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Macroeconomic impact of foot-and-mouth disease vaccination strategies for an outbreak in the Midwestern United States: A computable general equilibrium

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Abstract

The impacts of alternative responses to a hypothetical foot-and-mouth disease (FMD) outbreak occurring in the Midwestern United States are estimated using the Regional Economic Modelling Incorporated Policy Insight + (REMI) computable general equilibrium model, with particular attention paid to the employment impact estimates. The impact on employment and GDP is estimated using forecasts of a 10-year period with disease outbreak duration up to 2 years. Fifteen different vaccination protocols are compared to a disease control protocol that relies on animal depopulation with no vaccination. Results show that over the 10-year study period, the strictly depopulation strategy that made no use of vaccination results in approximately 677,000 jobs lost with $47 billion GDP loss. Based on the analysis conducted, losses can be reduced through protocols that utilize vaccination strategies. Through a vaccinate-to-live strategy with the highest vaccination capacity and largest vaccination zone, savings can be as many as 509,000 jobs in comparison to the strategy that relies strictly on slaughter with no use of vaccination. By including detailed job losses by occupation, this study highlights the downstream employment effects and shows that job losses resulting from an FMD outbreak can go far beyond the farm sector impacts that have been reported in earlier studies. Understanding the impacts on employment by sector provides more actionable information than producer and consumer surplus estimates frequently reported in economic impact studies.

KEYWORDS
computable general equilibrium (CGE), direct impacts, economic model, foot-and-mouth disease (FMD), secondary impacts, vaccination, vaccination model

1 | INTRODUCTION

Foot-and-mouth disease (FMD) is considered a low-mortality disease, but the resultant drop in productivity and the highly contagious nature of the virus make it one of the most economically damaging livestock diseases. Although an outbreak of the disease has not occurred in the U.S. since 1929, the turn of the millennium was marked by a number of FMD outbreaks in Europe, Asia, and Africa. In 1999 an outbreak occurred in Taiwan, followed in 2000 by outbreaks in South Africa, the Republic of Korea, and Japan. An outbreak in the United Kingdom in 2001 spread, within a month, to Ireland, France, and the Netherlands (Knowles & Samuel, 2003). These outbreaks highlighted the need for proactive consideration of the possibility of an outbreak in the U.S., not just amongst veterinarians and epidemiologists, but also among economists.

The economic concern is largely motivated by the scope of U.S. animal agriculture, which dwarfs those of other countries that have dealt with outbreaks. In 2014, cash receipts from U.S. livestock were

$107.7 billion. A single state in the U.S. may have more FMD-susceptible animals than any of the countries mentioned above. For example, the beginning inventories of cattle in the Republic of Korea were 3.087 million in 2006. There was twice this number, 6.25 million head, just in Kansas (National Agricultural Statistics Service, 2016; and Ban, 2017). Thus, an FMD outbreak in the U.S. could impose heavy losses on the economy. Providing estimates of the potential economic impact has been a research focus of numerous studies.

The estimates of economic impacts of FMD vary depending on the assumptions invoked about the size of the herd, location of the outbreak modelled, and the timing of detection. Ekboir (1999) used an input-output model to estimate the economic impact of a hypothetical FMD outbreak in California. As a fore-runner to many of the papers that have followed, he used epidemiological modelling to estimate disease spread based on hypothetical introduction sites and then estimated direct impacts and modelled the induced effects. His total economic impacts ranged from $6.7 billion to $13.5 billion, depending on the outbreak scenario. Following suit, Elbakidze, Highfield, Ward, McCarl, and Norby (2009) evaluated an outbreak scenario located in the Panhandle of Texas and found $1 billion in economic losses. Paarlberg, Lee, and Seitzinger (2002) estimated the potential revenue impact of a hypothetical FMD outbreak in the U.S. that was similar to the one in U.K. in 2001. Their model includes removal of animals and an export ban. Consumer fear and removal of infected animals could cause an estimated decrease of $14 billion in U.S. farm income. Pendell (2007) found if the outbreak was localized in one cow/calf herd, the economic impacts were an estimated $35 million. However, if the outbreak occurred in five large feedlots, typical of a hypothetical agriterrorist attack, the impact reached $1 billion. Lee, Park, Gordon, Moore, and Richardson (2011) also imagined an outbreak characterized by agriterrorism. They used an outbreak scenario pulled from Ekboir (1999), but instead of limiting their analysis to the California economy as Ekboir had done, they expanded the economic analysis to the rest of the U.S., continuing to use a regional Input-Output model (I-O model). Changing the scope of the model raised the economic impact estimate to between $23 billion and $34 billion for the U.S. Carpenter, O'Brien, Hagerman, and McCarl (2011) simulated an FMD outbreak from a dairy with a herd of over 2,000 cows in California and found a median economic impact in national agriculture welfare losses of $2.3 to $69 billion, if detection was delayed for 7–22 days.

