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Change of dietary patterns on CO_2 emissions under the African swine fever in South Korea

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African swine fever (ASF) occurred in Gyeonggi of South Korea in 2019 and there were 21 reported cases in domestic swine farms. South Korea is the one of top countries for pork consumption, and half of the 2.9 million tons of meat consumed in 2022 were pork. Outbreaks from animal products have a severe impact on the shift of diet and the change in dietary patterns of consumers shape climate change. Moreover, animal products account for 18% of worldwide GHG emissions which is more than industry (16%), transportation (13.5%), and energy usage (13%). This study is the first study to analyze the regional impact of animal products associated with climate change in South Korea. The objective of this study is to analyze the regional effect of dietary shifts on per capita CO_2 emissions from household consumption in South Korea. Synthetic Control Method (SCM) is employed to analyze the impact of ASF on the change of per capita CO_2 emissions from household consumption by shifting the nutritional patterns in South Korea. The dependent variable is per capita CO_2 emissions from household consumption, and the type of event is an epizootic disease. The event period is between 2010 and 2021 (pre-intervention: 2010–2018 and post-intervention: 2019–2021). By establishing synthetic Gyeonggi from the optimal synthetic control unit, the trajectories present how dietary shifts have influenced per capita CO_2 emissions from household consumption in a positive direction after ASF. ASF caused consumer dietary shifts from pork to other types of meat. This divergence between Gyeonggi and synthetic Gyeonggi indicates that there is an impact influencing per capita CO_2 emissions from household consumption after ASF. Performing an SCM analysis with the treated (Gyeonggi) and control (thirteen municipalities) units, the study found that the two trajectory lines (Gyeonggi and synthetic Gyeonggi) were similar before diverging after the introduction of ASF. The gaps also indicate the impact of the shift in dietary patterns on per capita CO_2 emissions from household consumption.

JEL classification: C31, Q54.

KEYWORDS

African swine fever, meat consumption per capita, per capita CO_2 emissions, change of dietary patterns, synthetic control method (SCM)

1 Introduction

Pork is the most-consumed meat in the world, and it has an expanding and highly competitive global market (USDA, 2023).[1] South Korea is among the top countries for pork consumption; in 2022, around 2.9 million tons of meat were consumed, and half of that meat was pork [Korea Meat Trade Association (KMTA), 2024]. Pork consumption in South Korea has rapidly grown

1 Pork is the most widely eaten meat in the world (36%) followed by poultry (33%), beef (24%), and goat (5%) (USDA, 2023).

since the early 2000s, and the demand for pork is still highly imbalanced due to Korean consumers' unique preferences for specific cuts of meat (Shi, 2021). Consumers in South Korea have a unique consumption pattern and a strong preference for high-fat cuts such as belly and Boston butt (Choe et al., 2015). Table 1 indicates that in 2019, per capita beef and poultry consumption increased by 7.6% and 6.6%, respectively, while per capita pork consumption decreased by 1.2%. Per capita pork consumption is increasing by an annual average of 2.4%.

High feed and energy costs restrict South Korea's domestic pork production, so the total swine supply is expected to decline due to high production costs. Compound feed prices during the first 11 months of 2022 increased by 22% over the same period in 2021 (Ban, 2023). In agriculture, overuse of resources has increased greenhouse gas (GHG) emissions, causing serious environmental consequences such as climate change, and global warming. Animal products, such as red meat, dairy, and eggs, account for 18% of worldwide GHG emissions, more than industry (16%), transportation (13.5%), and energy usage (13%) (Jeong et al., 2023). Considering that over one-third of GHG emissions originate from the food system, livestock meat production plays a large part in the industry (Sugimoto et al., 2020; Liu et al., 2023). Growing demand for meat products causes the release of more GHG emissions into the atmosphere.[2]

Rogissart et al. (2019) found that the dietary patterns of consumers shape climate change. Nutritional patterns normally comprise 10%−30% of CO_2 emissions from households, and animal-based products have a larger impact on GHG emissions than plant-based products (Center for Sustainable Systems, University of Michigan, 2022; Afrouzi et al., 2023). In 2019, African swine fever (ASF)[3] occurred in Gyeonggi of South Korea in Figure 1; there were twenty-one reported cases in domestic swine farms and over 2,600 cases in wild boar (Cho et al., 2022). Loss of livestock, decreased market value, food insecurity, environmental impacts, and efforts to respond to animal diseases come at considerable costs to livelihoods and both public and private sector interests (Weaver and Habib, 2020).

