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From meat to plant-based products? The enduring impact of BSE on beef consumption

Jader Velásquez[a] and Shon Ferguson[b]

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[a] Department of Economics, University of Antioquia, Box 1226, calle 67 No. 53 – 108, Medellín, Colombia.
[b] Department of Economics, Swedish University of Agricultural Sciences (SLU), Box 7013, 750 07 Uppsala, Sweden.

Sveriges lantbruksuniversitet, Institutionen för ekonomi
Swedish University of Agricultural Sciences,
Department of Economics, Uppsala
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Corresponding author:
jader.velasquez@udea.edu.co

From meat to plant-based products? The enduring impact of BSE on beef consumption

Jader Velásquez* and Shon Ferguson†

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Abstract

This study redefines the impact of the BSE outbreak on EU dietary patterns, revealing a lasting shift toward plant-based consumption. Utilizing advanced difference-in-differences techniques on 1980-2020 data, we demonstrate that while beef consumption exhibited a transient U-shaped recovery relative to other meats, it declined sharply compared to plant-based products, with average reductions of 79%, 29%, and 28% for pulses, cereals, and vegetable oils, respectively. This highlights a structural dietary change, overlooked by previous analyses focused on meat substitution. Results are robust to sensitivity tests and support plant-based consumption policies that promote health and sustainability in response to meat safety scares.

Highlights:

- BSE led to a sharper decline in beef consumption relative to plant-based foods than to other meats.
- Post-BSE, beef consumption did not revert to its prior levels relative to plant-based food groups
- BSE had lasting effects only in early-affected countries, which currently exhibit the highest per capita plant-based consumption.

Keywords: Food Safety, Meat reduction, Event Study, Difference-in-differences

JEL Classification: Q11, Q18, C14

* Department of Economics, University of Antioquia, Box 1226, calle 67 No. 53 – 108, Medellín, Colombia e-mail: jader.velasquez@udea.edu.co

† Department of Economics, Swedish University of Agricultural Sciences (SLU), Box 7013, 750 07, Uppsala, Sweden, e-mail: shon.ferguson@slu.se/

Introduction

Shifting toward plant-based diets lower in red meats is a priority on the global policy agenda to tackle both environmental and health goals (Semba, 2020; Chand, 2020). The transition to a more plant-based diet with less red and processed meat is also at the heart of the European Union's food systems strategy (European Commission [EC], 2020). However, there is little understanding of how shocks to red meat demand have impacted its long-term consumption relative to plant-based products (Kwasny, Dobernig & Riefler, 2022). Understanding this behavior through aggregated observed data is crucial for designing effective interventions to promote dietary transitions.

This study aims to measure the impact and persistence of the Bovine Spongiform Encephalopathy (BSE – a.k.a. "Mad Cow Disease") outbreak on consumption patterns towards plant-based products in the European Union (EU). We use 20 aggregated categories of domestic consumption in 19 EU member states, including the UK, spanning the period from 1980 to 2020. We employ an event study methodology incorporating the latest advancements in difference-in-differences (DID) techniques, both to compute a robust DID estimator for the group-time average treatment effect (ATT) and to conduct a thorough sensitivity analysis.

As the BSE outbreak provides a natural experiment to examine consumption patterns from various perspectives, including substitution effects (e.g. Burton and Young, 1996, 1999; Mangen and Burrell, 2001; Mazzocchi and Lobb, 2005), consumer expectations (Zhen and Wohlgenant, 2006), persistence and habit formation (Adda, 2007), and media influence (e.g. Mazzocchi et al., 2004; Rieger et al., 2016; Lee et al., 2023), the impact of BSE on beef consumption has been extensively studied. Regarding the measurement of substitution effects, studies suggest a temporary preference for pork and chicken before beef consumption returns partially to pre-outbreak levels.

However, such substitution effects overlook two key points. First, a broader timeframe beyond the EU's beef import bans and media exposure is needed. As with other outbreaks (e.g., COVID-19), there was a surge of literature in the early years following or even during the outbreak, making it difficult to assess the persistence of estimated structural changes. Second, chicken and pork are close substitutes for beef, so the BSE outbreak likely affected their consumption too, making them less suitable for isolating red meat effects. In contrast, plant-based products form a distinct category without this issue, making them a more appropriate comparison group.

Our results suggest that the BSE outbreak in the EU led to a structural decrease in beef consumption relative to plant-based products. This effect was less pronounced when compared to the consumption of other meats (chicken, pork, and fish). Furthermore, beef consumption never fully recovered its pre-outbreak relationship with plant-based products, unlike its recovery relative to other meats.

Aggregate estimators revealed an average decline in beef consumption of 15% and 7% compared to pork and poultry, respectively. When compared to pulses, cereals, and vegetable oils, the average reductions in beef consumption were 79%, 29%, and 28% respectively. The estimators perform adequately during the pre-treatment period, exhibiting no significant differences between the treatment group and the control group. They also demonstrated post-treatment results that align with previous research, suggesting a partial substitution effect for chicken and pork.

We contribute to the literature on meat safety scares by examining the long-run effects on plant-based food consumption and applying recent DID techniques to study BSE’s dynamic impact. This addresses two gaps: first, most studies don’t assess consumption beyond five years, limiting insights on long-term shifts, especially in the EU context. Second, prior research focuses mainly on meat preferences, analyzing BSE’s effect on beef within meat demand models that emphasize substitution with pork and chicken. This study represents the first application of event study methods to examine the impact of BSE on aggregate consumption.

Due to the various bans on beef trade, BSE has attracted policy evaluation research to measure impacts on trade (Peterson E., Grant J. H. & Sydow, 2017; Taha & Hahn, 2014; Webb, Gibson & Strutt, 2018; Zongo & Larue, 2019; Soon & Thompson, 2020), changes in competitiveness (Rude, Carlberg & Pellow, 2007; Chen et al. 2020), agribusiness (Henson & Mazzocchi, 2002), prices and future markets (Houser et al., 2019; Houser & Karali, 2020; Schlenker & Villas-Boas, 2009; Jin et al., 2008), general equilibrium and sectoral adjustments (Hubbard & Philippidis, 2001; Devadoss et al., 2006; Wigle et al., 2007; de Menezes et al., 2024), price transmission (Sanjuan & Dawson, 2003; Lloyd et al., 2006; Hassouneh et al., 2010) or policy instrument design (Le Roy, Klein, & Arbenser 2007). Our research, however, is distinct from these areas.

The remainder of this paper is structured as follows. Section 2 reviews BSE and summarizes its consumption impact literature. Section 3 explains the empirical strategy, including the panel regression, event study estimator, and sensitivity analysis. Section 4 describes the data. Section 5 presents results. Conclusions and discussion follow in Sections 6 and 7, respectively.

BSE and the impact on consumption patterns

The BSE outbreak in the EU

BSE is a neurodegenerative disease in cattle first identified in the UK during the 1980s. The country was disproportionately affected by BSE compared to other European countries (Figure 1). At its peak in 1992, the UK reported over 37,000 cases, while Ireland had only 18. By 2001, BSE had spread to most EU member states (see Appendix 1). Since BSE is highly transmissible through contaminated feed, more than 4.4 million cattle were slaughtered in Europe. The EU implemented stringent import bans on UK beef between 1994 and 1996, with the latter ban remaining in effect for 10 years. The disease's impact on human health became apparent with the emergence of the lethal Variant Creutzfeldt–Jakob disease (vCJD). As of 2018, a total of 231 cases of vCJD had been reported globally.

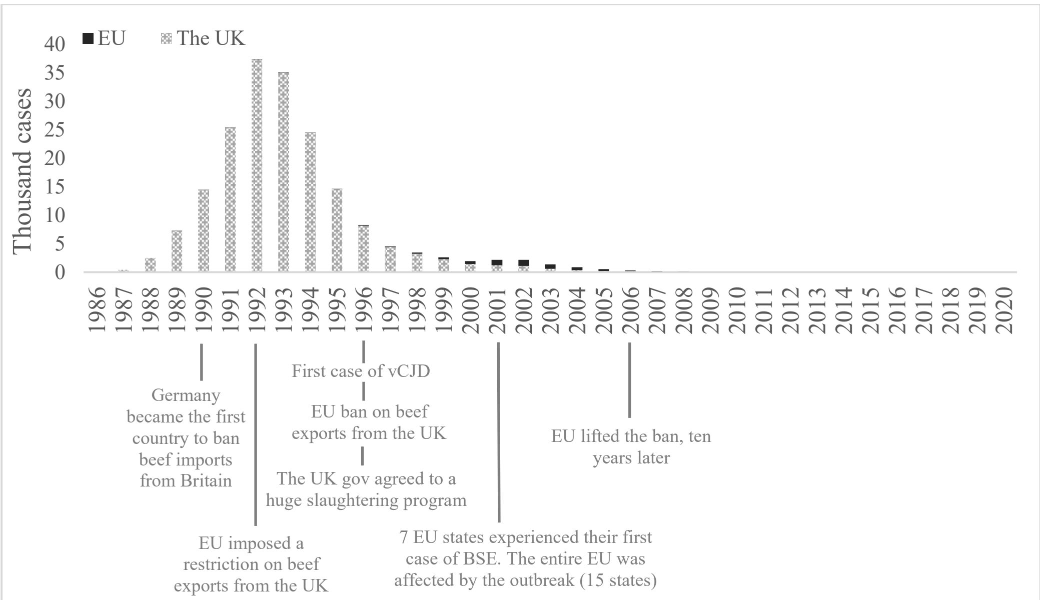

Figure 1. Timeline of the BSE reported cases and key events in the UK and EU

Data source: EFSA.