There are a number of advances in vaccine technology that also may shift the calculus of how to best respond to an FMD outbreak. Vaccine technology being investigated allows the distinction between vaccinated animals and infected animals, potentially mitigating some of the trade restrictions associated with using a vaccination response to outbreaks. Empty capsid vaccines, DNA vaccines, recombinant protein vaccines, and peptid vaccines are advances that allow an alternate to the risks associated with using the currently available inactivated virus vaccines (Smith, Bennett, Grubman, & Bundy, 2014). Since trade-related issues are one of the major drivers of economic impacts from an FMD outbreak, stamping-out approaches have been favoured because they are assumed to allow quicker return to the normalized trade that is possible with a "FMD-free without vaccination" designation. However, even without relying on advances in vaccine technology, several papers (Parent, Miller, & Hullinger, 2011; Burrell & Mangen, 2001; Rich & Winer-Nelson, 2007) note that if stamping-out cannot contain the disease, emergency vaccination may be justified. These papers argue that the benefits of more effectively arresting the spread may justify the increased time before a return to normalized trade. Studies evaluating the outbreaks in the Netherlands and in Japan considered emergency vaccination an effective tool for limiting the outbreak size (Pluimers, Akkerman, Van Der Wal, Dekker, & Bianchi, 2002; Muroga et al., 2012). Alternatively, Hagerman, McCarl, Carpenter, Ward, and O'Brien (2012) used two simulations, one in California and one in the Texas Panhandle. For California, they found no statistically significant difference between culling rates and duration of outbreak resulting from the use of vaccination, unless the vaccination zone was increased to 20 km. The economic welfare losses, which included losses to producer and consumer surpluses, transfer payments, and net welfare effects, were higher in the scenarios that utilized vaccination for the Californian outbreak. In their Texas scenario, results showed that vaccination decreased outbreak duration by 2 days, but still found lower maximum losses under no vaccination. However, despite the study's findings against the use of vaccine, these findings are in direct opposition to other research on the benefits of using vaccine (Schroeder, Pendell, Sanderson, & McReynolds, 2015; Pluimers et al., 2002; Muroga et al., 2012).

Schroeder et al. (2015) considered an outbreak that occurred in the Midwestern U.S. They move the economic discussion a step beyond quantifying economic costs for hypothetical outbreaks and add a level of decision support for disease response policy by comparing the economic impacts of different outbreak strategies. This helps to develop the economic research to complement advancements that have occurred in the FMD epidemiological and vaccine research. They used a partial equilibrium framework and estimated producer and consumer costs approaching $188 billion, with government costs likely to exceed $11 billion.

Economic impact of an FMD outbreak can include GDP loss in billions of dollars, job loss, and impact on trade. In this paper, we focus especially on the impact on employment, which is not examined in previous literature. This paper builds on the work by Schroeder et al. (2015) and estimates the impacts of a hypothetical FMD output in terms of job loss. Instead of a partial equilibrium model used in Schroeder et al. (2015), we adopt a general equilibrium model. The employment effects of the modelled FMD outbreak, and the distance they reach beyond the farm sector, provide additional information for policy makers charged with shaping U.S. disease responses.

2 | METHODS

Using the North American Animal Disease Spread Model (NAADSM Development Team, 2013), Schroeder et al. (2015) simulated an outbreak occurring in the Midwest and impacting eight states, including Kansas, Nebraska, Colorado, South Dakota, Wyoming, northern Oklahoma, Texas Panhandle, and northern New Mexico. The model is a herd-based, state transition model that estimates the spread of the hypothetical outbreak under different response protocols. This paper uses the NAADSM simulation results in Schroeder et al. (2015) as inputs in a computable general equilibrium (CGE) model to estimate the annual impact on employment.

The partial equilibrium model used in the source paper allows policy makers to consider the different vaccination options in the context of the agricultural industry. In a CGE model, the economic impact considered is not confined to the agricultural industries that are directly affected by the outbreak. Economic impacts on industries that are indirectly affected, such as those providing supportive services to agriculture, are also considered. By illustrating the impact to downstream industries linked to the livestock sector, including detailed job losses by occupation, policy makers can target management policies that minimize the effects to potentially impacted industries. Providing this measurement allows policy makers outside the agricultural industry to evaluate the effects of different FMD responses on both the general economy and within particular employment sectors of the full economy.

The specific CGE model used is REMI Policy Insight + (REMI is the company name from acronym for Regional Economic Models, Inc.). The REMI model is more complex than input-output models. It links an input-output model to a dynamic econometric model, allowing for the estimation of time path of economic impacts from an exogenous shock (Rickman & Schwer, 1995).

The FMD scenario and response parameters used here and in Schroeder et al. (2015) are summarized in Table 1. The vaccination protocols included in the underlying analysis include a no vaccination (NOVAC) protocol and two distinct vaccination strategies, Vaccinate-To-Live (V2L) and Vaccinate-To-Die (V2D).[1] The NOVAC protocol, referred to by USDA as "stamping-out," relies on animal slaughter without the use of FMD vaccine. The goal in this approach is to destroy all infected and susceptible animals within 24 hours of detection. The NOVAC, or stamping-out, strategy also includes destroying infected carcasses and cleaning the facilities. These costs were estimated by Schroeder et al. (2015) and included in the analysis here. The second strategy, V2D, is also known as suppressive vaccination. Under this approach, a protective buffer is established around an outbreak location. Any potentially infected animals within the buffer are vaccinated but will be destroyed as soon as circumstances allow. The third type of strategy, the V2L approach, also establishes a buffer zone within which all susceptible animals will be vaccinated but does not require premature slaughter. All vaccinated animals are instead allowed to enter the food chain normally.