The presence of ASF in China and Southeast Asia indicates the importance of animal diseases to economics, and epizootic diseases highlight the associated economic and human costs and the potential costs of other animal disease outbreaks in the future. Table 2 indicates the cost of living[4] of consumer goods in Gyeonggi, South Korea. In 2019, the indexes of beef and poultry increased by 3.4% and 1.2%, respectively, while pork decreased by 4.1% after the outbreak of ASF in Figure 2.

TABLE 1 Food consumption per capita in South Korea (kg/person).

Year	Beef	Pork	Poultry	Fish
2011	13.5	30.5	16.1	59.7
2012	13.2	32.3	16.0	56.4
2013	13.6	32.9	16.1	52.3
2014	14.6	33.5	18.1	55.4
2015	14.7	35.9	18.9	56.4
2016	14.5	37.0	19.3	54.9
2017	15.3	37.7	18.8	56.7
2018	15.8	40.6	19.7	56.8
2019	17.0	40.1	21.0	54.7
2020	16.7	38.0	22.5	54.7
2021	20.5	38.3	22.2	55.6

Source: Food and Agriculture Organization of the United Nations (2023).

FIGURE 1
Map of South Korea. Source: Created by author.

This study is limited to an analysis of dietary patterns for various foods, making regional data collection difficult. However, this paper is the first study to analyze the regional impact associated with climate change in South Korea. The objective of this study is to analyze the regional effect of dietary shifts on per capita CO_2 emissions from household consumption in South Korea. By applying the synthetic control method (SCM), this study shows how ASF has affected dietary changes, causing an increase in per capita CO_2 emissions. The food industry causes GHG emissions, and shifts in dietary practices influence the environment and human health (Aleksandrowicz et al., 2016).

2 Each kilogram of beef product produces 99.48 kgCO2eq, while poultry and pig products produce 9.87 and 12.31 kgCO2eq, respectively STATISTA (2024).

3 ASF is a highly contagious disease in domestic pigs [World Organization for Animal Health (WOAH), 2023], and it causes tremendous socioeconomic damage.

4 Cost of living is calculated periodically in nearly representative baskets of consumer goods.

TABLE 2 Index of cost of living in Gyeonggi (2020 = 100).

Year	Beef	Pork	Poultry	Fish	Fruit	Vegetable
2011	69.2	92.9	104.1	105.0	108.9	95.9
2012	67.5	80.9	103.1	95.8	119.4	93.7
2013	68.2	76.3	110.2	93.3	120.5	77.6
2014	71.9	89.0	108.2	93.9	100.7	74.2
2015	77.2	90.5	103.5	95.3	102.7	88.6
2016	89.6	92.3	99.0	92.9	89.4	87.3
2017	88.0	97.8	102.7	91.4	91.3	110.4
2018	89.1	94.6	102.7	91.7	91.9	128.4
2019	92.1	90.7	103.9	91.0	90.5	96.0
2020	100.0	100.0	100.0	100.0	100.0	100.0
2021	109.0	120.5	108.6	106.7	119.8	110.1

Source: Korea Statistical Information Service (KOSIS) (2024).

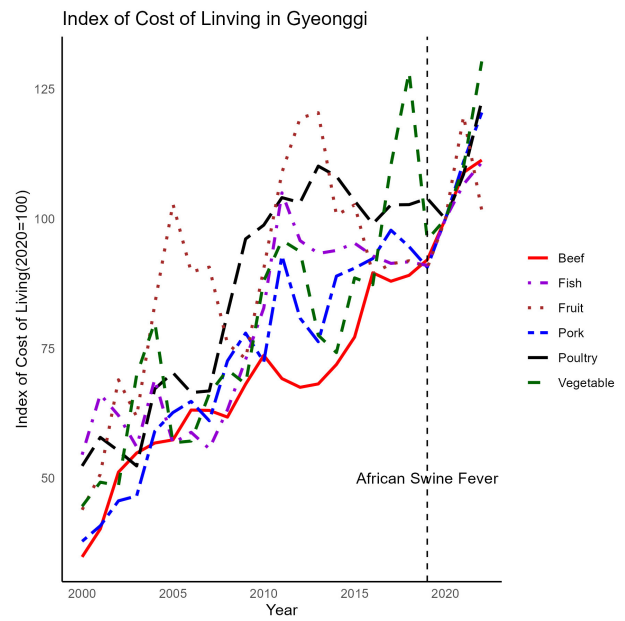

FIGURE 2
Index of cost of living in Gyeonggi (2020 = 100).

