Appendix Table A.1**.

Table 2. Percentage Changes in Brazilian Output

Sectors	Scenario I	Scenario II	Scenario III	Scenario IV
Grains	0.08	0.03	0.10	0.18
Other agricultural products	0.12	0.05	0.14	0.25
Cattle	-1.40	-0.58	-1.75	-3.02
Poultry and other animals	0.11	0.04	0.13	0.23
Beef	-1.62	-0.67	-2.02	-3.48
Other meat	0.24	0.10	0.30	0.52
Dairy products	0.01	0.01	0.02	0.03
Other processed foods	0.02	0.01	0.02	0.04
Other primary products	0.01	0.01	0.02	0.03
Manufacturing	0.05	0.02	0.07	0.12
Services	0.00	0.00	0.00	0.01

Note: Scenario I considers bans on Brazilian imports into China for 3 months, Egypt for 1 month, and Saudi Arabia for 1 month. Scenario II assumes bans on Brazilian imports into all the countries for 1 month. Scenario III assumes the same import bans from Scenario I with an additional decrease in domestic demand for beef in Brazil of 0.42%. Scenario IV represents the worst-case scenario, with bans on Brazilian imports into China for 6 months, Egypt for 1 month, and Saudi Arabia for 1 month, in addition to a 0.42% decrease in Brazilian domestic demand for beef.
Source: Authors' simulations

Table 3. Percentage Changes in Brazilian Producer Prices

Sectors	Scenario I	Scenario II	Scenario III	Scenario IV
Grains	-0.08	-0.03	-0.10	-0.17
Other agricultural products	-0.07	-0.03	-0.08	-0.14
Cattle	-0.28	-0.11	-0.34	-0.59
Poultry and other animals	-0.08	-0.03	-0.09	-0.16
Beef	-0.18	-0.07	-0.26	-0.42
Other meat	-0.05	-0.02	-0.07	-0.12
Dairy products	-0.05	-0.02	-0.06	-0.11
Other processed foods	-0.05	-0.02	-0.06	-0.10
Other primary products	0.00	0.00	0.00	0.01
Manufacturing	-0.03	-0.01	-0.03	-0.06
Services	-0.04	-0.02	-0.05	-0.08

Note: Scenario I considers bans on Brazilian imports into China for 3 months, Egypt for 1 month, and Saudi Arabia for 1 month. Scenario II assumes bans on Brazilian imports into all the countries for 1 month. Scenario III assumes the same import bans from Scenario I with an additional decrease in domestic demand for beef in Brazil of 0.42%. Scenario IV represents the worst-case scenario, with bans on Brazilian imports into China for 6 months, Egypt for 1 month, and Saudi Arabia for 1 month, in addition to a 0.42% decrease in Brazilian domestic demand for beef.
Source: Authors' simulations

Table 4. Percentage Changes in Brazilian Exports

Sectors	Scenario I	Scenario II	Scenario III	Scenario IV
Grains	0.39	0.16	0.48	0.84
Other agricultural products	0.28	0.12	0.35	0.61
Cattle	0.49	0.20	0.61	1.05
Poultry and other animals	0.17	0.07	0.25	0.40
Beef	-5.69	-2.34	-5.29	-10.27
Other meat	0.37	0.15	0.45	0.78
Dairy products	0.39	0.16	0.49	0.84
Other processed foods	0.18	0.08	0.22	0.39
Other primary products	-0.03	-0.01	-0.05	-0.08
Manufacturing	0.19	0.08	0.24	0.41
Services	0.14	0.06	0.17	0.30

Note: Scenario I considers bans on Brazilian imports into China for 3 months, Egypt for 1 month, and Saudi Arabia for 1 month. Scenario II assumes bans on Brazilian imports into all the countries for 1 month. Scenario III assumes the same import bans from Scenario I with an additional decrease in domestic demand for beef in Brazil of 0.42%. Scenario IV represents the worst-case scenario, with bans on Brazilian imports into China for 6 months, Egypt for 1 month, and Saudi Arabia for 1 month, in addition to a 0.42% decrease in Brazilian domestic demand for beef.
Source: Authors' simulations

Overall, Brazilian exports in sectors other than beef are not substantially affected. Cattle exports slightly increase in each scenario (between 0.2% and 1.05%). However, this increase is small in quantity or monetary terms, as Brazilian live cattle exports are relatively small compared to animal products. The negative shocks applied to live cattle exports are relatively small since Brazil does not export many animals to China, Egypt, and Saudi Arabia. Total beef exports decrease by 2.34% in Scenario I and 10.27% in Scenario IV (**Table 4**). This effect accounts for the negative exogenous shocks caused by the trade bans imposed by China, Egypt, and Saudi Arabia. Surprisingly, the bans on Brazilian beef exports do not affect world beef prices, and world beef export quantity increases by 1.39% in Scenario IV. This increase is caused by simulated increases in beef exports from Argentina (3.43%), Uruguay (3.98%), Chile (4.1%), and Paraguay (4.63%).