The other parameters used in the simulation include the vaccination capacity, trigger size, and the size of the vaccination zone. Vaccine capacity is based on the ability to vaccinate herds by the 22nd and 40th days after the initial detection of the disease outbreak, with those days serving as a measuring point of the capacity to

TABLE 1 FMD scenario and response parameters analysed

Scenario Name[a]	Vaccination Strategy[b]	Daily Herd Vaccination Capacity[c] (Day 22, Day 40)	Initial # of Herds Infected (vaccine trigger)[d]	Vaccination Zone[e] in km
NoVac	Slaughter without use of vaccine			
V2D/Feedlot/Fast/10 km	V2D	1, 3 (feedlots)	10 (fast adoption)	10
V2D/Feedlot/Fast/50 km				50
V2D/Low/Fast/10 km		5, 10 (low capacity)	10 (fast adoption)	10
V2D/Low/Fast/50 km				50
V2D/Low/Slow/10 km			100 (slow adoption)	10
V2D/Low/Slow/50 km				50
V2D/High/Fast/10 km		50, 80 (high capacity)	10 (fast adoption)	10
V2D/High/Fast/50 km				50
V2L/Low/Fast/10 km	V2L	5, 10 (low capacity)	10 (fast adoption)	10
V2L/Low/Fast/50 km				50
V2L/Low/Slow/10 km			100 (slow adoption)	10
V2L/Low/Slow/50 km				50
V2L/High/Fast/10 km		50, 80 (high capacity)	10 (fast adoption)	10
V2L/High/Fast/50 km				50

[a]Scenario name: The scenarios are unchanged from Schroeder et al. (2015), but the naming convention is simplified for ease of discussion. The final scenario, V2L/High/Fast/50 km, is also referred to as V2LMax, also in the interest of simplicity. This is the scenario with the highest level of vaccination capacity. [b]Vaccination Strategy. The three broad categories are no vaccination, or stamping-out, or "Vaccinate-to-Live" or "Vaccinate-to-Die." [c]Daily Herd Vaccination Capacity. In Schroeder et al. (2015), vaccination capacity was described using the number of herds that could be vaccinated at the 22nd and 40th days of an outbreak. The numbers shown in the top line of each cell are directly from the Schroeder et al. (2015) parameters, here they are simplified to either feedlot, low or high capacity. [d]Initial Number of Herds Infected. This refers to the amount of spread prior to adopting vaccination as part of response. Schroeder et al. (2015) modelled this as either 10 herds infected (fast adoption) or 100 herds infected (slow adoption). [e]Vaccination Zone. The diameter, in kilometres, of the vaccination zone around infected animals.

administer vaccine. Schroeder et al. (2015) set the 22nd day capacity at five herds (low capacity), 50 herds (high capacity), or one large feedlot (feedlot scenario). On the 40th day, this was set at 10 herds (low capacity), 80 herds (high capacity), or three large feedlots (feedlot scenario). The main difference between the low and high capacity depends on whether or not producers will be allowed to administer vaccinations, which increases the capacity to vaccinate. If USDA personnel are required to administer or supervise vaccinations, it reduces the vaccination capacity.[2] The vaccination trigger describes the initial number of herds infected before the vaccination strategy is implemented. This was set at either 10 or 100 herds. The vaccination zone is the size of the buffer to vaccinate herds around the infected herds and was set at either 10 or 50 km (Schroeder et al., 2015).

For example, the first line in Table 1 indicates a scenario where no vaccination was used. The second line in the table describes a scenario where the outbreak occurred in a feedlot and animals were vaccinated to die. It indicates that vaccination stores and the vaccination protocols were assumed to be sufficient to vaccinate one feedlot by day 22 of the outbreak and five feedlots by day 40 of the outbreak. In this scenario, there were 10 herds infected before FMD vaccination began and all susceptible farm animals within a 10-km zone were targeted for vaccination.

Data used in this study include the number of animals culled, vaccinated, and the duration of the total epidemic sourced from Schroeder et al. (2015), which are entered as exogenous shocks in a CGE model. The CGE model is set to forecast a period of 10 years postoutbreak. The period simulated is from 2014 through 2024. A baseline scenario was created by forecasting normal economic growth for the period of 2014–2024 without any exogenous shocks. All of the scenarios analysed are compared against this baseline scenario. For example, the job losses and economic impacts estimated from the NOVAC scenario are calculated as the difference between the forecast results from the NOVAC scenario and the baseline scenario that did not include exogenous shocks from a hypothetical FMD outbreak.

In all modelling decisions, choices were made to assure that the results presented here are lower bound estimates for the economic impact. The amount of livestock industry output estimated by Schroeder et al. (2015) as affected by the hypothetical FMD outbreak was entered as shocks in the corresponding sectors of REMI, which are based on the North American Industry Classification System (NAICS), with some consolidation of categories. Impacts in beef cattle were entered in the *beef cattle ranching and farming* in REMI, dairy costs were entered in *dairy cattle and milk production* in REMI, and sheep and swine impacts from Schroeder et al. (2015) were entered in the *animal production, except cattle, poultry, and eggs* category of REMI.[3] The detailed values entered for each sector under each vaccination scenario are given in Table B.1 in Appendix S1.[4] While disease outbreak durations modelled in the source study are quarterly based, the CGE model used only allows for estimates on an annual basis. In splitting the impact between years, 80% of the impact is assumed to occur within the first and 20% in the second year if the duration lasts more than 1 year.[5] For robustness check, the model was also evaluated with an alternative scenario where only 60% of the outbreak occurred in the first year and the remaining 40% in the second year. These results are included in the Appendix S3. A 5% drop in beef output in the third year is assumed to occur due to prolonged effects. For durations shorter than a year, all losses are assumed to occur in the first year with a 5% drop in beef demand in the second year.