2 Method and data

This study applies the Synthetic Control Method (SCM)[5] to analyze the impact of ASF on the change of per capita CO_2 emissions from household consumption by shifting the nutritional patterns in South Korea. SCM is a particularly useful analysis tool for case studies with relatively small sample data in comparison to other methods. Constructing the donor pool is a critical step for getting an acceptable estimate and two outcomes derive from SCM. The synthetic control unit relies on the analogous factors between the predictor's estimates of the exposed and unexposed units (Bouttell et al., 2018). The weighted average of the control unit from the SCM is needed to make it feasible and similar to the treated unit (Abadie et al., 2010).

Assume that observable units $i = 1, \ldots, J$ and time $t = 1, \ldots, T_0$, $T_0+1, \ldots, T$, without the loss of generality, the treated (exposed to the event) unit is $i = 1$, and the control units (unexposed to the event) are $i = 2, \ldots, J$; the pre-event period is $t = 1, \ldots, T_0$, and the post-event period is $t = T_0+1, \ldots, T$ (Abadie et al., 2010). Let Y_{it}^N be the outcome with no event, and Y_{it}^I be the outcome with an event at time t and unit i.[6] D_{it} be an indicator that indicates the value 1 if unit i experienced the event at time t and the value 0 otherwise; the impact of the event is assessed by the subtraction Y_{it}^N from Y_{it}^I in Equation 1 that is, $\alpha_{it} = Y_{it}^I - Y_{it}^N$ in the post-event period in Equation 2.

$$Y_{it}^I = Y_{it}^N + \alpha_{it} \cdot D_{it} \quad (1)$$

$$\alpha_{it} = Y_{it}^I - Y_{it}^N \quad (2)$$

The optimal synthetic control unit is constructed from four vectors (X_0, X_1, Z_0, and Z_1) with two weights (W and V). The X_0 and Z_0 indicate the predictor's and outcome's values of the control unit, and X_1 and Z_1 indicate the predictor's and outcome's values of the treated unit. Then, two weights W present the minimized distance between the predictors and each control unit's weight in Equation 3, and V present the minimized distance between the outcomes of treated and control unit in the pre-event period in Equation 4. From a minimized MSPE[7] of the outcomes of treated/control units, the outer optimization is derived. The optimization provides asymptotically unbiased estimates of the treated unit (Abadie et al., 2010). Therefore, the optimal weight (W_j^*) is estimated from four vectors showing the impact of the event in Equation 5.

$$W^* = \underset{W}{argmin} \sqrt{(X_1 - X_0 W)' V (X_1 - X_0 W)} \quad (3)$$

$$V^* = \underset{V}{argmin} \left(Z_1 - Z_0 W^*(V)\right)' \left(Z_1 - Z_0 W^*(V)\right) \quad (4)$$

$$\widehat{\alpha_{it}} = Y_{it}^I - \sum_{j=2}^{J+1} W_j^* \cdot Y_{jt} \quad (5)$$

In this study, the dependent variable is per capita CO_2 emissions from household consumption, and the type of event is an epizootic disease. The event period is between 2010 and 2021 (pre-intervention: 2010–2018 and post-intervention: 2019–2021).

The treated unit, Gyeonggi, and the selected 13 municipalities in South Korea which are not exposed to ASF in 2019 are included. The predictors from 14 municipalities are employment ratio, gross regional domestic product (GRDP) per capita, economic growth rate, and cost of living index (beef, pork, poultry, and fish) in Table 3.

5 The Synthetic Control Method (SCM) has been employed to estimate the impact of an intervention on various research interests: terrorism (Abadie and Gardeazabal, 2003), political action (Bohn et al., 2014), local construction (Ando, 2015), and disasters (Wang et al., 2013).