The potential changes in world beef exports can be further examined by investigating bilateral trade variations. Changes in bilateral beef trade for Brazil, China, Egypt, and Saudi Arabia in Scenarios I and IV are presented in **Table 5**. Changes in bilateral beef trade for all regions in each scenario are in the **Appendix Tables A.2** to **A.5**. China and Egypt increase beef imports from all other regions after banning Brazilian beef products. On the other hand, Saudi Arabia does not substantially change beef import sources since the ban lasts only one month in each scenario. In Scenario I, China increases beef imports from other sources by approximately 6%. However, China's beef imports from different regions in the world increase by approximately 13% in Scenario IV, when the ban on Brazilian beef lasts six months. There is trade diversion from Brazil to other countries in terms of beef exports to China. With the inclusion of the domestic demand shock in Scenarios III and IV, Brazil increases beef imports by approximately 70%. However, Brazil is self-sufficient in beef supply for the domestic market, importing only a relatively small quantity of premium beef cuts. Therefore, the 70% increase in beef imports is insignificant in quantity and monetary terms. The changes in imports by China and Hong Kong, Egypt, and Saudi

Table 5. Changes in Welfare (Equivalent Variation, $US Million)

Country	Scenario I	Scenario II	Scenario III	Scenario IV
China, Hong Kong	-104.00	-37.60	-113.00	-214.00
Brazil	-68.90	-28.50	-85.00	-147.00
Egypt	-23.50	-23.30	-23.70	-23.90
Japan	-6.08	-2.42	-8.42	-14.10
Saudi Arabia	-1.08	-0.83	-1.10	-1.47
Paraguay	-0.12	-0.08	24.30	26.70
Mexico	0.67	0.21	0.53	1.20
Chile	0.80	0.31	0.39	1.08
Canada	1.80	0.36	1.52	3.65
Korea	1.80	0.71	0.62	2.14
Argentina	2.67	0.92	7.37	10.50
Russia	4.66	1.69	4.34	8.76
India	7.23	11.00	5.08	-0.71
USA	8.22	3.22	5.60	12.80
Europe (28)	11.10	3.40	6.77	17.90
Australia	11.40	3.92	12.80	24.20
Uruguay	12.80	4.21	30.90	45.60
New Zealand	13.30	5.11	13.60	25.90
Rest of the World	1.58	-1.47	-1.64	2.60

Note: Scenario I considers bans on Brazilian imports into China for 3 months, Egypt for 1 month, and Saudi Arabia for 1 month. Scenario II assumes bans on Brazilian imports into all the countries for 1 month. Scenario III assumes the same import bans from Scenario I with an additional decrease in domestic demand for beef in Brazil of 0.42%. Scenario IV represents the worst-case scenario, with bans on Brazilian imports into China for 6 months, Egypt for 1 month, and Saudi Arabia for 1 month, in addition to a 0.42% decrease in Brazilian domestic demand for beef.
Source: Authors' simulations

Arabia are similar for suppliers other than Brazil. These homogeneous changes stem from having a standard elasticity of substitution for import sources for each importing country in the GTAP model.

The aggregate changes in welfare are included in **Table 5**. The world's total welfare losses range from US$59.14 million in Scenario II to US$218.15 million in Scenario IV. The potential total world welfare loss could have been about US$125.7 million for Scenario I, which simulates bans closer to what was observed in Brazil in 2021. When looking at monetary amounts at first glance, it is important to highlight that it seems like China is the region most negatively affected, with welfare losses between US$37.6 million and US$214 million for Scenario II and Scenario IV, respectively. However, these losses correspond to 0.0003% and 0.002% of China's GDP, respectively. Potential welfare losses in Brazil range between US$28.5 million (0.002% of Brazil's GDP) and US$147 million (0.01% of Brazil's GDP), showing that in relative terms, Brazil has higher welfare losses than China. After the notification of two atypical BSE cases, Brazil may have lost approximately US$69 million in welfare in 2021 from beef export restrictions. The countries that benefit the most from BSE in Brazil are Australia (welfare ranging from $3.9 million to $24.2 million), Uruguay ($4.2 million to $45.6 million), and New Zealand

($5.1 million to $25.9 million). The countries that benefit the most are Brazil's competitors in the international market for beef, especially exports to China. In general, welfare changes are driven by changes in terms of trade.

Given that Brazil exports approximately 15% to 20% of its total beef production (Menezes and Bacha, 2020), the relatively modest effects resulting from trade bans associated with an atypical case of BSE are justifiable. If Brazil's beef exports constitute 15% of total domestic production, the reduction in beef exports across Scenarios I through IV translates to a range of 0.35% to 1.54% of total domestic beef production. Alternatively, if exports represent 20% of total beef production, the decline in beef exports in all four scenarios corresponds to a range of 0.47% to 2.05% of Brazil's annual beef production. Therefore, the simulated minor impacts on the domestic market are reasonable.