One assumption of the approach is static herd populations. Zhao, Wahl, and Marsh (2006) compared a model that assumed a static beef population with one that considers a "stamping-out" approach on the U.S. beef cattle inventories. They found total welfare losses under the static assumption were lower than the depopulation approach. This suggests that the results obtained under static herd population are likely to be lower bound estimates.

Total government spending related to the outbreak is reported in Schroeder et al. (2015). Here, it was assumed that the governmental response would come either from budgeted emergency funds or from a reallocation of funds away from other ongoing programmes and would not constitute any government borrowing or increased taxation. In the CGE model, it is important to note that if mitigation expenses come from other borrowing or taxation, and thus reduced consumer consumption, the resulted economic impact can be substantially higher than the estimates shown here. The multiplier for government spending is higher, relative to private sector spending. This assumption is consistent with the intention of providing a conservative estimate.

Government mitigation expenses were entered into REMI as a direct impact on affected sectors within the model, not as an increase in government spending. The government costs include five categories: euthanasia was entered as *vet services*, vaccination was entered as *vet services*, disposal costs were entered in the *waste management* category, cleaning and disinfecting expenditures were entered as *services to building and dwellings*, and indemnity payments were entered as *compensation to agriculture*. Since only total government costs are reported in Schroeder et al. (2015), these had to be disaggregated to determine the cost for each category. The government cost for each category per head of species and the total number of depopulated or vaccinated animals are reported in Schroeder et al. (2015). Therefore, the cost for each category of government cost can be calculated as:

$$\text{Cost}_i = \sum_k P_{ik} \times Q_k$$

Here, Cost_i is the total government cost of category i, where i = euthanasia, vaccination, disposal, cleaning and disinfecting, and indemnity; P_{ik} is the cost of category i for species k, and Q_k is the number of species k that are depopulated or vaccinated. More detailed information on the animal impacts used as inputs into the CGE model is provided in Appendix S2. Table B.2 in Appendix S2 shows the cost for each category per head of species. Table B.3 in Appendix S2 shows the number of animals depopulated or vaccinated. The resulting government cost by category is reported in Table B.4 in Appendix S2, columns (1)–(6).[6]

Lastly, changes in consumer surplus estimated by Schroeder et al. (2015) are treated as changes in purchasing power for consumers.[7] There are no sectors that directly correspond to consumer surplus in REMI, but assuming linear demand, the changes in consumer surplus are entered in REMI as the oppositive changes in consumer prices for the *Food and nonalcoholic beverages purchased for off-premises consumption* category. While this is not a perfect equivalence, the change in prices will effectively capture the change in consumer purchasing power.

There are a few caveats that are important to note methodologically in any comparisons between this paper and Schroeder et al. (2015). The source study estimated a quarterly model, while an annual model is used here. For example, outbreak scenarios lasting for two or three quarters in the model used by Schroeder et al. (2015) were both modelled as a 1 year duration in the annual CGE model used here. Since the impact of 1 year of government spending on an outbreak is more stimulative than one quarter of government spending, this may cause some upward distortion of results, especially for outbreaks lasting only one quarter. Because of this, one quarter duration results are not included in this analysis.

Schroeder et al. (2015) modelled the 10th, 50th, and 90th percentiles of outbreaks from the NAADSM output in order to present confidence bands on the economic impacts. In the interest of presenting conservative results, only disease duration at the 50th percentile was used in the study here.

3 | RESULTS

Results are reported in Table 2. While we report the impact on GDP, our focus is on employment impact. Over the 10-year study period, an FMD outbreak response that relies on animal depopulation without the use of vaccine results in approximately 677,000 jobs loss with a $47 billion GDP loss to the U.S. economy.[8] Losses are reduced through various types of vaccination strategies. The V2D strategies reduce the job loss by 128,000–477,000 compared to the NOVAC scenario. If the vaccination strategy is changed to allow animals to continue through normal production channels, then the losses are further reduced. The V2L strategies save 169,000–509,000 jobs. In every comparable scenario, the V2L strategy results in greater savings than a V2D strategy. In terms of GDP, V2D and V2L can reduce the loss by $9–$35 billion.

As expected, the savings in job loss increase with greater vaccination capacities and larger vaccination zones. The maximum vaccination capacity modelled was the vaccination protocol where 50 herds could be treated by day 22, a vaccination zone of 50 km, and the vaccination response began quickly with only 10 herds infected. Under the naming convention, this is *V2L/High/Fast/50 km*, or *V2D/High/Fast/50 km* respectively. For simplicity of discussion, this is also called V2Lmax or V2Dmax because it is the scenario that assumed the highest level of vaccine capacity. With both the V2Lmax and the V2Dmax strategies, job losses are reduced by 509,000 for V2Lmax strategy and 477,000 for V2Dmax strategy. Under V2Lmax, the total employment loss is 168,000. In comparison to the NOVAC strategy, the V2Lmax strategy can save 509,000 jobs.