Unlike global trends, the BSE outbreak appears to have shifted EU food consumption patterns. Figure 2 illustrates the long-term per capita growth in both animal- and plant-based food consumption. Globally, meat consumption experienced more rapid growth, particularly after the 1990s.

In contrast, in the United Kingdom, the growth rate of plant-based products is not only higher, but the growth of animal-based products is negative. This gap widens in the mid-1980s. Germany showed a similar shift in the mid-1990s[1], a pattern also observed in Belgium and Ireland during the late 1980s. These shifts in consumption roughly coincide with each respective country's BSE outbreak, suggesting that plant-based products warrant further investigation as a relevant comparison group for analyzing post-outbreak beef consumption.

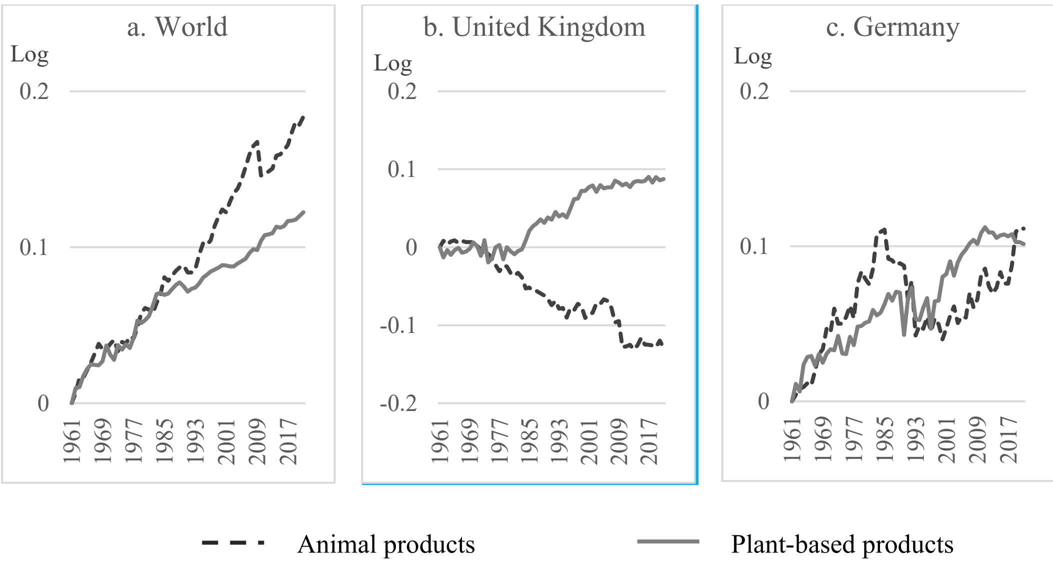

Figure 2. Long-run (60 years) growth rate of Food supply (kcal/capita/day) by aggregated food sources. Data source: FAOstat.

The impact of BSE on consumption behavior

Consumers generally exhibit weakly separable preferences for meat (Schösler et al., 2012; Graça and Calheiros, 2015; Apostolidis, 2016), suggesting beef, pork, and chicken are close

[1] The data for Germany includes both East and West Germany prior to reunification in 1990.

substitutes (Andersen et al., 2007; Lusk et al., 2016). Accordingly, BSE-related research has focused on substitution among meats, the persistence of consumption changes, and whether shifts were permanent or temporary.

UK studies (Burton and Young, 1996, 1999; Tilson et al., 1992; McDonald and Roberts, 1998) found a moderate but structural decline in beef consumption, offset by increased pork and chicken intake. Philippidis & Hubbard (2005) reported negligible long-term effects.

France saw a sharper reaction: beef demand dropped 26% within weeks, with a U-shaped recovery showing habit persistence over 76 weeks (Adda, 2007). The effect lasted at least three years (Allais & Nichele, 2007), though a second 2000 outbreak lasted five months. Denmark's 1996 incident had no significant effect on pork or chicken markets, nor did the UK outbreak affect Danish consumers (Andersen et al., 2007). In Italy, the 1996 impact was brief (Mazzocchi and Lobb, 2005), but the 2000 outbreak raised chicken demand for 14 months. In the Netherlands, beef demand recovered within a month after a short shift to chicken and pork (Mangen and Burrell, 2001).

Outside Europe, the 2003 U.S. outbreak had a minimal impact. Kuchler and Tegene (2006) found effects lasted under two weeks, aligned with Piggott & Marsh (2004) and Pritchett et al. (2007), who observed a quick pork substitution. Taylor et al. (2016) estimated recovery within two years. Canada showed similar patterns (Peng et al., 2004; Maynard, 2008; Ding et al., 2011). In contrast, Japan's 2001 outbreak triggered persistent reductions in beef demand (Ning et al., 2021), with pork and chicken replacing specific cuts (Jin & Koo, 2003; Saghaian & Reed, 2007; Dinku and Matsuda, 2018).

Timing was critical. Countries hit in the early 1990s showed slower recovery and more structural shifts (1.5–5 years). In contrast, late 1990s episodes resolved within a year, and post-2000 effects typically lasted only weeks. While U-shaped recoveries were common, persistence, not magnitude, was the key difference.

Overall, food safety-related consumption responses seem more linked to whether consumer expectations are seen as permanent or transitory, rather than to habit persistence (Zhen and Wohlgenant, 2006). Media coverage plays a key role in shaping those expectations (Verbeke et al., 1999; Lloyd et al., 2001; Mazzocchi et al., 2004; Verbeke & Ward, 2005; Yang & Goddard, 2011; Rieger et al., 2016; Myae & Goddard, 2020; Lee et al., 2023). Longer-lasting declines occurred during early outbreaks or second waves, when uncertainty and fear were higher (Mangen and Burrell, 2001; Pritchett, 2007; Ding et al., 2011).

Empirical methodology

Panel regression methodology

We begin our analysis by estimating a panel regression model. An Ordinary Least Squares (OLS) regression is performed on the natural logarithm of the dependent variable, allowing us to interpret coefficients as percentage changes. Individual and time fixed effects are included. The baseline regression is specified as follow:

$$ln\left(\frac{beef}{product_m}\right)_{i,t} = \alpha_0 + \beta \cdot BSE_{i,t} + \alpha_1 \cdot X_{i,t} + v_i + w_t + \varepsilon_{i,t} \tag{1}$$

where *i* denotes countries and *t* denotes years. The dependent variable is the natural logarithm of the ratio between per capita beef consumption and per capita consumption of other groups of foods (m), which can be animal-based or plant-based. BSE is the dummy variable $BSEdummy_{i.t}$. The vector of controls, $\mathrm{X}_{i,t}$, includes the gross domestic product (GDP), GDP per capita, consumer price index (CPI) and two dummy variables: *EUdummy* that takes a value of 1 if country c was a member of the EU in year t and 0 otherwise; and *FMDdummy,* representing Foot-and-Mouth Disease (FMD) outbreaks, coded as 1 for years in which country i reported any FMD serotype and 0 otherwise. The terms v_c and w_t represent country and year fixed effects, respectively.

We focus on coefficient β. Prior studies predict a significant substitution effect from beef to other meats, especially pork and chicken ($\beta > 0$), due to rigid preferences and low meat budget elasticity in households in developed countries. Therefore, significant β values for plant-based products are less expected.

In terms of duration, once the outbreak is contained, it is expected beef consumption will return, partially or fully, to its original trend, as suggested by prior studies (see Section 2). This potential recovery warrants further investigation through event study analysis.

Event study

In recent analyses of event studies with dynamic effects, practitioners have widely adopted the approaches of Callaway and Sant'Anna (2021) and Chaisemartin and D'Haultfoeuille (2024) to address the pitfalls of traditional two-way fixed effects (TWFE) event-study regressions (Borusyak, Jaravel & Spiess, 2021). We begin by presenting our preferred DID methodology, following Callaway and Sant'Anna, and then explain the rationale for choosing it over the approach proposed by Chaisemartin and D'Haultfoeuille.

DID methodology framework

Callaway and Sant'Anna (2021, henceforth CS) introduced a causal parameter *group-time average treatment effect*, $ATT(g,t)$, which captures the average treatment effect for the countries in the cohort g at time t. The causal parameter has the same content as the 2x2 DID estimand, but does not limit the heterogeneity among different cohorts or over time.