6 The superscript *N* above *Y* indicates the outcome is not exposed to the event, and the superscript *I* above *Y* indicates the outcome is exposed to the event.

7 MSPE stands for mean squared prediction error that presents the difference between the fitted and the true value.

TABLE 3 Variables description.

Variables	Description
Dependent variable	Per capita CO_2 emissions from household consumption (2010–2021)
Treated region	Gyeonggi in South Korea
Control units (Donor pool)	13 municipalities in South Korea
Predictors[a]	• Cost of living index (Poultry, Beef, Pig, and Fish) • Employment ratio (Male and Female)[a] • Gross regional domestic product[b] • Economic growth rate[c]
Intervention year	Year of the African Swine Fever occurred (Year of 2019)

Source: KOSIS, Korea Statistical Information Service; GIR, Greenhouse gas Inventory and Research center; GDD, Gyeonggi Data Dream.
[a]Employment of ratio of each municipality in South Korea.
[b]Gross regional domestic product (GRDP) measures the size of region's economy.
[c]Economic growth rate is measured annually of each municipality in South Korea.

3 Result

This study describes the per capita CO_2 emissions from household consumption as a dependent variable, and ten independent variables are taken to create the synthetic control unit. The estimates of predictors in the pre-intervention period are presented in Table 4, which shows the similarity between Gyeonggi and synthetic Gyeonggi.[8]

In Table 5, the weights/regression weights of every municipality for creating the synthetic control unit are stated.[9] The numbers in parentheses indicate the optimum synthetic unit for construction, such as Jeju (36.1%), Seoul (34.1%), Gyungbuk (22.0%), and Ulsan (5.5%). This implies that the mix of weighted municipalities provides the optimal synthetic control unit in the pre-event period. The regression weights of the unexposed units also deliver a synthetic control unit.[10]

By establishing synthetic Gyeonggi from the optimal synthetic control unit, Figures 3, 4 present how dietary shifts have influenced per capita CO_2 emissions from household consumption in a positive direction after ASF. Figure 3 presents the comparison of per capita CO_2 emissions between Gyeonggi and synthetic Gyeonggi between 2010 and 2021.

That trajectory of per capita CO_2 emissions of synthetic Gyeonggi closely follows Gyeonggi's per capita CO_2 emissions in the pre-intervention period. However, in 2019, the per capita CO_2 emissions of Gyeonggi and synthetic Gyeonggi diverged in different directions. ASF caused consumer dietary shifts from pork to other types of meat. This divergence between Gyeonggi and synthetic Gyeonggi clearly indicates that there is an impact influencing per capita CO_2 emissions from household consumption after ASF. Figure 4 presents the gaps in the per capita CO_2 emissions between Gyeonggi and synthetic Gyeonggi. While the difference in the pre-intervention period is within ±1%, a divergence emerged after the introduction of ASF.

TABLE 4 Characteristics in the pre-intervention.

		Gyeonggi	Synthetic Gyeonggi
Per capita CO_2 emissions from household consumption ($kgCO_2eq$/person)[a]		65.61	65.82
Cost of living index (2020 = 100)[b]	Beef	75.67	76.10
	Pork	85.52	84.96
	Poultry	103.70	100.96
	Fish	93.81	92.87
	Fruit	102.93	85.56
	Vegetable	89.46	87.37
Employment ratio (%)	Male	73.19	72.76
	Female	48.43	53.95
Per capita gross regional domestic product (million KRW)[c]		33.80	37.63
Economic growth rate (%)[d]		5.70	2.60

Source: Estimated by SCM.
[a]CO_2 emission from household consumption (tons/person), average between 2010 and 2018.
[b]Cost of living index measures relative cost of living over regions and measures differences in the price of goods and services, average between 2000 and 2018.
[c]GRDP measures the size of a region's economy, average between 2000 and 2018.
[d]Economic growth rate measures a region's economic growth, average between 2000 and 2018.

TABLE 5 Weight for each control unit.