Table 3 shows the estimated job losses for the ten industries with the greatest impact. The sum shows the impact of all jobs, including the industries with minimal impacts not included in the top ten listed industries. Regardless of the vaccination strategies, the top ten impacted industries are the same, with minor differences in ranking. In all scenarios, Sales, Construction, and Transportation are the

TABLE 2 Vaccination strategies and impacts on GDP and employment over 10-year study period

Vaccination strategy	GDP loss (in billions)	Employment loss (in thousands)	GDP Savings vs no vaccination (in billions)	Employment Savings vs No Vaccination (in thousands)
NoVac	$47	677	-	-
V2D/Feedlot/Fast/10 km	$35	505	$12	172
V2D/Feedlot/Fast/50 km	$26	377	$21	300
V2D/Low/Fast/10 km	$38	543	$9	134
V2D/Low/Fast/50 km	$19	282	$28	395
V2D/Low/Slow/10 km	$38	549	$9	128
V2D/Low/Slow/50 km	$19	279	$28	398
V2D/High/Fast/10 km	$33	463	$14	214
V2D/High/Fast/50 km	$28	200	$19	477
V2L/Low/Fast/10 km	$35	502	$12	175
V2L/Low/Fast/50 km	$17	244	$30	433
V2L/Low/Slow/10 km	$35	508	$12	169
V2L/Low/Slow/50 km	$17	247	$30	430
V2L/High/Fast/10 km	$30	425	$17	252
V2L/High/Fast/50 km	$12	168	$35	509

This assumes a total disease outbreak duration of 2 years. GDP and employment losses are estimated in comparison to a baseline scenario in which no vaccination was used. The strategies with maximum vaccination capacity are shaded.

TABLE 3 Job Losses by industry sector

Schroeder et al. (2015) scenario name	NoVac NOVAC	V2D/ Feedlot/ Fast/ 10 km D1- 10-10	V2D/ Feedlot/ Fast/ 50 km D1- 10-50	V2D/ Low/ Fast/ 10 km D5- 10-10	V2D/ Low/ Fast/ 50 km D5- 10-50	V2D/ Low/ Slow/ 10 km D5- 100-10	V2D/ Low/ Slow/ 50 km D5- 100-50	V2D/ High/ Fast/ 10 km D50- 10-10	V2D/ High/ Fast/ 50 km D50- 10-50	V2L/ Low/ Fast/ 10 km L5- 10-10	V2L/ Low/ Fast/ 50 km L5-10-50	V2L/ Low/ Slow/ 10 km L5- 100-10	V2L/ Low/ Slow/ 50 km L5- 100-50	V2L/ High/ Fast/ 10 km L50- 10-10	V2L/High/ Fast/50 L50- 10-50
Sales and related office and administrative support occupations	−248	−185	−138	−199	−105	−201	−104	−169	−74.67	−184	−91	−186	−92	−155	−63
Construction and extraction occupations	−75	−55	−42	−60	−31	−60	−31	−52	−22.24	−55	−27	−56	−28	−47	−19
Transportation and material moving occupations	−71	−53	−40	−57	−29	−57	−29	−50	−20.7	−53	−26	−53	−26	−46	−17
Management, business, and financial occupations	−59	−44	−33	−47	−23	−48	−23	−40	−16.19	−44	−20	−44	−21	−37	−14
Production occupations	−59	−44	−33	−47	−24	−47	−24	−41	−17.28	−44	−21	−44	−22	−38	−15
Installation, maintenance, and repair occupations	−39	−29	−22	−31	−16	−31	−16	−27	−11.62	−29	−14	−29	−14	−25	−10
Farming, fishing, and forestry occupations	−26	−18	−14	−19	−6	−19	−6	−23	−3.38	−19	−6	−18	−7	−23	−3
Building and grounds cleaning and maintenance, personal care and service occupations	−21	−16	−12	−18	−10	−18	−10	−13	−7.43	−16	−9	−16	−9	−12	−6
Food preparation and serving-related occupations	−16	−12	−9	−13	−8	−13	−7	−10	−5.61	−12	−6	−12	−6	−9	−5
Healthcare occupations	−15	−12	−9	−13	−8	−13	−7	−9	−5.71	−12	−6	−12	−6	−8	−5
Sum	−677	−505	−377	−543	−282	−549	−279	−463	−200	−502	−244	−508	−247	−425	−168

Job losses in thousands. For outbreaks longer than 1 year in duration, 80% of the impact was assumed to occur in the first year, and 20% in the second year. An alternate 60:40% distribution is available in the Appendix S2.

top three industries that are impacted by the FMD outbreak in terms of job loss. The granularity of the results can be most helpful as policy makers can see how impacts are distributed among various occupations and industries.

Results of the robustness check using the scenario with 60% of outbreak impacts in the first year and 40% of outbreak impacts occurring in the second year further confirm the general findings discussed above, as shown in Appendix S3. For example, the NOVAC strategy results in the highest number of job loss while savings in job loss increase as vaccination capacities and zones increase. Specifically, *V2L/High/Fast/50 km*, and *V2D/High/Fast/50 km* are still the strategies that result in the highest savings in job loss among the vaccinate-to-live and vaccinate-to-die scenarios. Also, the rank of industries impacted by the outbreak is virtually the same as in the 80% and 20% split situation. Sales, Construction, and Transportation are still the top three impacted industries.

Further examination of the impact on employment is shown in Figure 1, which shows a comparison of the two extreme vaccination protocols: NOVAC and V2Lmax, response strategies with the most and least economic impact, respectively on the top eight impacted occupations. The occupation category most heavily impacted is "Sales and related, office and administrative support". In the first year of our simulation, a NOVAC strategy would cost 266,000 jobs in that occupation, relative to the control scenario of no FMD outbreak, while V2Lmax would cost 84,000 jobs relative to the control.

Figure 2 shows the remaining occupations impacted under the NOVAC and V2Lmax strategies. The rankings of the impacted occupational categories are not the same between the two scenarios. Clearly, different strategies affect various industries differently. In particular, *farming, fishing, forestry occupation* (which includes the livestock industry in the REMI CGE model) is the 9th impacted category under NOVAC while under V2Lmax, it is within the bottom five.