The identification strategy depends on whether the sample provides a 'never-treated' or a 'not-yet-treated' comparison group. In this study, only five countries: Cyprus, Bulgaria, Hungary, Malta, and Romania, never reported BSE outbreaks, making them a small and unrepresentative 'never-treated' control group. Since most countries experienced outbreaks progressively, we adopt a 'not-yet-treated' approach: countries yet to report an outbreak in year t also act as control group.

Due to the strong effect of per capita income and prices on aggregate consumption, we adopt a nonparametric identification approach that accounts for covariate-specific trends while relaxing the parallel trends assumption. Among the family of nonparametric estimators[2], we selected the doubly robust (DR) DID estimator developed by Sant'Anna and Zhao (2020).

The DR DID estimator takes the $ATT^{ny}(g,t)$ and applies a normalization factor to ensure that the effect of the event is comparable across different time periods and treated groups, accounting for differences in the frequency of event initiation and country characteristics. Using the non-parametric DR estimator, we denote our final estimator as $ATT_{dr}^{ny}(g,t)$.

Consequently, following CS our event study regression equation is:

$$ln\left(\frac{beef}{product_m}\right)_{i,t} = \alpha_i + \lambda_t + \sum_{g}\sum_{e\neq -1} ATT_{dr}^{ny}(g,t)\cdot G_g \cdot 1\{t-g=e\}\cdot BSE_{i,t} + \gamma \cdot X_{i,t} + \epsilon_{i,t} \quad (2)$$

G_g is a binary variable that takes a value of 1 if the country had the first BSE case in period g and 0 otherwise. And e denotes the event-time relative to treatment, i.e., $e = t - g$, capturing the number of years since the country initially experienced the outbreak. Therefore, if condition $t - g = e$ is met, then $1\{t - g = e\} = 1$. Note that negative values of e indicate pre-treatment periods (lags), while positive values indicate post-treatment periods (leads).

We apply Equation (2) to compare beef consumption with other product groups. The model uses the year prior to the outbreak (t-1) as the baseline year. To manage the evolving control group inherent in the 'not-yet-treated' strategy and ensure robust long-term DID comparisons, the analysis was limited to 13 periods before and 14 periods after the baseline. As a result, 27 $ATT_{dr}^{ny}(g,t)$ estimators for each comparison product were calculated and plotted, visualizing the dynamic percentage change in beef consumption.

[2] Under nonparametric identification, the ATT(g, t) can be also estimated using outcome regression (OR), inverse probability weighting (IPW), or doubly robust (DR) methods (Callaway and Sant'Anna, 2021)

Lastly, we gather all *group-time average treatment effects* to be estimated into one aggregated causal parameter, $\theta(e)$ (see CS, 2021, p. 10), for both pre and post treatment effects, $\theta(e)_{pre}$ and $\theta(e)_{post}$ respectively. $\theta(e)$ is our target parameter in the event study results.

Choice of the DID methodology

Among recent DID methods, de Chaisemartin and D'Haultfoeuille (2024, henceforth dCDH) introduced the DID_L estimators, which are robust to heterogeneous treatment effects and allow the use of 'not-yet-treated' units as controls[3]. These estimators suit two designs: (i) Absorbing treatment, where groups remain treated once exposed, aligned with the CS approach; and (ii) Non-absorbing treatment, where groups can enter and exit treatment, allowing for lagged effects.

However, dCDH emphasize that their DID_L and the $\theta(e)$ estimator by CS are not equivalent when initial treatment differs across groups. DID_L compares groups with the same period-one treatment, while CS compares groups regardless of initial status.

A key distinction is that CS estimates incremental effects for each group and period, capturing dynamic effects under constant-period assumptions. In contrast, dCDH assumes parallel trends and rules out dynamic treatment effects.

Given this, the CS framework is better suited for our setting, few treated and untreated groups under a 'not-yet-treated' approach, while dCDH fits larger samples with switchers and non-switchers sharing initial status. Though dCDH estimates may be more robust, they risk downward bias in our context. Therefore, we adopt the CS framework.

[3] Sun and Abraham (2021) provide a similar 'not-yet-treated' approach by using a 'last-treated' units as control group. This approach demands a robust control group at the end of the study period, a condition unmet in the EU BSE context. However, the authors acknowledge that their pointwise confidence interval estimates converge to those of CS 'not-yet-treated' estimations.

Threats to identification

The event study mitigates concerns about omitted variable bias while testing for violations of the conditional mean independence assumption. Similarly, the DR DID estimator (Sant'Anna and Zhao, 2020) accommodates covariate-specific trends and enables valid inference with limited groups.

Nevertheless, in practice, event-study coefficients are often estimated with imprecision (Rambachan and Roth, 2023), raising concerns about when the parallel trends assumption supports causal inference. Following Roth et al. (2024) and Rambachan and Roth (2023), a sensitivity analysis is conducted by imposing restrictions on post-treatment violations of the parallel trends assumption.

In addition, to evaluate the robustness of the results to the DID methodology, we compute the DID_L estimators proposed by dCDH, also widely adopted by researchers in recent DID models. We then compare them with the $\theta(e)$ estimates from CS. A placebo test is also implemented for the dCDH estimates.

Sensitivity analysis of parallel trends assumption

The Milk Quota crisis of the 1980s, the European political instability of the early 1990s, Common Agricultural Policy (CAP) reforms addressing overproduction and environmental concerns from 1990 to 2000, the late 2000s financial crisis, and the Russia's 2010 grain export ban represent significant sector-specific and macroeconomic shocks within the EU. These events likely induced country- and product-specific trends that could have influenced both beef production and consumer preferences, even in the absence of the BSE outbreak, thereby challenging the validity of the parallel trends assumption.

To preserve causal interpretation under potential violations of parallel trends, we apply the robust inference method by Rambachan and Roth (2023). This approach restricts post-treatment deviations to remain proportionally close to pre-treatment trends, bounding them by $\overline{M}$ times the largest pre-treatment violation. For instance, $\overline{M} = 1$ bounds the worst-case post-treatment difference in trends by the equivalent maximum in the pre-trends. $\overline{M}$=2 imposes that violations in post-treatment are no more than twice of the violations from the pre-trends, and so on[4].

Results in section 0 report the uniformly valid confidence sets for different $\overline{M}$ values and discuss the 'breakdown value', the value of $\overline{M}$ from which a null effect is observed.

Robustness to the choice of DID estimator

We compare the three average treatment effect estimators: our preferred choice, the $\theta(e)$ estimator by CS, and the two alternatives introduced by dCDH, the DID_L estimators for absorbing and non-absorbing treatment designs. Importantly, the non-absorbing treatment better reflects BSE's treatment pattern, particularly in countries with multiple outbreaks (Austria, Denmark, France, Germany, and Italy). All designs incorporate the same covariates as CS and use 'not-yet-treated' as control groups to ensure comparability. Following dCDH we also compute a placebo estimator to test the no anticipation hypothesis and parallel trends assumption.

[4] Note that a natural benchmark is $\overline{M} = 1$. $\overline{M} = 1$ assumes that country and product-specific trends affect equal during pre and post treatment periods. The assumption is reinforced by the equal number of pre- and post-treatment periods (13 each). The choice of $\overline{M}$ depends on how strict we are with the vioations of PT in the post-treatment. Nevertherless, $\overline{M} = 1$ serves as a reference point and does not influence the calculation of confidence sets or the breakdown values

Data and descriptive statistics

Sample and years

This study encompasses 19 EU countries, including the UK, over the 1980-2020 period, allowing sufficient pre-treatment years before initial BSE reports. Seven current EU states were excluded due to unavailable economic data before their early 1990s dissolution, while Belgium and Luxembourg were omitted as disaggregated data exist only from 1999. Except for Belgium, excluded countries reported few BSE cases, ensuring valid control and treatment groups (Appendix 1). The included countries are Austria, Bulgaria, Cyprus, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Malta, the Netherlands, Poland, Portugal, Romania, Spain, Sweden, and the UK.

Dependent variable: Food consumption

We used FAOstat data on domestic food demand by item and country, merging the "old methodology" Food Balance Sheets (1961–2013) with the post-2010 database. To ensure consistency, we harmonized categories using the older coding system and incorporated marginal new categories introduced after 2010.

The merged dataset contains 98 food items grouped into 21 categories (Appendix 2), classified using EFSA's FoodEx2 system. For clarity, we used the group classification in the dependent variable: the ratio of per capita beef consumption to that of each food group (Appendix 2, column 3). From the meat group, we separately included pork, poultry, and mutton & goat to assess meat substitution effects.

Four items were excluded: ‘Animal Fats’ and ‘Offals’ (mixed sources with low relevance), ‘Peas’ (affected by U.S. soybean embargo[5]), and ‘Alcoholic Beverages’ (nutritionally irrelevant).