Export shocks were varied by 25% through sensitivity analysis to calculate confidence intervals and show that the study's main results are robust and statistically different across scenarios. In Scenario I, Brazilian welfare changes range between -$69.04 million and US$6.04 million. Brazil's welfare ranges between -US$28.63 million and US$2.23 million in Scenario II and between -US$85.10 million and US$6.41 million in Scenario III. The sensitivity analysis for Scenario IV shows that the welfare changes for Brazil were between -US$147.34 million and US$12.74 million.

BSE can result in changes in the elasticity of substitution for cattle and beef imports originating in the affected country. This change in preferences tends to favor alternative sources, thereby increasing importer bias against cattle and beef from the affected country (Susanto et al., 2008; Kawashima and Sari, 2010; Soon and Thompson, 2020). Additional simulations were investigated to evaluate the effects of atypical BSE given the four scenarios considered in this study with modified Armington import demand elasticities to reflect negative bias against Brazilian beef and cattle imports. In the original scenarios, Brazilian cattle and beef exports to China, Egypt, and Saudi Arabia were exogenously decreased, and consequently, Brazilian products became relatively cheaper in other import markets. The additional simulations impose a 75% reduction in the Armington import demand elasticities for Brazilian cattle and beef, which means that importers are less willing to substitute for Brazilian products when relative prices change.

Table 6 describes the results for key variables for Scenarios I, II, III, and IV with import bias against Brazilian cattle and beef. The additional simulations show larger negative impacts on Brazilian beef exports and smaller declines in domestic beef production and prices in Brazil relative to the original scenarios with higher substitutability for imports from Brazil. For Scenarios I through IV, Brazilian beef output decreases between -0.36% and -2.2%, while the decrease was between -0.67% and -3.48% for the original simulations. On the other hand, the decrease in Brazilian beef prices ranges from -0.01% and -0.18% across scenarios, which is lower than the range from the original simulations (from -0.07% to -0.42%). The welfare loss for Brazil is larger in all four scenarios, from -$45.6 to -$274 million in the new simulations, while in the original simulations, this range was from -$28.5 million to -$147 million. At the same time, global aggregated welfare losses worsen by 20 times more on average, ranging from -$2.5 billion to -$4.2 billion across the four atypical BSE scenarios in the new simulations with negative bias against imports from Brazil, compared to the range from -$59 million to -$218 in the original simulations. The increase in aggregate welfare losses is primarily driven by deteriorated terms-of-trade and allocative inefficiencies worldwide. Heightened bias against Brazilian products across importers jeopardizes Brazil and adversely impacts other countries and regions, particularly China, Saudi Arabia, and the EU. Additionally, Australia, New Zealand, India, and Uruguay still experience increases in economic welfare with a simulated atypical BSE outbreak in Brazil for scenarios across varied assumptions for import demand elasticities.

Table 6. Key Variables for Scenarios I, II, III, and IV with Negative Importer Bias Against Brazilian Cattle and Beef

	Scenario I		Scenario II		Scenario I		Scenario II	
Variable	**Import Bias Against Brazil**	**Difference from Original Results**	**Import Bias Against Brazil**	**Difference from Original Results**	**Import Bias Against Brazil**	**Difference from Original Results**	**Import Bias Against Brazil**	**Difference from Original Results**
Change in Brazilian beef output	-0.89%	0.73 p.p.	-0.36%	0.31 p.p.	-1.39%	0.63 p.p.	-2.20%	1.28 p.p.
Change in Brazilian producer prices	-0.05%	0.13 p.p.	-0.01%	0.06 p.p.	-0.12%	0.14 p.p.	-0.18%	0.24 p.p.
Change in Brazilian beef exports	-6.00%	-0.31 p.p.	-2.44%	-0.10 p.p.	-5.91%	-0.62 p.p.	-11.25%	-0.98 p.p.
Change in Brazil's welfare ($ million)	-$111.74	-$42.84	-$45.55	-$17.05	-$172.38	-$87.38	-$274.27	-$127.27

Note: p.p. = percentage points. Scenario I considers bans on Brazilian imports into China for 3 months, Egypt for 1 month, and Saudi Arabia for 1 month. Scenario II assumes bans on Brazilian imports into all the countries for 1 month. Scenario III assumes the same import bans from Scenario I with an additional decrease in domestic demand for beef in Brazil of 0.42%. Scenario IV represents the worst-case scenario, with bans on Brazilian imports into China for 6 months, Egypt for 1 month, and Saudi Arabia for 1 month, in addition to a 0.42% decrease in Brazilian domestic demand for beef. The Armington import demand elasticities are decreased by 75% for Brazilian-sourced cattle and beef to represent bias against imports from Brazil. This table includes the results for key variables for the same exogenous shocks to simulate the atypical BSE case considered in Scenarios I throughout IV with modified Armington import demand elasticities with the assumption of negative import bias against Brazilian cattle and beef. The columns named "Import Bias Against Brazil" present the results for key variables when Armington import demand elasticities are modified, while the columns named "Difference from Original Results" compares the results from the modified Armington simulations and the original results for Scenarios I, II, III, and IV.
Source: Authors' simulations