4 | DISCUSSION

This paper adds to the current literature that characterizes the potential economic impact of a potential FMD outbreak. It does so by providing employment impact with detailed effects by industry. In addition, the paper provides a further argument for increasing the capacity for vaccination-based responses. Such results offer researchers an opportunity to move policy discussions into potentially unexplored directions.

One interesting finding is that the job losses are concentrated in the Sales and related office and administrative support occupations. Also, job losses in the farming, fishing, and forestry occupations do not even make the top five of impacted industries. Actually, under V2Lmax, this industry is within the bottom five. With a V2L strategy, uninfected but vaccinated animals are still going through the normal production process, thus the farm sector impacts are lower. Under a strict culling strategy, all animals within a certain area are depopulated with much more significant impacts to agricultural industry jobs. In fact, the job losses in the Sales category are ten times higher than the number of jobs lost in the farm sector for many of the response

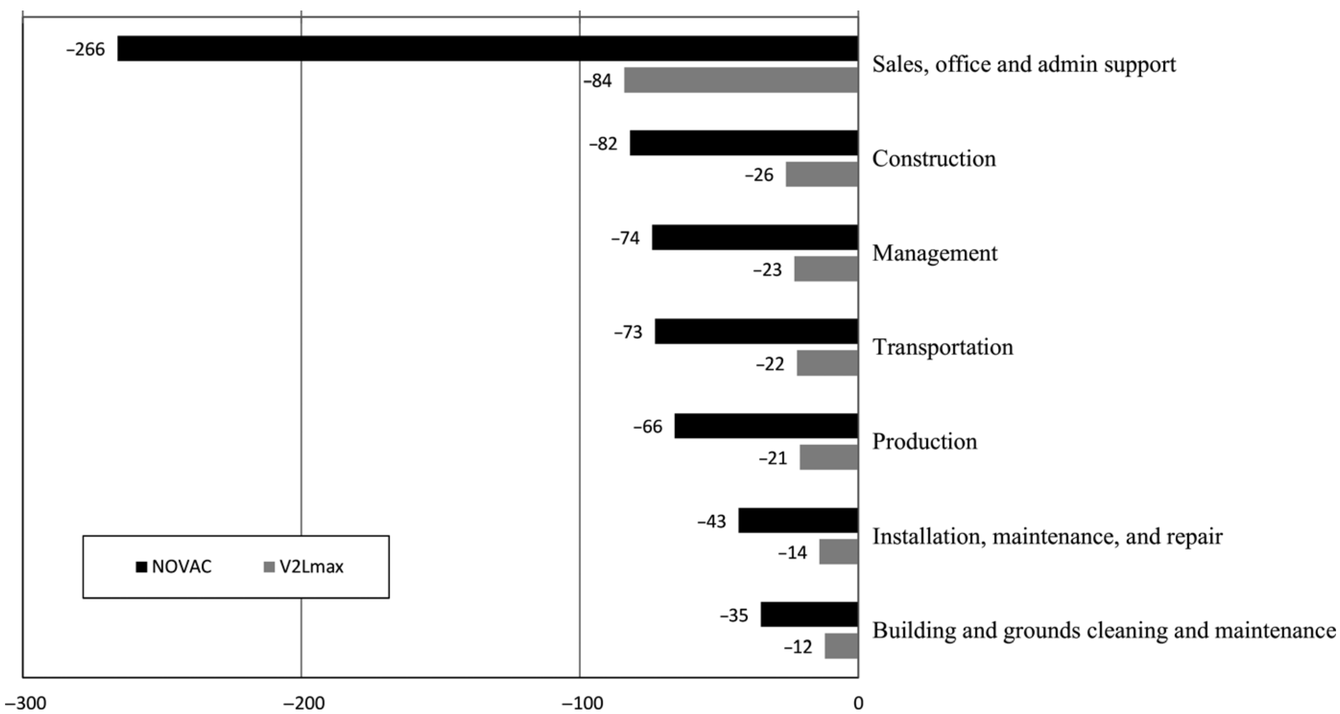

FIGURE 1 Detailed 2014 Occupational Impacts (job losses in thousands) from FMD simulation. The black (top) bars indicate the lost jobs resulting from a NOVAC, or stamping-out approach. The grey bars (bottom) describe the estimated job losses resulting from the V2Lmax strategy, or vaccinate-to-live approach with sufficient capacity to vaccinate 50 herds by day 22, 80 herds by day 40 of the outbreak, a trigger of 10 infected herds and a vaccination buffer zone of 50 km