The final set includes 20 comparison pairs: 7 animal-based and 13 plant-based, with a strongly balanced panel across selected groups.

BSE cases

Before 2013, BSE case data by country and year were obtained from the European Commission’s Health and Food Safety department (European Commission, 2015). For subsequent years, data were sourced from EFSA Scientific Reports (2020, 2023), ensuring continuity with the earlier dataset. The presence of BSE cases determined the assignment of the treatment dummy variable.

Measurement of BSE

The timing and severity of BSE outbreaks influence the appropriate treatment variable. For instance, first cases reported post-2000 (e.g., Greece, Sweden, Finland), when better control measures existed, likely had less impact than early 1990s cases (e.g., Portugal, France, Germany). Similarly, the UK's 37,301 cases in 1992 likely had a more substantial effect than isolated reports elsewhere. Moreover, EU-wide prohibition policies were enacted in 1994, 1996 (following the first vCJD case), and 2001.

To evaluate treatment efficacy, we examined beef consumption's relationship with six distinct treatment options. We considered two country-level dummies: (i) *BSEdummy*, a non-absorbing variable (1 for years with reported cases), and (ii) *BSEdummy_abs*, an absorbing

[5] The US imposed a soybean export embargo in 1973 due to exceptional drought conditions. Around 1985, France, the leading pea producer, increased pea cultivation by 1,000-fold to address the protein deficit. Domestic pea consumption soared 20-fold (1980-1994) in France, then fell dramatically, stabilizing at a fraction by 2020. This significantly increases the beef/pea ratio in the EU in the post-BSE outbreak period, which biases the analysis. Pulses group still includes beans, chickpeas, and lentils among others.

variable (1 from the initial case year onward). From an EU-wide perspective, we included two additional dummies: (iii) *BSEdummy_EU92* (1 from 1992 onward for all countries) and (iv) *BSEdummy_EU96* (1 from 1996 onward). We also explored the natural logarithm of reported BSE cases as a continuous treatment measure at both (v) country and (vi) EU levels. Results are in Appendix 3.

Only the EU dummies and the absorbing country-level dummy (*BSEdummy_abs*) show the expected consumption-reducing effect. In contrast, other treatments suggest a counterintuitive increase in beef consumption.

We select the *BSEdummy_abs* variable, which captures country heterogeneity and aligns with the EU-wide response. It also reflects the persistent nature of the BSE risk, as EU restrictions remained even when case numbers fluctuated locally. The non-absorbing dummy is included in sensitivity analyses.

Control variables

Seven control variables were included. Real GDP and GDP per capita data were sourced from FAOstat, and the Consumer Price Index (CPI) from the World Bank, all log-transformed. EU membership was captured with a dummy equal to 1 in membership years and 0 otherwise, assigned based on each country's accession or exit year.

To isolate BSE effects from food safety concerns, we added a dummy for FMD, equal to 1 in years with reported cases. FMD data came from the World Organisation for Animal Health (WOAH), with 12 countries affected during the study period.

Finally, country and year fixed effects were applied to account for time-invariant national characteristics and global shocks, respectively. Population changes were indirectly controlled by using per capita measures.

Descriptive statistics

Table 1 reveals considerable heterogeneity across countries. Regarding meat consumption, A closer inspection of the dataset shows that countries such as Denmark, Sweden, France, Malta, Portugal, and the UK exhibit high per capita beef consumption levels (>20 kg/year), while pork emerges as the most consumed meat overall. Dairy products (excluding butter) show the highest per capita consumption among animal-based products, albeit with high cross-country variation.

Among plant-based foods, cereals—particularly wheat—lead in average consumption. Denmark, the Netherlands, Ireland, and Hungary report over 300 kg/capita/year. Sugar crops and starchy roots follow, reflecting notable potato consumption, while fruits and vegetables show similar patterns across countries.

Control variables also vary widely, though values span 1980–2020, making direct interpretation difficult due to economic cycles. Table 2. shows expected correlations: price levels correlate more with income than with overall GDP, and higher income is linked to increased meat consumption. Vegetable intake remains relatively stable despite income variation.

GDP and GDP per capita are only weakly correlated. Including both helps separate the effects of total economic size and individual wealth, offering more precise insights into consumption patterns.

Appendix 4 shows beef consumption negatively correlates with pork (-0.22), poultry (-0.25), cereals (-0.16), and spices (-0.36), indicating substitution behavior. Correlations among plant-based products are moderate to weak (<0.40).

Table 1. Panel Data descriptive statistics

Description	Variable name	Mean	SD	Min	Max
Beef kg/capita	beef	17.15	7.26	0.13	39.47
Pork kg/capita	pork	39.18	12.48	12.99	80.01
Poultry kg/capita	poultry	19.95	7.37	3.14	39.34
Mutton & Goat kg/capita	mutton&goat	3.32	3.61	0	15.55
Offal kg/capita	offal	4.38	3.15	-5.3	18.86
Milk Ex. Butter kg/capita	milk	337.41	169.97	93.29	1643.91
Eggs kg/capita	eggs	13.8	3.38	5.54	24.94
Fish, Seafood kg/capita	fish&seafood	39.39	28.99	1.56	200.55
Other Aquatic kg/capita	other aquatic	0.54	1.64	0	11.23
Cereals kg/capita	cereals	620.09	258.18	271.32	1616.25
Starchy roots kg/capita	starchy roots	169.35	169.46	29.09	1188.11
Sugar crops kg/capita	sugar crops	221.93	180.29	-2.44	723.75
Sugar and Sweeteners kg/capita	sugar&sweeteners	51.95	22.12	22.67	169.9
Pulses Ex. Peas kg/capita	pulses	10.8	10.1	1.21	77.99
Tree nuts kg/capita	treenuts	4.68	4.17	-2.43	26.71
Oil crops kg/capita	oilcrops	97.08	80.58	2.49	396.92
Vegetable oils kg/capita	vegetable oils	36.14	25.54	7.93	238.95
Vegetables kg/capita	vegetables	142.85	62.45	35.62	383.42
Fruit Ex. wine kg/capita	fruits	155.02	71.78	29.29	349.74
Stimulants kg/capita	stimulants	8.01	4.14	-12.68	27.11
Spices kg/capita	spices	0.72	1.16	-0.1	8.83
Miscellaneous kg/capita	miscellaneous	-1.35	6.94	-43.8	21.97
Real Gross Domestic Product	GDP	654497	854260	2726	3595200
Real GDP per capita	GDPpc	25647	14541	3382	79670
Consumer Price Index 2010=100	CPI	73.81	32.1	0	127.04
BSE outbreak indicator	BSEdummy_abs	0.45	0.5	0	1
EU member indicator	EUdummy	0.73	0.44	0	1
FMD outbreak indicator	FMD	0.03	0.18	0	1
Reported cases of BSE	bsecases	979.44	4699.61	1	37301

Notes: The variables in 'kg/capita' represent the domestic supply (as a proxy of consumption) of the corresponding product.

Table 2. Pairwise correlation: controls, aggregates food categories and BSE cases

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) GDP	1.00								
(2) GDPpc	0.39	1.00							
(3) CPI	0.27	0.55	1.00						
(4) BSEdummy_abs	0.45	0.62	0.58	1.00					
(5) EUdummy	0.37	0.53	0.63	0.53	1.00				
(6) FMDdummy	0.02	-0.06	-0.13	-0.10	0.00	1.00			
(7) animal products	0.23	0.61	0.21	0.32	0.27	-0.10	1.00		
(8) plant-based products	0.15	-0.10	0.06	0.26	0.23	0.03	-0.29	1.00	
(9) BSEcases	0.13	-0.01	-0.28		0.02	-0.02	-0.04	-0.22	1.00

Results

Panel regression results

Table 3 to Table 5 present panel regression estimates of the BSE impact on beef consumption relative to 20 food groups, using our preferred specification with full controls and fixed effects. Table 3 covers animal-based comparisons; Table 4 and Table 5 show plant-based comparisons.

Table 4 indicates a negative effect on beef consumption across all animal-based products, with statistically significant declines relative to pork, poultry, eggs, and mutton and goat meat, ranging from -19% to -23%[1]. These results support the view that beef, pork, and chicken are close substitutes. Comparisons with fish and seafood, and milk show smaller, less significant effects, -14% and -10%, respectively[2]. Although dairy products come from cows, early evidence suggested BSE could not be transmitted through their milk, even from infected animals (WHO, 1996; EC, 2001). The largest estimated decline appears for aquatic products but lacks statistical robustness.