The findings of this study can be compared to the results from Menezes et al. (2022), which determined that an FMD outbreak in Brazil could result in domestic welfare losses ranging from US$132 million to $271 million. In contrast, the results from this analysis indicate that potential welfare losses due to an atypical BSE case range between US$28.5 million and US$147 million, depending on the restrictions imposed by the international market. This implies that in the worst-case scenario (Scenario IV), atypical BSE-related welfare losses may be comparable to the losses caused by minor outbreaks of FMD. This comparison is interesting because we would expect more severe policy restrictions in response to FMD because of its highly infectious nature. The findings of this study indicate that the overall impacts of an atypical BSE case in Brazil are relatively minor for Brazil and the countries that temporarily suspended imports of Brazilian cattle and beef. Despite the relatively modest impacts of the scenarios considered, trade policy restrictions could extend beyond what was observed in the aftermath of the 2023 atypical BSE event in Brazil, highlighting the importance of maintaining the surveillance and control program for BSE. Furthermore, the insights provided by this research serve as a foundation for evaluating more severe international trade policy responses in the event of classical BSE detection in Brazil or other beef-producing regions.

Conclusions and Policy Implications

Beef trade is a complicated system of relationships, including shifting patterns in domestic production capacity, processing infrastructure, consumption demand, and macroeconomic factors that affect the market. Since the emergence of BSE in the 1980s and high-profile discoveries in the 1990s, much has changed in the global beef trade, including the expanding roles of China as an important global beef importer and Brazil as an important global beef exporter. Brazil is a substantial beef supplier to China, with more than 60% of Brazilian beef exports destined for the Chinese market. China and several other protein-importing countries impose stringent beef import restrictions when animal health outbreaks occur in export partners. Even though classical BSE has been essentially eradicated globally, atypical BSE cases like those identified in Brazil in 2021 and 2023 cause substantial disruptions in global trade patterns.

Results for the simulated trade bans and domestic consumer response to a BSE event in Brazil show a relatively small effect on domestic beef production and price in Brazil. BSE is not a contagious disease that can spread from animal to animal by direct or indirect contact. BSE-related production losses are generally small, and this work does not simulate disease-related production shocks. Beef market effects are simulated as entirely driven by trade restrictions and consumer responsiveness to the detection of atypical BSE in Brazil. However, risk mitigation procedures and surveillance investments are still needed to prevent the re-emergence of widespread classical BSE, which has historically resulted in more significant trade bans than atypical BSE.

An atypical BSE case does little to disrupt domestic supply chains for a country like Brazil, which is largely self-sufficient in beef production. However, restrictions on export flows present substantial losses, especially for Brazil's total welfare. On the other hand, Brazil's most important competitors in the global beef market, such as Australia, Uruguay, and New Zealand, benefit from trade diversion away from Brazil. History shows that a loss in market share can be difficult to regain, even after the initial disease-related trade ban has been removed (Johnson and Stone, 2011).

One limitation of this study includes uncertainty regarding how countries will respond in the event of BSE detection in Brazil because trade restrictions have varied substantially from one country to another in the past. This is highlighted by simulations that consider scenarios based on historical data about atypical BSE cases in Brazil since the country has never experienced a classical BSE case. In addition, there is a limitation in simulating monthly restrictions on exports and changes in domestic demand using an annual model. An important contribution of future research would be implementing disease-related trade restrictions in a monthly model.

This study shows that the economic consequences of BSE-related trade bans burden the affected country, even though atypical BSE does not change a country's risk status within the WOAH. No past research has examined the impact of BSE on the Brazilian beef industry. Nevertheless, even in a disease outbreak with negligible production losses, trade losses and domestic consumption changes have the potential to cause damage to Brazilian beef producers, consumers, and trade partners. This provides a valuable addition to studies completed for other countries that export large volumes of domestic production, like Australia, and studies about countries that import large volumes of consumption, like the EU and Japan. Import bans associated with animal disease outbreaks may result in supply shortages in the international market and trade diversion away from the affected country and towards its competitors. This, consequently, causes spillover effects of trade restrictions in other exporting and importing countries. Establishing new bilateral trade partnerships is time-consuming, and it can be difficult to regain market share once lost. SPS trade restrictions have evolved in the twenty-first century and will continue evolving based on scientifically driven risk factors. This is particularly true for countries that export or import significant volumes of animal protein, balancing the need to protect consumers and domestic industries against market volatility and price swings caused by uncertain international market supplies.

[First submitted July 2023; accepted for publication March 2023.]