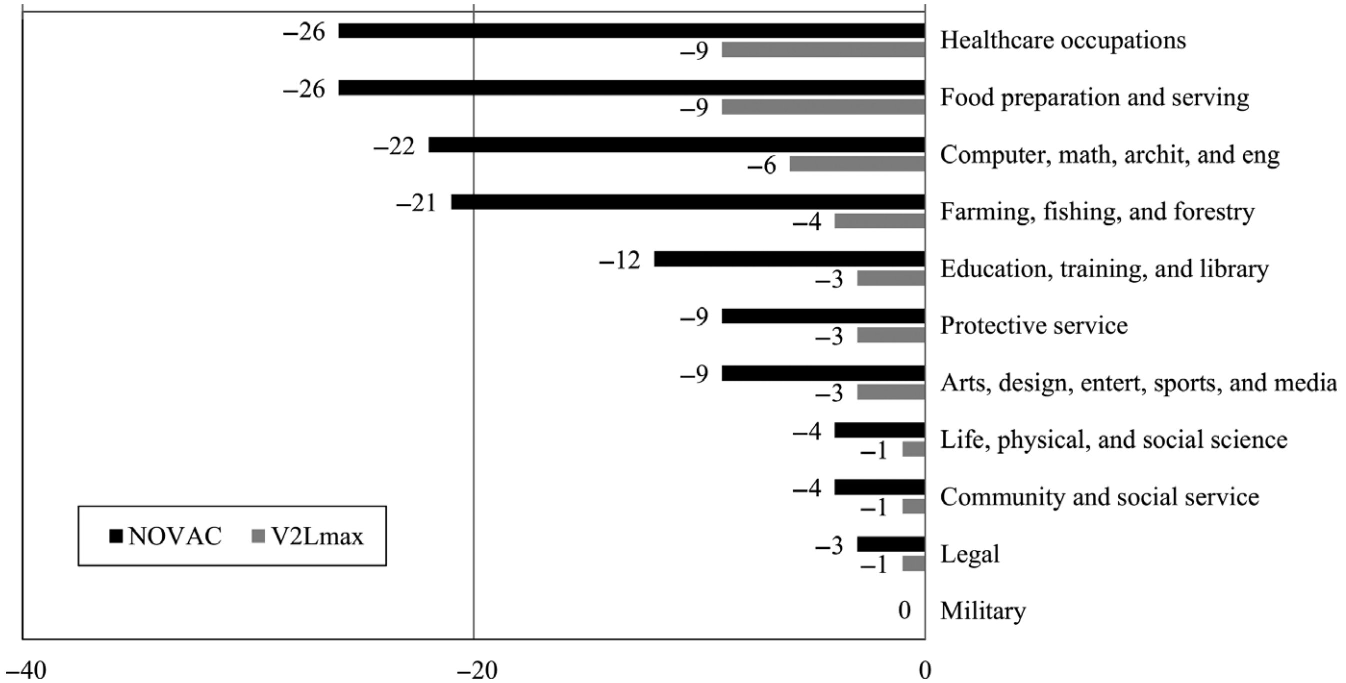

FIGURE 2 Other Impacted Occupations in 2014. Job losses in thousands. The black (top) bars indicate the lost jobs resulting from a NOVAC, or stamping-out approach. The grey bars (bottom) describe the estimated job losses resulting from the V2Lmax strategy

strategy scenarios. Clearly, the threat of a large Midwestern regional outbreak of FMD would be felt far beyond the farm gate.

Regardless of the rankings, it should be noted that various occupations will be impacted by the outbreak, whether or not they are directly or indirectly related to the agricultural industry. The detail that a CGE model provides allows policy researchers to drill down and expose such differences. With that knowledge, policies could then be crafted according to the differential impacts.

The source paper did not include simulations to allow comparison between high vaccination capacity and slow response time. However, to provide a more direct comparison, Table 4 shows the job loss for scenarios with vaccinations zone held to 10 and 50 km. When the vaccination zone is held to 10 km, approximately 6 thousand jobs were saved from the fast adoption of vaccination; regardless of whether vaccinate-to-live or vaccinate-to-die strategies were used. Part of the benefit in jobs might have been attributable to the quick response time. However, when the vaccination zone is increased to 50 km, the

TABLE 4 Total Job Losses under 10 and 50 km vaccination zone scenarios

	V2D/Low	V2L/Low	Difference
At 10 km vaccine zone			
Slow Response	−549,000	−508,000	41,000
Fast Response	−543,000	−502,000	41,000
Difference	6,000	6,000	
At 50 km vaccine zone			
Slow Response	−279,000	−247,000	32,000
Fast Response	−282,000	−244,000	38,000
Difference	−3,000	3,000	

job losses actually increase with a fast adoption of vaccine under vaccinate-to-die but decrease by the same amount under vaccinate-to-live protocol. In terms of minimizing employment impacts, the most important variable appears to be the vaccination zone. Job losses are reduced by half with a 50 km vaccination zone compared to the same protocol with a 10 km vaccination zone.

While it appears that the difference between vaccinate-to-live or vaccinate-to-die is important, care should be taken in interpreting these results. A vaccinate-to-live protocol saves between 32,000 and 41,000 jobs. However, the effect of different vaccination protocol on exports is not included in this model. The main concern about a vaccinate-to-live protocol is the increased time until FMD-free trade status is obtained. While changes in vaccine technology may mitigate some of the export impacts of vaccination, with current technologies and trade agreements, the domestic job savings under vaccinate-to-live could easily be offset or reversed when export implications of vaccinate-to-live are included in modelling.

Results obtained based on the different vaccination responses are of considerable significance and highlight a number of important policy implications. Beyond the question of whether to vaccinate or not is a host of other important policy decisions. These include: what distance is the appropriate vaccination zone; what level of vaccine capacity should be maintained; should producers be allowed to administer FMD vaccination; and what steps should be taken to minimize the detection time. An FMD outbreak could be expected to have caused 677,000 job losses if mitigation measures did not make use of emergency vaccination protocols and were limited to movement control, biosecurity, and animal depopulation. In contrast, various vaccination strategies can be adopted to lower the losses. The V2Lmax results in the most savings in job loss, as shown in Figure 1. Overall, the results support prior findings that increased capacity for vaccination reduces the economic impacts. The results here add to the existing body of research that supports an FMD response that includes vaccination. Homeland Security Presidential Directive 9 orders that a National Veterinary Stockpile (NSV) should be created to contain sufficient amounts of animal vaccine to respond to the most damaging animal diseases (Homeland Security Presidential Directive No. 9, 2004). The findings related to the size of the vaccination zone support, at a minimum, a critical evaluation of the size of the vaccine stockpile relative to the size of a potential outbreak in the U.S. This is especially critical considering the possibility of an outbreak in an area of high livestock concentration.