Country	Synthetic control	Regression weight
Seoul	0.341	−0.81
Busan	0.001	1.56
Daegu	0.002	−0.21
Gwangju	0.000	0.16
Daejun	0.016	0.53
Ulsan	0.055	−0.30
Gangwon	0.000	−0.96
Chungnam	0.000	1.45
Geonbuk	0.000	−1.23
Geonnam	0.000	0.34
Gyungbuk	0.220	−1.19
Gyungnam	0.004	1.32
Jeju	0.361	0.35

Source: Estimated by SCM.

8 There are variables indicating a not-quite resemblance between Gyeonggi and synthetic Gyeonggi. This is because Gyeonggi's consumption is moderate relative to the regions in the control unit, which means there is no linear combination of regions that implies that synthetic Gyeonggi is not perfectly reproduced (Chelwa et al., 2015).

9 The results are from R, and the codes are modified by Becker et al. (2016).

10 The regression weights are not restricted to lie between zero and one, allowing extrapolation. The synthetic control method makes explicit the contribution of each comparison unit to the counterfactual of interest (Abadie et al., 2012).

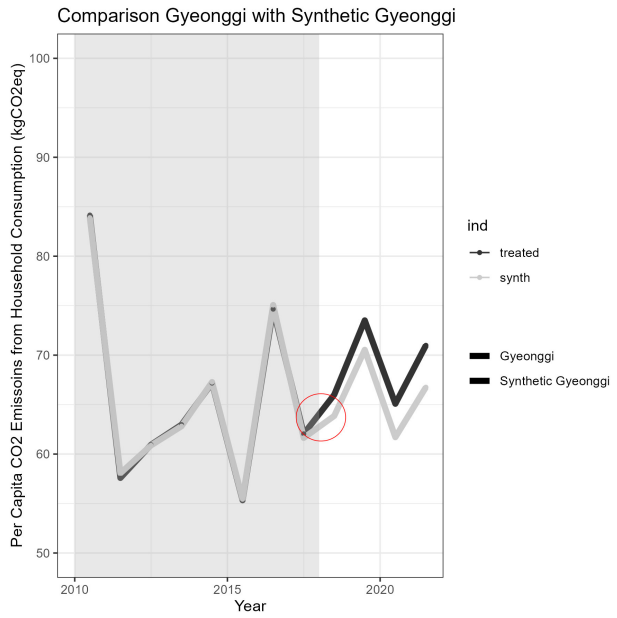

FIGURE 3
CO_2 emissions from household consumption (Gyeonggi and Synthetic Gyeonggi).

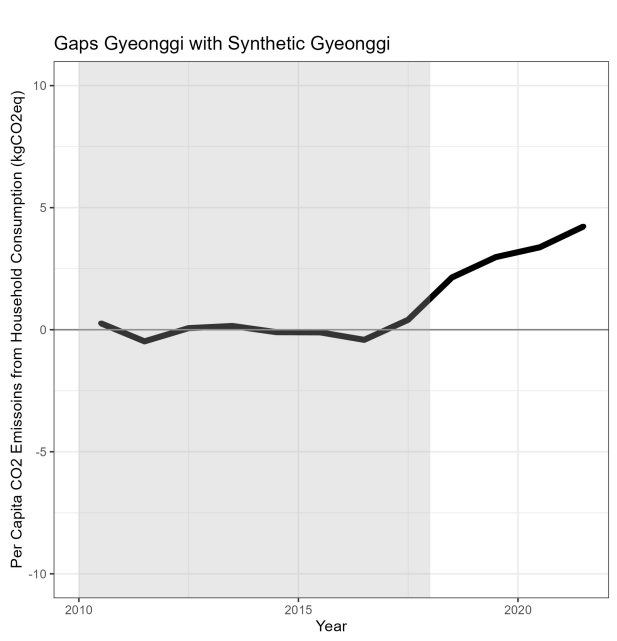

FIGURE 4
Gaps in CO_2 emissions household consumption of Gyeonggi.