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Appendix

Table A.1 Percentage Changes in Land Use in Brazil

Sectors	Scenario I	Scenario II	Scenario III	Scenario IV
Grains	0.13	0.05	0.16	0.28
Other agricultural products	0.16	0.07	0.20	0.34
Cattle	-1.13	-0.47	-1.41	-2.43
Poultry and other animals	0.15	0.06	0.18	0.32
Beef	-0.56	-0.23	-0.70	-1.21
Other meat	0.32	0.13	0.39	0.68
Dairy products	0.15	0.06	0.19	0.32
Other processed foods	0.21	0.09	0.26	0.45
Other primary products	0.09	0.04	0.11	0.18
Manufacturing	0.24	0.10	0.30	0.51
Services	0.22	0.09	0.28	0.48

Source: Authors' simulations

Table A.2 Percentage Changes in Beef Bilateral Trade: Scenario I

Country	Argentina	Australia	Brazil	Canada	China, Hong Kong	Chile	Egypt	Europe (28)	India	Japan	Korea	Mexico	New Zealand	Paraguay	Russia	Saudi Arabia	Uruguay	USA	Rest of the World
Argentina	-0.05	0.15	-1.03	-0.01	6.54	-0.47	12.77	-0.12	-0.05	0.04	0.03	-0.06	0.31	-0.84	-0.53	0.04	-0.25	0.02	-0.23
Australia	-0.27	-0.06	-1.24	-0.22	6.32	-0.69	12.55	-0.34	-0.27	-0.18	-0.19	-0.27	0.10	-1.07	-0.75	-0.18	-0.48	-0.20	-0.45
Brazil	1.41	1.63	0.45	1.46	-25.00	0.96	-8.33	1.31	1.43	1.49	1.51	1.42	1.79	0.60	0.90	-8.33	1.19	1.49	1.20
Canada	0.03	0.23	-0.95	0.08	6.62	-0.39	12.85	-0.04	0.03	0.12	0.11	0.03	0.39	-0.76	-0.45	0.12	-0.17	0.10	-0.15
China, Hong Kong	-0.11	0.09	-1.09	-0.07	6.47	-0.54	12.70	-0.19	-0.12	-0.03	-0.04	-0.12	0.25	-0.91	-0.60	-0.03	-0.32	-0.04	-0.29
Chile	0.11	0.31	-0.87	0.15	6.69	-0.32	12.92	0.03	0.10	0.19	0.18	0.10	0.47	-0.69	-0.38	0.19	-0.10	0.17	-0.08
Egypt	0.03	0.23	-0.95	0.07	6.61	-0.40	12.84	-0.05	0.02	0.11	0.10	0.02	0.39	-0.77	-0.46	0.11	-0.18	0.10	-0.15
Europe (28)	0.06	0.26	-0.92	0.10	6.64	-0.37	12.87	-0.02	0.06	0.14	0.14	0.05	0.42	-0.74	-0.43	0.15	-0.15	0.13	-0.12
India	0.04	0.24	-0.94	0.08	6.62	-0.39	12.85	-0.04	0.03	0.12	0.11	0.03	0.40	-0.76	-0.45	0.12	-0.17	0.10	-0.15
Japan	0.05	0.25	-0.93	0.09	6.63	-0.38	12.86	-0.03	0.04	0.13	0.12	0.04	0.41	-0.75	-0.44	0.13	-0.16	0.12	-0.14
Korea	0.06	0.26	-0.92	0.11	6.65	-0.36	12.88	-0.01	0.06	0.15	0.14	0.06	0.42	-0.73	-0.42	0.15	-0.14	0.13	-0.12
Mexico	0.05	0.25	-0.93	0.09	6.63	-0.38	12.86	-0.03	0.04	0.13	0.12	0.04	0.41	-0.75	-0.44	0.13	-0.16	0.11	-0.14
New Zealand	-0.28	-0.07	-1.25	-0.22	6.32	-0.70	12.54	-0.34	-0.27	-0.18	-0.19	-0.27	0.08	-1.07	-0.75	-0.18	-0.48	-0.20	-0.45
Paraguay	0.16	0.36	-0.82	0.21	6.74	-0.27	12.98	0.09	0.16	0.25	0.24	0.16	0.52	-0.63	-0.33	0.25	-0.04	0.23	-0.02
Russia	0.09	0.29	-0.89	0.14	6.68	-0.33	12.91	0.02	0.09	0.18	0.17	0.09	0.45	-0.70	-0.39	0.18	-0.11	0.16	-0.09
Saudi Arabia	0.06	0.26	-0.92	0.10	6.64	-0.37	12.87	-0.02	0.05	0.14	0.13	0.05	0.42	-0.74	-0.43	0.14	-0.15	0.13	-0.13
Uruguay	-0.61	-0.42	-1.58	-0.55	5.99	-1.02	12.21	-0.67	-0.62	-0.53	-0.52	-0.61	-0.26	-1.39	-1.08	-0.53	-0.82	-0.53	-0.78
USA	0.04	0.24	-0.94	0.08	6.62	-0.39	12.85	-0.04	0.03	0.12	0.12	0.03	0.40	-0.76	-0.45	0.12	-0.17	0.11	-0.14
Rest of the World	0.07	0.27	-0.91	0.11	6.65	-0.36	12.88	-0.01	0.06	0.15	0.14	0.06	0.43	-0.73	-0.42	0.15	-0.14	0.13	-0.12

Source: Authors' simulations
Note: Numbers in red correspond to exogenous shocks applied to the model.