Table 4 and Table 5 compare beef to plant-based products, which serve as plausible counterfactuals. Table 4 reveals substantial and statistically significant reductions in beef consumption relative to pulses and vegetable oils (each -36%), and cereals (-24%)[3]. Notably, these foods are recognized as key sources of plant

[1] $(e^{-0.21} - 1) * 100 \cong -19\%$ w.r.t. pork. $(e^{-0.26} - 1) * 100 \cong -23\%$ w.r.t. poultry.
[2] $(e^{-0.15} - 1) * 100 \cong -14\%$ w.r.t. fish and seafood. $(e^{-0.1} - 1) * 100 \cong -10\%$ w.r.t. milk.
[3] $(e^{-0.44} - 1) * 100 \cong -36\%$ and $(e^{-0.27} - 1) * 100 \cong -24\%$

protein and fat within the EU strategy for promoting sustainable food systems (Frezal et al., 2022; World Economic Forum [WEF], 2019).

Other groups in Table 4 show mixed results. Beef consumption fell by 20% relative to vegetables[4]. Oil crops had a similar but less stable effect, while the decline relative to starchy roots, mainly potatoes, was neither substantial nor significant.

Table 5 reports consistent negative and significant effects across all plant-based groups. The largest declines, ranging from -40% to -49%[5], occur relative to sugar crops, tree nuts, and miscellaneous foods, followed by fruits and spices, -25%. Processed sugars and stimulants (coffee, tea, and cocoa products) show smaller effects, -13%.

Among the control variables, per capita income and CPI show a strong, negative, and statistically significant effect on consumption as expected. GDP and EU membership have mixed effects, while FMD's impact is small and insignificant.

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[4] $(e^{-0.22} - 1) * 100 \cong -20\%$.

[5] $(e^{-0.51} - 1) * 100 \cong -40\%$; $(e^{-0.6} - 1) * 100 \cong -45\%$ and $(e^{-0.67} - 1) * 100 \cong -49\%$, for sugar crops, tree nuts, and miscellaneous comparison groups respectively.

Table 3. Panel regression results. Beef vs specific animal-based products in Country & Year FE specification

	(1) beef vs pork	(2) beef vs poultry	(3) beef vs fish& seafood	(4) beef vs eggs	(5) beef vs milk	(6) beef vs mutton& goat	(7) beef vs other aquatic
BSEdummy_abs	-0.21***	-0.26***	-0.13*	-0.23***	-0.09**	-0.22***	-0.33
	(0.05)	(0.06)	(0.07)	(0.05)	(0.05)	(0.06)	(0.2)
ln_GDPpc	-0.87***	-1.89***	-1.28***	-0.56**	-1.38***	-1.71***	-3.8***
	(0.32)	(0.34)	(0.41)	(0.28)	(0.28)	(0.34)	(1.32)
ln_CPI	-0.16***	-0.14***	-0.15***	-0.15***	-0.15***	.12***	.03
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.2)
ln_GDP	-0.39	0.58**	-0.79**	-0.39	-0.07	1.23***	2.5**
	(0.27)	(0.29)	(0.35)	(0.24)	(0.24)	(0.29)	(1.18)
EUdummy	-0.17***	-0.24***	0.14**	-0.01	0.02	-0.22***	-0.42**
	(0.05)	(0.05)	(0.07)	(0.05)	(0.05)	(0.05)	(0.19)
FMDdummy	0.01	-0.03	0.24**	-0.01	0.07	-0.02	-0.21
	(0.08)	(0.08)	(0.1)	(0.07)	(0.07)	(0.08)	(0.27)
Constant	13.42***	12.39***	22.43***	11.29***	12.23***	3.71***	12.67**
	(1.26)	(1.36)	(1.65)	(1.12)	(1.14)	(1.39)	(5.2)
Observations	764	764	764	764	764	756	625
R-squared	0.8	0.81	0.64	0.77	0.76	0.92	0.76

*Notes: The dependent variable is the natural logarithm of the ratio between the consumption of beef and the consumption of specific animal products (kg/capita/day). BSEdummy_abs: Absorbing treatment. Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1*

Table 4. Panel regression results. Beef vs specific plant-based products in Country&Year FE specification.

	(1) beef vs cereals	(2) beef vs starchy roots	(3) beef vs pulses[a]	(4) beef vs oil crops	(5) beef vs vegetable oils	(6) beef vs vegetables
BSEdummy_abs	-0.27***	0.06	-0.44***	-0.17**	-0.44***	-0.21***
	(0.05)	(0.05)	(0.09)	(0.07)	(0.06)	(0.05)
ln_GDPpc	-1.44***	-0.67**	-2.51***	-4.44***	-2.32***	-1.02***
	(0.3)	(0.3)	(0.56)	(0.44)	(0.35)	(0.3)
ln_CPI	-0.12***	-0.13***	-0.23***	-0.11***	-0.14***	-0.13***
	(0.02)	(0.02)	(0.03)	(0.02)	(0.02)	(0.02)
ln_GDP	0.3	-0.02	0.29	2.06***	1.2***	-0.07
	(0.25)	(0.26)	(0.48)	(0.38)	(0.3)	(0.26)
EUdummy	0.19***	-0.09*	0.58***	0.03	0	-0.08
	(0.05)	(0.05)	(0.09)	(0.07)	(0.06)	(0.05)
FMDdummy	-0.03	0.04	-0.09	0.01	-0.11	-0.07
	(0.07)	(0.07)	(0.14)	(0.11)	(0.08)	(0.07)
Constant	7.43***	5.31***	23.46***	17.67***	8.18***	9.54***
	(1.19)	(1.21)	(2.25)	(1.76)	(1.4)	(1.22)
Observations	764	764	736	764	764	764
R-squared	0.84	0.86	0.69	0.85	0.78	0.81

*Notes: The dependent variable is the natural logarithm of the ratio between the consumption of beef and the consumption of of specific plant-based products (kg/capita/day). BSEdummy_abs: Absorbing treatment. Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1*

[a]Excluding peas.

Table 5. (continuation Table 4) Panel regression results. Beef vs specific plant-based products in Country&Year FE specification.

	(1) beef vs fruits	(2) beef vs sugar crops	(3) beef vs sugar& sweeteners	(4) beef vs tree nuts	(5) beef vs spices	(6) beef vs stimulants	(7) beef vs miscellaneous
BSEdummy_abs	-0.28***	-0.51***	-0.14***	-0.6***	-0.33***	-0.13**	-0.67***
	(0.06)	(0.13)	(0.05)	(0.09)	(0.08)	(0.07)	(0.23)
ln_GDPpc	-3.21***	-5.2***	-0.63**	-2.04***	-0.94	.12	-1.53
	(0.33)	(1.02)	(0.3)	(0.56)	(0.62)	(0.39)	(0.94)
ln_CPI	-0.13***	.1**	-0.12***	-0.13***	-0.24***	-0.29***	-0.13
	(0.02)	(0.04)	(0.02)	(0.03)	(0.03)	(0.02)	(0.11)
ln_GDP	1.32***	4.31***	-0.38	-0.48	-0.82	-1.52***	-2.25**
	(0.28)	(0.92)	(0.26)	(0.48)	(0.56)	(0.33)	(1.03)
EUdummy	.24***	-0.34***	-0.08	.09	.15*	-0.1	.59**
	(0.05)	(0.13)	(0.05)	(0.09)	(0.08)	(0.06)	(0.23)
FMDdummy	-0.08	-0.18	.03	-0.05	-0.08	.18*	.01
	(0.08)	(0.18)	(0.07)	(0.14)	(0.11)	(0.09)	(0.23)
Constant	13.92***	-5.02	10.43***	28.59***	24.3***	19.76***	46.28***
	(1.32)	(3.64)	(1.2)	(2.25)	(2.33)	(1.57)	(8.11)
Observations	764	661	764	741	675	762	323
R-squared	.76	.74	.76	.68	.86	.61	.82

*Notes: The dependent variable is the natural logarithm of the ratio between the consumption of beef and the consumption of specific plant-based products (kg/capita/day). BSEdummy_abs: Absorbing treatment. Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1*

The findings presented in Table 3 to Table 5 align with both prior research and empirical evidence. The BSE outbreak had a significant impact on the consumption of other meats, particularly pork and poultry (Table 3). Conversely, there is growing empirical evidence supporting the expansion of the plant-based product market as meat substitutes in Europe (EC, 2020; STOA&EPRS, 2024), primarily for the groups listed in Table 4 (cereals, pulses and vegetable oils). This study now enables us to infer the impact of the outbreak on this latter food group.

Event study regression results

The section is divided into three. First, we graphically analyze the ATT estimates for each group-time (non-dynamic effects), to enable cross-country comparisons by outbreak year. Second, we present the dynamic ATT estimates, which represent our preferred analysis. Third, we summarize the dynamic effects into a single aggregate effect for each comparison group.

Based on the panel data regression results, this section focuses on eight comparison groups: pork, poultry, fish, and eggs (from Table 3), and cereals, pulses, vegetable oils, and vegetables (from Table 4). Results for the remaining food groups are available in Appendix 5.

Average treatment effects by group

Figure 3 shows the estimated ATTs by cohort (non-dynamic effects), grouping countries by the year of their first reported BSE outbreak. The analysis includes eight groups across nine countries with sufficient controls for non-dynamic effects.