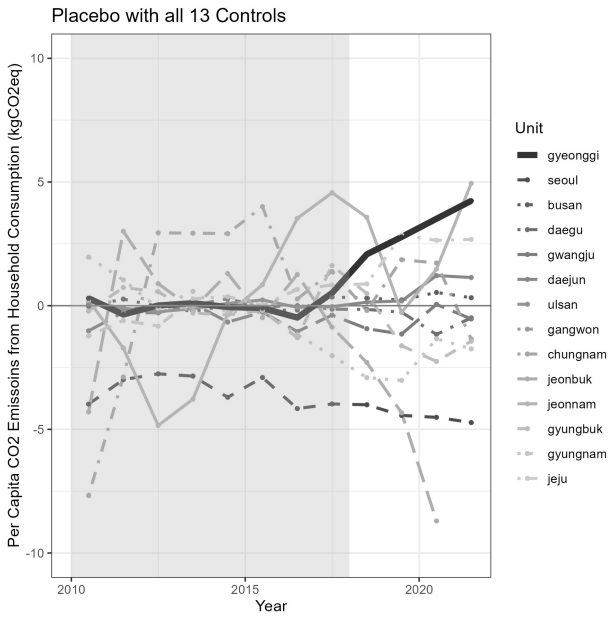

FIGURE 5
Placebo studies (13 control countries).

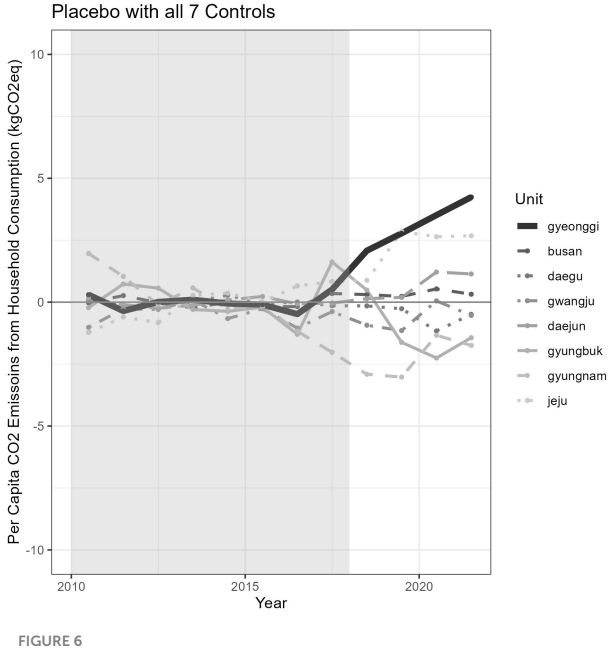

FIGURE 6
Placebo studies (7 control countries).

Placebo studies were performed by applying the SCM to support the statistical significance of ASF. The significance of the event is not established if there are gaps indicating a distinct magnitude between the tested and synthetic tested units (Abadie and Gardeazabal, 2003). For all thirteen municipalities in the control unit, placebo tests were conducted (Figures 5–7). For per capita CO_2 emissions, the study presents a good fit, and other studies present the worst fit if it brings out the distant MSPE. Figure 6 presents the placebo studies, excluding municipalities showing an MSPE 20 times higher than that of the exposed unit (Gyeonggi). Six municipalities, including Seoul, are excluded, and there are still considerable deviations from zero. Figure 7 presents the exclusion of municipalities with 10 times higher MSPE, and one municipality was discarded. After exclusion through placebo studies (Figures 6, 7), there

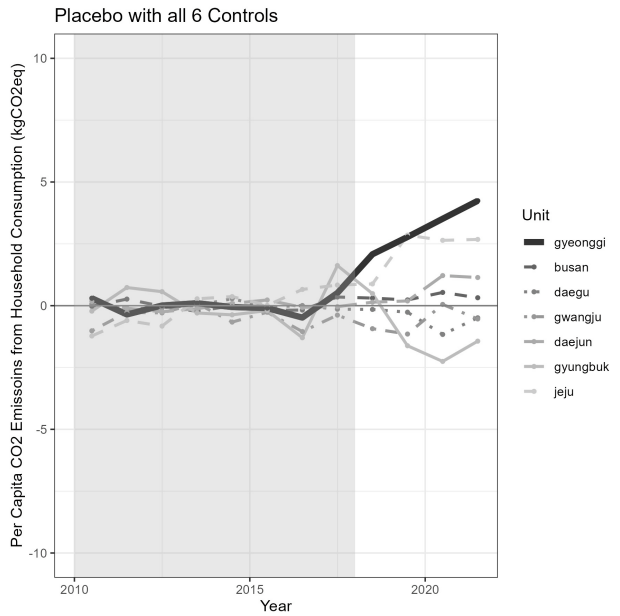

FIGURE 7
Placebo studies (6 control countries).