Table A.3 Percentage Changes in Beef Bilateral Trade: Scenario II

Country	Argentina	Australia	Brazil	Canada	China, Hong Kong	Chile	Egypt	Europe (28)	India	Japan	Korea	Mexico	New Zealand	Paraguay	Russia	Saudi Arabia	Uruguay	USA	Rest of the World
Argentina	-0.02	0.06	-0.42	0.00	2.19	-0.19	12.66	-0.04	0.01	0.02	0.02	-0.01	0.13	-0.34	-0.21	0.04	-0.12	0.01	-0.08
Australia	-0.11	-0.02	-0.51	-0.08	2.10	-0.27	12.58	-0.13	-0.08	-0.07	-0.07	-0.10	0.04	-0.43	-0.30	-0.04	-0.21	-0.07	-0.17
Brazil	0.57	0.66	0.18	0.60	-8.33	0.39	-8.33	0.54	0.61	0.61	0.62	0.59	0.73	0.24	0.37	-8.33	0.46	0.61	0.50
Canada	0.01	0.09	-0.40	0.03	2.21	-0.16	12.69	-0.02	0.03	0.04	0.04	0.01	0.15	-0.31	-0.19	0.06	-0.10	0.04	-0.06
China, Hong Kong	-0.04	0.04	-0.45	-0.02	2.16	-0.21	12.64	-0.07	-0.02	0.00	-0.01	-0.04	0.10	-0.36	-0.24	0.02	-0.15	-0.01	-0.11
Chile	0.04	0.12	-0.37	0.06	2.24	-0.13	12.71	0.01	0.06	0.07	0.07	0.04	0.18	-0.29	-0.16	0.09	-0.07	0.07	-0.03
Egypt	-0.01	0.07	-0.42	0.01	2.19	-0.19	12.66	-0.04	0.01	0.02	0.02	-0.01	0.13	-0.34	-0.21	0.04	-0.12	0.02	-0.08
Europe (28)	0.02	0.10	-0.39	0.04	2.22	-0.16	12.69	-0.01	0.04	0.05	0.05	0.02	0.16	-0.31	-0.18	0.07	-0.09	0.05	-0.05
India	-0.01	0.07	-0.41	0.01	2.20	-0.18	12.67	-0.03	0.02	0.03	0.03	0.00	0.14	-0.33	-0.20	0.05	-0.11	0.02	-0.07
Japan	0.01	0.09	-0.39	0.03	2.22	-0.16	12.69	-0.01	0.04	0.05	0.05	0.01	0.15	-0.31	-0.18	0.07	-0.09	0.04	-0.06
Korea	0.02	0.10	-0.39	0.04	2.22	-0.15	12.70	-0.01	0.04	0.06	0.05	0.02	0.16	-0.30	-0.17	0.08	-0.09	0.05	-0.05
Mexico	0.01	0.09	-0.39	0.03	2.22	-0.16	12.69	-0.01	0.04	0.05	0.04	0.01	0.15	-0.31	-0.18	0.07	-0.09	0.04	-0.06
New Zealand	-0.11	-0.03	-0.52	-0.09	2.10	-0.29	12.57	-0.14	-0.09	-0.07	-0.08	-0.11	0.03	-0.44	-0.30	-0.05	-0.22	-0.08	-0.18
Paraguay	0.06	0.14	-0.34	0.08	2.27	-0.11	12.74	0.04	0.09	0.10	0.10	0.07	0.21	-0.26	-0.13	0.12	-0.04	0.09	-0.01
Russia	0.03	0.11	-0.37	0.05	2.24	-0.14	12.71	0.01	0.06	0.07	0.06	0.03	0.17	-0.29	-0.16	0.09	-0.08	0.06	-0.04
Saudi Arabia	0.01	0.10	-0.39	0.04	2.22	-0.16	12.69	-0.01	0.04	0.05	0.05	0.02	0.16	-0.31	-0.18	0.07	-0.09	0.05	-0.05
Uruguay	-0.20	-0.12	-0.60	-0.18	2.01	-0.37	12.48	-0.22	-0.18	-0.17	-0.16	-0.19	-0.06	-0.52	-0.39	-0.15	-0.31	-0.17	-0.26
USA	0.01	0.09	-0.40	0.03	2.21	-0.16	12.69	-0.02	0.03	0.04	0.04	0.01	0.15	-0.31	-0.19	0.06	-0.10	0.04	-0.06
Rest of the World	0.02	0.10	-0.39	0.04	2.22	-0.15	12.70	-0.01	0.04	0.06	0.05	0.02	0.16	-0.30	-0.17	0.08	-0.09	0.05	-0.05

Source: Authors' simulations
Note: Numbers in red correspond to exogenous shocks applied to the model.