The UK (G1987) shows significant post-outbreak declines in beef consumption relative to all comparison groups. While the drop was moderate versus pork and poultry (17% and 10%), it was sharper compared to fish and seafood (50%) and strongest against pulses (92%). Ireland (G1989) followed a similar pattern.

France (G1991) recorded a 26% decline relative to pork, its main substitute, while effects for poultry were insignificant. This aligns with Adda (2007) and reflects France's high beef and low chicken consumption. Declines near 30% were also found for eggs, cereals, and vegetable oils.

For Germany and Denmark (G1992), no significant changes were found relative to pork or poultry, consistent with Andersen et al. (2007). Germany, with low beef intake, showed sharp shifts toward plant-based foods, with beef falling 37% relative to cereals and 85% to pulses. Germany also banned British beef early, and 1992 marked a shift in plant-based consumption trends.

Portugal (G1990) and Spain (G2000) show mostly insignificant results, likely due to dietary patterns that favor pork and fish. In both countries, these proteins are consumed at rates four times higher than beef, diminishing the outbreak's impact.

Italy (G1994) saw mixed effects: declines of 18% and 20% versus pork and fish, largely reabsorbed within months (aligned with Mazzocchi & Lobb, 2005), but an 85% fall relative to pulses.

The Netherlands (G1997) experienced the most pronounced effects: beef fell 55% against fish and 43% against eggs. Plant-based comparisons show sharp declines of 56% for cereals and 52% for vegetable oils. These coincide with widespread fear during the outbreak's peak, intensified by early import bans and the first vCJD case.

This group-specific analysis aligns with prior literature and considers national consumption habits. It also extends the scope to understudied food groups, reinforcing the robustness of dynamic effect estimates that follow.

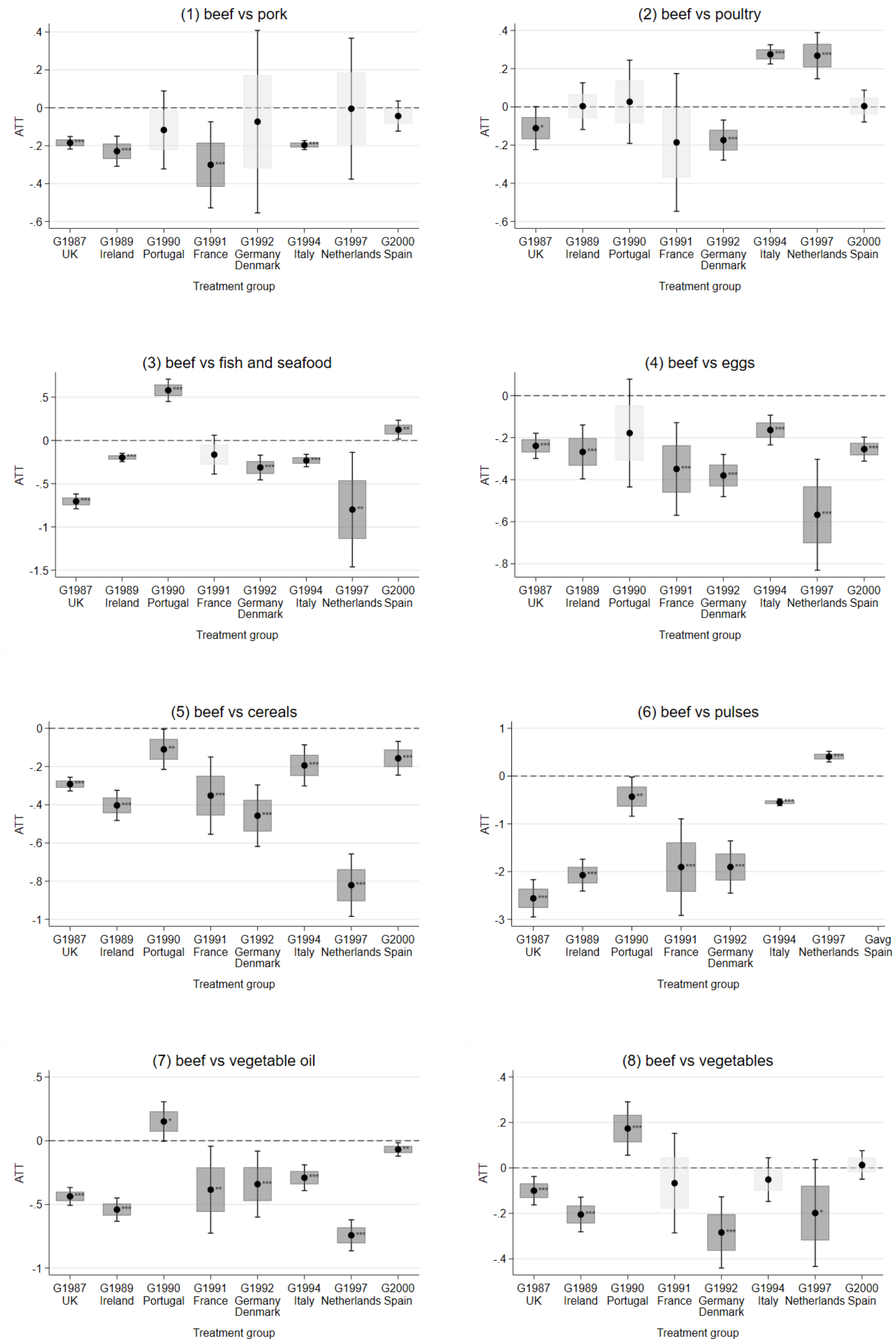

Figure 3. Event study (non-dynamic) results by cohorts

*Note: The central point denotes the point estimate (ATT), the box's length shows the standard error, and the whiskers indicate the 95% confidence interval. Significance is indicated by both the asterisks (*** p<0.01, ** p<0.05, * p<0.1) and the box's colour (dark for significant, white otherwise).*

Dynamic average treatment effects

Figure 4 visualizes the results of the event study regression analysis for each comparison group, with eight plots. The figure presents both the event's estimated effects (point estimates) and their associated uncertainty (95% C.I.).

We made two adjustments to reduce noise in estimating the $ATT(g, t)$. First, consistent with the results from the panel data section, we only selected income per capita and the consumer price index as covariates in the nonparametric estimation. Second, due to the 'Not-yet-treated' approach, there were very few 'treated' units/countries at the beginning of the treatment period, as well as a lack of control units at the end, leading to dramatic deviations at both extremes. Therefore, we trimmed five periods from each end.

Plots (1)-(4) in Figure 4 depict the effect of BSE on beef consumption compared to other animal-based protein sources. While there is an immediate reaction, it is short-lived and does not deepen. Pork and poultry exhibit an immediate response to the outbreak, Plots (1) and (2). Beef consumption declines relative to pork and poultry in a sustained manner until the fifth year, reaching a decrease of 24% and 17%, respectively. Thereafter, a recovery in relative beef consumption is observed, exhibiting the most significant rebound when compared with poultry.

Fish and seafood as a comparison group exhibit a delayed response, Plot (3) in Figure 4. The relative decline in beef consumption occurs from the fourth year onward. However, the decline is deeper than for pork and poultry as comparison groups and reaches 36% before reversing in the final years.

These three groups - pork, poultry, and fish and seafood - all share the characteristic that the relative decline in beef consumption exhibits a U-shape in the post-outbreak period. This U-shape is most evident in poultry and fish and seafood.

In contrast, when compared to egg consumption, beef consumption shows a continuous decline throughout the entire post-outbreak period. This decline reaches a maximum of 38%.

Conversely, Plots (5)-(8) in Figure 4 highlight a consistent downward trend in beef consumption relative to each comparative plant-based group following the BSE outbreak. All groups exhibit an immediate response. However, the most profound impact is seen on pulses, Plot (2). Beef consumption decreased by up to 93% when using pulses as comparison groups[1]. Cereals and vegetable oils, as comparison groups in Plot (5) and Plot (7), also exhibit sharp declines in relative beef consumption, falling below 40% in each case, although the decline is more sustained for cereals. Regarding vegetables as a comparison group, Plot (8), the relative decline in beef consumption is less pronounced but stabilizes around 13%.

Across all eight plots analyzed, no clear evidence of an anticipation effect is observed. This suggests that consumers did not significantly alter their consumption patterns in anticipation of the BSE outbreak. The above, despite the gradual spread of BSE from Western to Eastern EU countries and the first EU import ban policies in 1994 and 1996.