The findings also support further research into the likely response and detection times. This is reinforcement of the results from Carpenter et al. (2011), which stresses that early detection is critically important. An interesting research question would be to evaluate how different disease responses – NOVAC versus Vaccinate-to-Live – might affect livestock producer attitudes towards self-reporting of disease, thus potentially affecting detection rates.

One advantage of a CGE model lies in the detail of the results provided to policy makers. The impacts resulting from the mitigation shock are diffused more broadly throughout the economy. This provides more actionable information for policy makers interested in the economic impacts beyond the farm gate, given the hypothesized rate of spread, vaccination capacity, and the number of herds infected before detection.

The partial equilibrium approach used by the source study from Schroeder et al. (2015) and the CGE model used here are fundamentally different approaches to estimate the potential economic impact of an FMD outbreak. Different models can be used for different research objectives. The CGE approach is more dynamic with greater sectoral and output detail represented within the model. In the Schroeder et al. (2015) partial equilibrium model, the reduction in consumer surplus does not have any economic substitution; this is captured in the CGE model used here. In the partial equilibrium model, the government spending on carcass removal and facilities disinfection is treated only as a cost. Here, the multiplier that results from that spending is captured and offsets some of the economic loss. This results in different estimates of total economic impact which should not be compared against each other; but should be taken as two complimentary estimates using different methodology to better understand the potential economic impacts of FMD.

5 | CONCLUSION

This paper estimates the impact on employment from an FMD outbreak simulated in Schroeder et al. (2015) using a general equilibrium model. In addition to reporting the economic losses, we focus on the impact of the outbreak on job losses and further disaggregate the losses by industry.

We find that responses that rely solely on animal depopulation result in approximately 677,000 jobs loss with $47 billion GDP loss. Losses are reduced through various types of vaccination strategies and as expected, the savings in job loss increase with greater vaccination capacities and larger vaccination zones. In particular, vaccination strategies with the highest level of vaccine capacity, either vaccinate-to-live or vaccinate-to-die, result in the most savings in GDP and job losses. Among all industries that can be affected by the outbreak, Sales incur the highest job loss, following by construction and transportation under all vaccination scenarios.

Our results add to the discussion on FMD disease and vaccination strategies. While there have been ample studies on the economic impact of FMD, our contribution lies in the impact of FMD on job losses in industries. Such study can provide policy makers another perspective when considering FMD vaccination strategies.

CONFLICT OF INTEREST

The authors received a contract in the prior year to investigate and report the macroeconomic effects of alternative vaccination strategies from Merial Animal Health (now Boehringer Ingelheim). Using the Schroeder et al. (2015) as the basis of the FMD outbreak scenario ensured that the hypothetical FMD outbreak scenario was predetermined and objectively free from any bias in constructing the outbreak scenario.

ENDNOTES

[1] More information on how these strategies will be implemented in the event of an outbreak is available in the Foot-And-Mouth Disease Response Plan, *The Red Book*, prepared by the USDA (2014)

[2] FMD vaccines are restricted and controlled vaccines, and animal health officials do not generally support the idea of producer administration

[3] In REMI, the appropriate section for sheep and swine is in the 'animal production, except cattle, poultry, and eggs' category

[4] Values in the tables are taken from Schroeder et al. (2015) with modifications to fit a CGE annual model

[5] According to Gibbens et al. (2001) (Table 2), among the FMD cases that occurred in the first 5 months in the 2011 Great Britain outbreak, 84% of them occurred within the first 3 months. Although the paper was written before the end of the outbreak, of the 1,849 confirmed cases at the time of writing, 7% occurred in the fourth month, 6% in the fifth month. For the simulation results used here that lasted longer than 1 year, it was assumed that the outbreak would follow a similar rate of progression as what was observed in the 2001 Great Britain outbreak reported by Gibbens et al. (2001). For simplicity, we assumed that 80% of the outbreak would occur in the first year and the remaining 20% in the second year.

[6] Since the inputs into this model are sourced from Schroeder et al. (2015), readers are encouraged to reference the source paper as well. Table B.1 in Appendix S2 in this paper is derived from Schroeder et al. (2015). Table B.2 in Appendix S2 is a reproduction of Table 2 in Schroeder et al. (2015); Table B.3 in Appendix S2 shows the depopulation and vaccination numbers from the median values from the table in Appendix S1 of Schroeder et al. (2015), and Table B.4 in Appendix S2 here is similarly taken from information in Table 4 of Schroeder et al. (2015).

[7] Again, the estimates were sourced from Schroeder et al. (2015), see Table 4, all estimates taken from 50th percentile disease duration.

[8] Our estimated economic impact of $47 billion GDP loss is substantially lower than the estimates in Schroeder et al. (2015), which reports an economic loss of $199 billion. In the Schroeder et al. partial equilibrium model,

the reduction in consumer surplus does not have any economic substitution. In our CGE model, the reduced price of beef or pork is allowed to result in consumer spending in other areas. Additionally, the government spending on carcass removal and facilities disinfection is treated only as a cost in Schroeder et al. (2015). The multiplier that results from that spending is captured, which offsets some of the economic loss.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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