Table A.4 Percentage Changes in Beef Bilateral Trade: Scenario III

Country	Argentina	Australia	Brazil	Canada	China, Hong Kong	Chile	Egypt	Europe (28)	India	Japan	Korea	Mexico	New Zealand	Paraguay	Russia	Saudi Arabia	Uruguay	USA	Rest of the World
Argentina	-0.08	-0.15	70.87	-0.29	6.31	-0.52	12.57	-0.44	-0.38	-0.26	-0.28	-0.38	0.01	-0.22	-0.85	-0.26	-0.27	-0.28	-0.59
Australia	-0.02	-0.08	70.93	-0.22	6.37	-0.46	12.63	-0.38	-0.31	-0.21	-0.21	-0.31	0.08	-0.17	-0.79	-0.20	-0.22	-0.21	-0.53
Brazil	2.31	2.26	73.27	2.10	-25.00	1.82	-8.33	1.90	2.03	2.10	2.13	2.03	2.42	2.12	1.47	-8.33	2.07	2.11	1.74
Canada	0.33	0.26	71.26	0.12	6.71	-0.13	12.97	-0.04	0.03	0.13	0.12	0.03	0.42	0.18	-0.46	0.13	0.13	0.12	-0.19
China, Hong Kong	0.18	0.10	71.11	-0.03	6.56	-0.28	12.81	-0.19	-0.12	-0.02	-0.03	-0.12	0.26	0.02	-0.61	-0.02	-0.02	-0.03	-0.34
Chile	0.35	0.28	71.29	0.14	6.73	-0.10	12.99	-0.02	0.05	0.15	0.15	0.05	0.44	0.20	-0.44	0.15	0.15	0.15	-0.17
Egypt	0.32	0.25	71.26	0.11	6.70	-0.13	12.96	-0.05	0.02	0.13	0.12	0.02	0.41	0.17	-0.47	0.13	0.12	0.12	-0.20
Europe (28)	0.36	0.28	71.29	0.14	6.73	-0.10	12.99	-0.02	0.06	0.16	0.15	0.06	0.44	0.20	-0.43	0.16	0.15	0.15	-0.17
India	0.33	0.26	71.27	0.12	6.71	-0.12	12.97	-0.04	0.04	0.14	0.13	0.03	0.42	0.18	-0.45	0.14	0.13	0.13	-0.19
Japan	0.34	0.27	71.28	0.13	6.72	-0.11	12.98	-0.03	0.05	0.15	0.14	0.04	0.43	0.19	-0.44	0.15	0.14	0.14	-0.18
Korea	0.36	0.29	71.30	0.15	6.74	-0.09	13.00	-0.01	0.06	0.16	0.16	0.06	0.45	0.21	-0.43	0.16	0.16	0.16	-0.16
Mexico	0.34	0.27	71.28	0.13	6.72	-0.11	12.98	-0.03	0.04	0.14	0.14	0.04	0.43	0.19	-0.45	0.14	0.14	0.14	-0.18
New Zealand	0.01	-0.06	70.95	-0.19	6.40	-0.44	12.65	-0.35	-0.28	-0.18	-0.18	-0.28	0.10	-0.14	-0.77	-0.18	-0.18	-0.18	-0.50
Paraguay	-1.44	-1.55	69.51	-1.69	4.94	-1.88	11.16	-1.82	-1.77	-1.67	-1.68	-1.78	-1.39	-1.63	-2.20	-1.67	-1.68	-1.68	-1.94
Russia	0.39	0.32	71.33	0.18	6.77	-0.07	13.03	0.02	0.09	0.19	0.19	0.09	0.48	0.24	-0.40	0.19	0.19	0.18	-0.13
Saudi Arabia	0.35	0.28	71.29	0.14	6.73	-0.10	12.99	-0.02	0.06	0.16	0.15	0.05	0.44	0.20	-0.43	0.16	0.15	0.15	-0.17
Uruguay	-1.32	-1.42	69.65	-1.50	5.09	-1.75	11.32	-1.66	-1.64	-1.54	-1.50	-1.60	-1.26	-1.44	-2.08	-1.54	-1.54	-1.49	-1.81
USA	0.33	0.26	71.27	0.12	6.71	-0.12	12.97	-0.04	0.04	0.14	0.13	0.03	0.42	0.18	-0.46	0.14	0.13	0.13	-0.19
Rest of the World	0.37	0.29	71.30	0.15	6.74	-0.09	13.00	-0.01	0.07	0.17	0.16	0.07	0.45	0.21	-0.42	0.17	0.16	0.16	-0.16

Source: Authors' simulations

Note: Numbers in red correspond to exogenous shocks applied to the model.