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[1] Note that these percentages are the result of the exponential conversion of the ATT, as done in the results of the panel regression: $(e^{ATT\ coefficient} - 1) * 100$

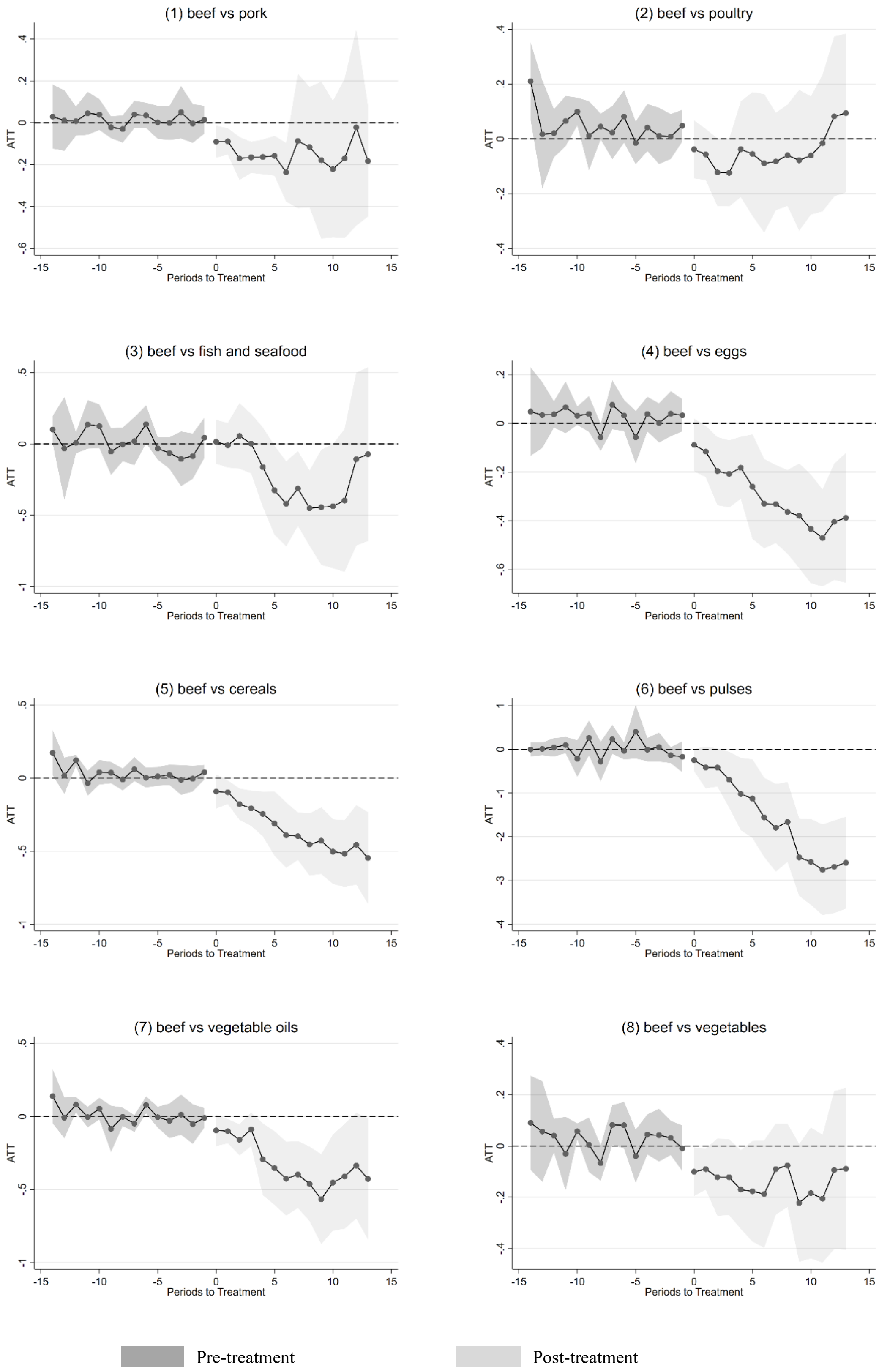

Figure 4. Event study (dynamic effects) results by specific comparison products

Note: Based on the absorbing treatment under the approach of CS.

Similarly, the pre-treatment consumption ratio between beef and all comparison products exhibits a relatively consistent pattern throughout the pre-treatment period. This consistency supports the assumption of parallel trends, implying that, in the absence of BSE, the consumption trajectories of the control and treatment groups were not systematically different.

In the previous section, under group-time non-dynamic ATT, we observed moderate declines in beef consumption compared to other meats (pork, chicken, and fish). The dynamic analysis suggests that, on average, these declines are reversed in subsequent years, refuting the formation of long-term habits claimed by some early studies. Although their findings are correct for truncated analysis periods, this effect isn't corroborated when extended to the long run, whereas the impact on plant-based food consumption proved deeper and more persistent

Aggregated estimation of the dynamic average treatment effects

We can summarize the dynamics shown in Figure 4 by calculating the aggregate estimates of the ATT. Table 6 presents the aggregated estimator for all pre-treatment and post-treatment effects along with their corresponding joint significance, Column (1). Note that the coefficients in column (1) are the aggregated estimators, $\theta(e)$. Columns (2) to (4) display the standard deviation and the confidence intervals, while column (5) is the transformation of the coefficient into percentage change, calculated as $(e^{ATT\ coefficient} - 1) * 100$.

Our primary interest focuses on the average ATT estimates in the post-treatment period (Column (1) "Post_avg" rows). These estimates reveal two key aspects: the magnitude and significance of the effect. When examining the comparison groups utilizing plant-based products, the estimators exhibit high statistical significance for the cereals, pulses and vegetable oils groups, indicating average reductions in relative beef consumption of 29%, 79% and 28%, respectively (Column (5).

In the comparison groups using animal-based products, the magnitude of the estimators is generally smaller, with relative beef consumption declines of 14%, 5%, and 20% for pork, poultry and fish and seafood groups, respectively. However, none of these latter reductions are precisely estimated. Only when eggs are used as the comparison group does the average decline in beef consumption become significant and stable, reaching 26%.

Findings from the event study largely align with the results of our baseline regressions. While our initial panel regression did not detect a clear increase in overall plant-based product consumption following the BSE outbreak, the event study analysis reveals a specific impact on certain plant-based groups considered nutritional alternatives to red meat. Notably, this observed increase in the consumption of these specific plant-based groups appears to be both greater in magnitude and more persistent compared to the effect of BSE on direct meat substitutes, such as pork and poultry.

Table 6. The aggregate ATT by Periods Before and After treatment

		Statistics				
		(1)	(2)	(3)	(4)	(5)
		Coef.	SD	[95% CI]		%
beef vs pork	*Pre_avg*	0.02*	0.01	0.00	0.03	1.6%
	Post_avg	-0.15*	0.09	-0.32	0.02	-13.6%
beef vs poultry	*Pre_avg*	0.05***	0.01	0.03	0.07	4.9%
	Post_avg	-0.05	0.07	-0.18	0.09	-4.5%
beef vs fish & seafood	*Pre_avg*	0.01	0.01	-0.01	0.04	1.4%
	Post_avg	-0.22	0.14	-0.49	0.06	-19.7%
beef vs eggs	*Pre_avg*	0.03***	0.00	0.02	0.03	2.6%
	Post_avg	-0.30***	0.06	-0.42	-0.18	-25.7%
beef vs cereals	*Pre_avg*	0.03***	0.01	0.02	0.05	3.3%
	Post_avg	-0.35***	0.07	-0.48	-0.21	-29.2%
beef vs pulses[a]	*Pre_avg*	0.02	0.02	-0.03	0.06	1.9%
	Post_avg	-1.57***	0.34	-2.23	-0.91	-79.3%
beef vs vegetable oils	*Pre_avg*	0.01	0.01	-0.01	0.03	0.9%
	Post_avg	-0.33***	0.10	-0.52	-0.14	-27.8%
beef vs vegetables	*Pre_avg*	0.03**	0.01	0.01	0.05	2.8%
	Post_avg	-0.14*	0.07	-0.28	0.00	-12.9%

Notes: The dependent variable is the natural logarithm of the ratio between the consumption of beef and the consumption of specific products (in kg/capita/day). Column (5) equals $(e^{Coefficient} - 1) * 100$*. Absorbing treatment applied. *** p<0.01, ** p<0.05, * p<0.1*

[a]*The group excludes peas*

Sensitivity analysis results

Sensitivity analysis results for parallel trends assumption

We assess the robustness of our causal estimates to potential violations of the parallel trends assumption in Appendix 6. We apply the sensitivity analysis proposed by Rambachan and Roth (2023). Recall that the method relaxes the strict parallel trends assumption by bounding post-treatment deviations relative to the largest pre-treatment deviation. The key parameter, $\overline{M}$, represents this relative bound, with higher values indicating greater tolerance for assumption violations.

Among animal-based comparison groups, our estimates for beef consumption relative to eggs and milk are the most robust. For the 'beef vs eggs' comparison, the post-treatment effect remains statistically significant even when post-treatment deviations are allowed to be up to eight times larger than the maximum pre-trend violation $\overline{M} = 8$. Similarly, in the 'beef vs milk' comparison, the effect is robust up to $\overline{M} = 5$. In contrast, comparisons with pork, poultry, and fish and seafood produce wide confidence sets around the null. These estimates are imprecise and fail to reject the hypothesis of no effect even under minimal relaxation ($\overline{M} = 1$).