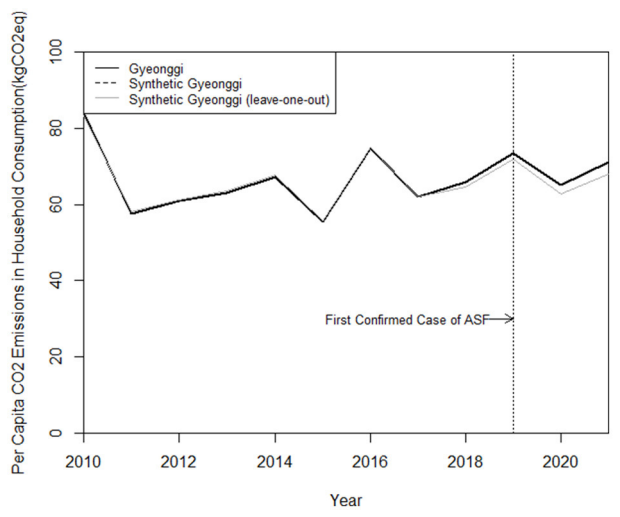

FIGURE 8
Leave-one-out distribution.

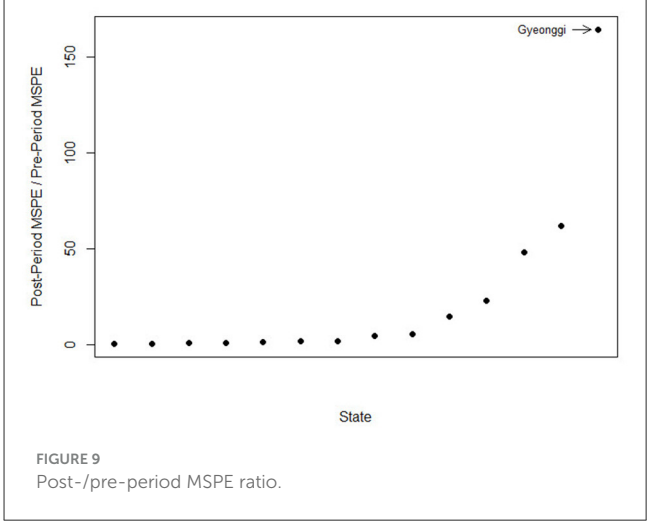

FIGURE 9
Post-/pre-period MSPE ratio.

were six unaffected units left. Thus, this study finds that the random permutation possibility of the event is 1/6 = 0.166, representing an 84% statistical significance for the study.[11]

The leave-one-out in Figure 8 was performed next to estimate the sensitivity of the results, and the test was applied to give positive weights to the municipalities. The analysis used an optimal W^* to minimize the distance between Gyeonggi and synthetic Gyeonggi in the pre-event span (Abadie et al., 2012). The gray lines of synthetic Gyeonggi with one of the six municipalities left out are recreated, and they are close to one another. The gaps between actual Gyeonggi and the six gray lines indicate that the study is robust to the exclusion of any particular municipality (Gong and Rao, 2016). The ratio of the post- to pre-event span MSPE of all 14 municipalities (one treated and 13 control units) is presented in Figure 9.

The MSPE ratio of Gyeonggi stands out, and the post-ASF MSPE is 164.53 times that of the pre-ASF MSPE. The second-highest MSPE ratio is 61.74 in Daejun, indicating that the ratio of Gyeonggi is 266% larger than that of the Daejun. The probability of having such a large ratio as Gyeonggi is 1/13 = 0.076 (7.6%) when any municipality randomly experiences ASF. Table 6 provides the ratio of post- to pre-ASF MSPE and RMSPE (root mean squared prediction error).[12] Empirically, by estimating MSPE/RMSPE, the study can assess goodness of fit. MSPE/RMSPE ratios showing the highest values indicate an impact from ASF. The two exhibitive ratios of Gyeonggi are far from the rest of the municipalities. Therefore, there is a substantial event influencing the per capita CO_2 emissions from household consumption.