Table A.5 Percentage Changes in Beef Bilateral Trade: Scenario IV

Country	Argentina	Australia	Brazil	Canada	China, Hong Kong	Chile	Egypt	Europe (28)	India	Japan	Korea	Mexico	New Zealand	Paraguay	Russia	Saudi Arabia	Uruguay	USA	Rest of the World
Argentina	-0,13	-0,05	77,28	-0,33	12,81	-0,96	12,70	-0,59	-0,50	-0,27	-0,30	-0,48	0,25	-0,92	-1,37	-0,30	-0,47	-0,31	-0,84
Australia	-0,24	-0,14	77,16	-0,43	12,70	-1,07	12,60	-0,70	-0,60	-0,38	-0,39	-0,57	0,16	-1,04	-1,48	-0,41	-0,60	-0,40	-0,95
Brazil	3,66	3,78	81,08	3,46	-50,00	2,76	-8,33	3,12	3,32	3,48	3,53	3,35	4,08	2,81	2,33	-8,33	3,25	3,49	2,86
Canada	0,40	0,48	77,79	0,20	13,32	-0,44	13,22	-0,08	0,03	0,25	0,23	0,05	0,78	-0,40	-0,86	0,22	0,05	0,22	-0,33
China, Hong Kong	0,10	0,18	77,49	-0,10	13,03	-0,74	12,92	-0,37	-0,27	-0,05	-0,07	-0,25	0,48	-0,70	-1,16	-0,09	-0,25	-0,08	-0,63
Chile	0,48	0,56	77,87	0,28	13,40	-0,36	13,30	0,00	0,11	0,33	0,31	0,13	0,87	-0,32	-0,78	0,30	0,13	0,30	-0,25
Egypt	0,42	0,50	77,81	0,21	13,34	-0,42	13,24	-0,06	0,05	0,26	0,25	0,07	0,80	-0,38	-0,84	0,23	0,07	0,24	-0,31
Europe (28)	0,45	0,53	77,84	0,25	13,37	-0,39	13,27	-0,03	0,08	0,29	0,28	0,10	0,84	-0,35	-0,81	0,27	0,10	0,27	-0,28
India	0,43	0,51	77,82	0,23	13,35	-0,41	13,25	-0,05	0,06	0,27	0,26	0,08	0,82	-0,37	-0,83	0,25	0,08	0,25	-0,30
Japan	0,43	0,51	77,82	0,23	13,35	-0,41	13,25	-0,05	0,06	0,27	0,26	0,08	0,81	-0,37	-0,83	0,24	0,08	0,25	-0,30
Korea	0,46	0,54	77,85	0,26	13,38	-0,38	13,28	-0,02	0,09	0,30	0,29	0,11	0,84	-0,34	-0,80	0,28	0,11	0,28	-0,27
Mexico	0,42	0,50	77,81	0,22	13,35	-0,42	13,25	-0,05	0,05	0,27	0,25	0,08	0,81	-0,38	-0,83	0,24	0,07	0,25	-0,30
New Zealand	-0,21	-0,11	77,20	-0,39	12,74	-1,05	12,63	-0,66	-0,56	-0,34	-0,36	-0,53	0,18	-1,00	-1,44	-0,37	-0,54	-0,36	-0,91
Paraguay	-1,46	-1,41	75,95	-1,69	11,48	-2,28	11,33	-1,94	-1,86	-1,65	-1,66	-1,84	-1,11	-2,29	-2,69	-1,67	-1,84	-1,67	-2,16
Russia	0,52	0,60	77,90	0,31	13,44	-0,33	13,34	0,04	0,14	0,36	0,35	0,17	0,90	-0,28	-0,74	0,33	0,16	0,34	-0,21
Saudi Arabia	0,45	0,53	77,84	0,25	13,37	-0,39	13,27	-0,03	0,08	0,29	0,28	0,10	0,83	-0,35	-0,81	0,26	0,10	0,27	-0,28
Uruguay	-1,99	-1,96	75,43	-2,16	10,97	-2,81	10,82	-2,44	-2,41	-2,19	-2,13	-2,32	-1,65	-2,75	-3,21	-2,22	-2,39	-2,14	-2,69
USA	0,41	0,49	77,80	0,21	13,33	-0,43	13,23	-0,07	0,04	0,26	0,24	0,06	0,80	-0,39	-0,85	0,23	0,06	0,23	-0,32
Rest of the World	0,47	0,55	77,86	0,26	13,39	-0,37	13,29	-0,01	0,10	0,31	0,30	0,12	0,85	-0,33	-0,79	0,28	0,12	0,29	-0,26

Source: Authors' simulations
Note: Numbers in red correspond to exogenous shocks applied to the model