For plant-based comparisons, robustness is notably stronger. The 'beef vs pulses' estimate tolerates trend violations up to $\overline{M} = 27$, indicating a highly stable post-treatment effect. Likewise, comparisons with cereals and vegetable oils remain significant up to $\overline{M} = 6$ and $\overline{M} = 9$, respectively. Although the original confidence interval for 'beef vs pulses' is closer to zero, it is more stable than those of cereals and vegetable oils under increasing relaxation.

Other comparison groups shown in Appendix 6 exhibit a similar pattern: comparisons with animal-based products are less robust, whereas those with plant-based groups, particularly protein and fat alternatives, remain significant under moderate violations of the parallel trends assumption ($\overline{M} > 3$).

These findings underscore that beef consumption reductions following the BSE outbreak are most credibly identified when contrasted with plant-based products, reinforcing their suitability as counterfactuals for long-run dietary adjustments.

Robustness to the DID methodology

Table 7 compares the average treatment effect coefficient across various DID specifications. Columns (1) and (2) use the dCDH approach for absorbing and non-absorbing treatment designs. Column (3) presents our preferred estimates based on CS. Coefficients in column (3) are identical to those displayed in Table 6 for the average post-treatment effect. Column (4) provides the traditional TWFE estimates, as previously shown in Table 3 and Table 4. We used the eight primary comparison groups discussed in the preceding sections. The full set of comparison groups, including both DID estimators and event study plots under dCDH approach, can be found in Appendix 7.

Column (1) shows that the only significant results for a reduction in beef consumption occur in the plant-based comparison groups: cereals, pulses, and vegetable oils. The point estimate reveals relative decreases in beef consumption of

20%, 41%, and 18%, respectively[14]. These reductions are lower than those when we use a non-absorbing treatment under dCDH, column (2). In this column, the effects are significant for the same comparison groups showing estimates of 30%, 46%, and 31%, respectively[15]. Notably, among all specifications, the coefficients in column (2) are the closest to our benchmark estimate, CS in column (3).

In general, after correcting the pitfalls of TWFE, as shown in column (4), with all coefficients significant, the results in columns (1) to (3) have two sides. On the one hand, they support our initial finding that the largest and most permanent impact of the BSE outbreak on beef consumption occurred in comparison to the consumption of plant-based products and not in comparison to other meat alternatives. However, on the other hand, the table reveals that the results are sensitive to the DID specification. Primarily, we observe a loss of significance and magnitude in the coefficients when using dCDH specifications compared to CS. These results were anticipated due to the differing identification strategies employed by the dCDH and CS estimators (see discussion in section 3.4.2 Sensitivity to DID methodology). We primarily rely on the CS estimator displayed in column (3).

Finally, following dCDH we implement placebo estimators to test the parallel trends assumption. **Error! Reference source not found.** presents the estimated p-value for the joint significance of DID_L placebo estimators, testing the null hypothesis that the parallel trends assumption holds. These estimates are calculated for different numbers of pre-treatment periods. With only three periods, as shown

[14] $(e^{-0.228} - 1) * 100 \cong -20\%$, $(e^{-0.52} - 1) * 100 \cong -41\%$ $(e^{-0.1982} - 1) * 100 \cong -18\%$ w.r.t. cereals, pulses and vegetable oils.

[15] $(e^{-0.350} - 1) * 100 \cong -30\%$, $(e^{-0.617} - 1) * 100 \cong -46\%$ $(e^{-0.375} - 1) * 100 \cong -31\%$ w.r.t. cereals, pulses and vegetable oils.

in Column (1), we are unable to reject the null hypothesis (p-value > 0.05) for 16 out of 20 comparison groups, implying no significant differences in pre-treatment trends. The comparison groups that exhibited pre-treatment trend differences were related to pork, vegetable oils, oil crops, and sugar crops.

Table 7. Robustness to the DID methodology. ATT estimators under different DID specifications

	(1) dCDH Absorbing treatment	(2) dCDH Non-absorbing treatment	(3) CS Absorbing treatment	(4) TWFE
beef vs pork	-0.018	-0.093	-0.158*	-0.21***
	(0.076)	(0.170)	(0.09)	(0.05)
beef vs poultry	0.003	-0.102	-0.068	-0.26***
	(0.082)	(0.176)	(0.08)	(0.06)
beef vs fish&seafood	-0.203	-0.235	-0.211	-0.13*
	(0.208)	(0.238)	(0.14)	(0.07)
beef vs eggs	-0.111	-0.208	-0.297***	-0.23***
	(0.069)	(0.132)	(0.06)	(0.05)
beef vs cereals	-0.228 ***	-0.350 ***	-0.345***	-0.27***
	(0.078)	(0.120)	(0.07)	(0.05)
beef vs pulses[a]	-0.520 ***	-0.617 **	-1.573***	-0.44***
	(0.202)	(0.240)	(0.34)	(0.09)
beef vs vegetable oils	-0.198 **	-0.375 **	-0.316***	-0.44***
	(0.085)	(0.174)	(0.1)	(0.06)
beef vs vegetables	-0.085	-0.165	-0.14**	-0.21***
	(0.077)	(0.144)	(0.07)	(0.05)

*Notes: Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1*

[a]The group excludes peas

Appendix 7 shows that as the number of pre-treatment periods increases (moving from right to left across columns), it becomes increasingly difficult to support the parallel trends and no-anticipation assumptions for a larger set of comparison groups. For placebo tests with 4, 5, 7, and 10 pre-treatment periods, the number of comparison groups where the parallel trends assumption holds decreases to 10, 7, 5, and 2, respectively. It is well-known in DID models that if pre-treatment periods are extended sufficiently, p-values will eventually become insignificant[16].

[16] For example, see the discussion between Kearney & Levine (2015; 2016) and Jaeger, Joyce, and Kaestner (2020).

Discussion

Overall, our findings align with current EU food market trends and the need to reduce red meat consumption, at least in high-income countries with high rates of meat consumption, as the best alternative to mitigate the health and environmental risks inherent in its production (Parlasca & Qaim, 2022; Espinosa et al., 2020).

It is noteworthy that pork and poultry, being strong substitutes for beef, are not suitable comparison groups when evaluating the impact of food safety concerns on beef consumption. A more objective analysis can be achieved by comparing with plant-based food groups, which represent entirely separate products that are arguably suitable as a control group for beef (and red meat) consumption.

Our results show that the impact of the BSE outbreak on beef consumption was heterogeneous across comparison groups. While short-term substitution effects are observed for pork and chicken, these do not persist over the long term nor hold under sensitivity analysis, suggesting limited robustness. Among animal-based products, the most robust and persistent effect is observed in the comparison with eggs. In contrast, comparisons with plant-based groups consistently reveal strong and statistically significant reductions in beef consumption. These effects remain robust even under relaxed identification assumptions, indicating that dietary shifts toward plant-based alternatives were more sustained in the post-BSE period.

These results suggest that major food safety crises like BSE can trigger lasting shifts toward plant-based consumption, beyond temporary meat substitution. Policymakers should leverage such periods of heightened concern to encourage plant-based transitions, focusing on promoting alternatives rather than only mitigating impacts on the meat sector, supporting long-term health and environmental goals.

Conclusion

Current research often overlooks the substitution of red meat with plant-based products during beef consumption shocks. Our event study reveals a decline in beef consumption relative to other meats within five years post-outbreak before the 2000s, consistent with substitution effects found in the UK, Netherlands, and France. However, longer-term analyses show a U-shaped recovery to pre-outbreak levels, with post-2000 studies confirming only minor long-term changes. In contrast, we showed that beef consumption relative to plant-based products like pulses, cereals, and vegetable oils exhibited substantial, sustained reductions of 79%, 29%, and 27%, respectively, without evidence of anticipatory changes before the outbreak.

This study underscores the need for future research to explore broader impacts of meat demand shocks beyond meat substitution. While reduced red meat consumption is well studied in experimental settings, real-world responses to demand shocks remain underexplored. A more comprehensive analysis would improve our understanding of dietary transitions. Given the health risks linked to red meat (González et al., 2020), future work could use BSE-vCJD responses to guide policies for preventing diseases like diabetes, cardiovascular issues, and colorectal cancer.

This study has two main limitations. First, it omits the impact of media coverage on BSE-related consumption changes, despite research showing that media shapes consumer expectations, especially among “info adapters.” Second, although fixed effects and event study methods are used, incorporating factors such as environmental and agricultural policies and household purchases could improve robustness. A country-specific analysis may help address this EU-wide limitation.

Acknowledging these limitations, this study highlights the lasting impact of food safety crises on consumption. Findings suggest policymakers promote plant-based substitutions during red meat demand shocks for long-term public health and environmental benefits. We hope future research will explore the broader effects of meat demand shocks to better inform dietary transitions and policies reducing red meat–related diseases in high-income countries.

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