4 Conclusion and discussion

Dietary practices can be affected by various factors such as socioeconomic status, demographics, culture, and lifestyle (Czarnocinska et al., 2020; Hassan et al., 2020), and the health of dietary patterns are linked to environmental sustainability (Grosso et al., 2020). Animal-based foods require higher energy use and cause more GHG emissions than plant-based foods (Scarborough

11 The statistical inference presents the statistical significance of the proximity of the synthetic control unit to the treated unit. After excluding ten times higher MSPE than Gyeonggi, Figure 8 provides six unaffected units. The proximity of the synthetic control unit to the treated unit has a probability of 1/6 (0.166) and shows 84% significance of proximity.

12 RMSPE is the rooted value of MEPE.

TABLE 6 MSPE/RMSPE ratio (post- to pre-intervention).

Region	MSPE ratio (post/pre)	RMSPE ratio (post/pre)	Region	MSPE ratio (post/pre)	RMSPE ratio (post/pre)
Gyeonggi	164.53	12.83	Seoul	1.78	1.34
Daejun	61.75	7.86	Gyungnam	1.78	1.34
Daegu	47.85	6.92	Jeonnam	1.42	1.19
Jeonbuk	22.62	4.76	Ulsan	0.93	0.96
Jeju	14.59	3.82	Gwangju	0.55	0.74
Gyungbuk	5.21	2.28	Gangwon	0.39	0.63
Busan	4.22	2.05	Chungnam	0.17	0.42

Source: Estimated by MSCMT.

et al., 2014). This is what motivated this study to determine the relationship between per capita CO_2 emissions and shifts in dietary patterns. In 2019, the swine farms in Gyeonggi in South Korea lost economic animals and consumers had to alter their dietary patterns. When an epizootic disease occurs in a country, the industries related to production and consumption are influenced by the event. Therefore, this study analyzed changes in dietary patterns after the ASF outbreak in South Korea, influencing the per capita CO_2 emissions from household consumption.

To analyze the relationship between dietary patterns and per capita CO_2 emissions, the synthetic control method (SCM) is employed. In particular, the analysis focused on regional municipalities that provide little data. The SCM is widely used to estimate the impact of an event such as terrorism, political action, economic development plan, and natural disasters. There are studies (Aleksandrowicz et al., 2016; Geibel and Freund, 2023) analyzing the changes in dietary patterns and their impact on the emissions of greenhouse gas emissions, but they focus on the production side. However, this study concentrates on the consumption side, and how the consumers react to an external event such as an epizootic disease.

By performing an SCM analysis with the treated (Gyeonggi) and control (13 municipalities) units, the study found that the two trajectory lines (Gyeonggi and synthetic Gyeonggi) were similar before diverging after the introduction of ASF. The gaps also indicate the impact of the shift in dietary patterns on per capita CO_2 emissions from household consumption. These two decisive figures indicate the effects of an epizootic disease, and the critical point of applying the SCM is to establish a synthetic control unit. How the Gyeonggi and synthetic Gyeonggi are similar is provided in the previous section such as per capita CO_2 emissions, cost of living indices, and economic factors.

The SCM is an effective method for analyzing limited samples, but it causes statistical problems for sensitivity and robustness. Therefore, the critical part of performing the analysis is selecting predictors that indicate the similarities between the treated and control units. Placebo studies, a post- to pre-MSPE ratio, and a leave-one-out were performed to support the statistical inferences. The figures present evidence that the trajectory divergences result from shifts in consumer dietary patterns. This study is the first to analyze at the level of municipalities, presenting the relationship between dietary pattern shifts and per capita CO_2 emissions from household consumption after ASF.

The relationship between the shifts in dietary patterns and per capita CO_2 emissions is proven through the evidence supporting the statistical inferences. However, the collection of predictors of municipalities in South Korea for analysis was limited. Climate change is one of the biggest concerns this planet has, and it affects the living. Upon analyzing the relationship between the change in dietary patterns and per capita CO_2 emissions, the outcomes of this study are meaningful. When an unexpected epizootic disease occurs in a country, the authority tries to recover the losses of farms and stabilize a disequilibrium in consumption. By building a synthetic control unit, policymakers, farmers, and even consumers can expect how much an epizootic disease causes damage.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Korean Statistical Information Service.

Author contributions

SE: Writing – original draft, Writing – review & editing.

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Conflict of interest

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