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ORIGINAL ARTICLE

# The economic impacts of a hypothetical foot and mouth disease outbreak in Australia

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**Abstract**

This study uses a multicountry, dynamic, quarterly CGE model, GlobeTERM, to estimate the economic impacts of a hypothetical foot and mouth disease outbreak in Australia. The national welfare losses arising from the outbreak depend mostly on the duration of trade sanctions by importers of Australian animal products. If an outbreak is contained within several months, and trade sanctions are dropped within a year of the outbreak, the net present value of Australia's welfare losses may be around AUS$10 billion. If all importers restore Australian access within a year, other than China–Hong Kong, which delays by 5 years, welfare losses are around AUS$21 billion. In a less likely scenario, in which trade sanctions persist in all trading partners for 5 years after the disease has been eradicated, contrary to international guidelines, welfare losses may exceed AUS$85 billion. Trading partners also suffer welfare losses due to trade sanctions. These losses are large enough to imply, from a global perspective, that a shift towards vaccinate-to-live policies combined with global efforts to eradicate the disease may be cost-effective.

**KEYWORDS**

CGE modelling, foot and mouth disease, trade sanctions, welfare

**JEL CLASSIFICATION**

C68, N50, Q17, R10

## 1 | INTRODUCTION

The objective of this study is to provide computable general equilibrium (CGE) analysis of a hypothetical foot and mouth disease (FMD) outbreak in Australia. In addition to modelling the direct impacts of an outbreak, CGE models, unlike partial equilibrium models, capture the

interaction between trade sanctions and the macroeconomy. A dynamic model with quarterly periodicity has been chosen, as welfare impacts may depend critically on the duration of trade sanctions. The model, GlobeTERM, includes regions of Australia plus those of major importers of Australian animal products. The model is suitable for examining the welfare impacts of an outbreak on Australia and on countries that import Australian livestock products. This enables us to move beyond the national perspective, to consider what actions may be best globally.

Agricultural productivity is vulnerable to disease outbreaks. In countries in which agricultural exports account for a significant share of total exports, routine quarantine measures aim to minimise the probability of animal and plant diseases entering the country. Identified outbreaks may raise alarm in other countries. Indonesia reported an FMD outbreak in May 2022, which has renewed Australian concerns. A media release by the Australian Department of Agriculture, Fisheries and Forestry on 9 May 2022 noted:

> In response to the outbreak in Indonesia, the department has advised livestock industries to be alert, raised awareness at the border, particularly in the north, provided advice to state and territory governments and liaised with Indonesian counterparts.[1]

In part, trade responses to animal disease outbreaks depend on whether an outbreak is a threat only to farm productivity in importing countries, or is also a threat to human health. 'Mad cow' disease (bovine spongiform encephalopathy) is an example of the latter. Australia maintained a ban between 2000 and April 2022 on donations of blood, breast milk and tissues from anyone who lived in the UK between 1980 and 1996 for a period longer than 6 months (Rigby, 2022).

Although international guidelines are in place to encourage the resumption of sales of animal products after a foot and mouth outbreak has been eliminated, individual countries may choose to maintain trade sanctions beyond the duration of guidelines. From the perspective of both the country suffering the outbreak and the importing nation, the duration of sanctions has a marked impact on welfare outcomes.

## 1.1 | The disease

FMD causes blister-like sores in the mouth, tongue and lips, on teats and between hooves on affected animals. The Office International des Epizooties (OIE, representing 162 countries of the World Organisation for Animal Health) reports that is rarely fatal in adult animals but has high mortality among young animals. OIE estimates that FMD circulates in 77% of the global livestock population.[2] In countries where FMD is endemic, it has adverse impacts on productivity. The share of global costs reported by OIE for FMD prevention and control in Africa is around 50% and in Eurasia around 33%. The disease is prevalent in Africa, the Middle East, Asia and parts of South America. OIE describes FMD status of different countries in four categories, namely

- endemic;
- sporadic;
- free with vaccination; and
- free without vaccination.

[1] https://www.agriculture.gov.au/about/news/media-releases/media-statement-foot-and-mouth-disease-detected-indonesia. Accessed 16 October 2023.

[2] https://www.OIE.org/en/disease/foot-and-mouth-disease/. Accessed 17 November 2022.

## 1.2 | Sources of economic losses

The relevance of FMD status is that the responses within countries following an FMD outbreak differ widely. In many countries in which FMD is endemic, the direct losses through diminished productivity account for most of the economic losses. In the event of intervention, the objective is to minimise the direct economic damage from local outbreaks. Many countries in which the disease is endemic may have poor infrastructure and communications. Though there may be high net marginal benefits from countering FMD, institutional structures may be too fragile for effective action. Consequently, there is little response in many endemic regions to disease outbreaks, as noted by McLachlan et al. (2019) when comparing the move towards widespread vaccination in South America with the lack of progress in sub-Saharan Africa.

The source of economic losses differs in countries whose livestock product sales are export-oriented: They aim to maintain OIE free-without-vaccination status, as it is a signal that livestock products imported from these countries entail a minimal chance of disease importation. In the event of trade sanctions arising from FMD outbreaks, economic losses from trade disruption far exceed the direct impacts of disease on livestock productivity or direct losses due to the destruction of infected livestock.

Blancou et al. (2004) noted that vaccination may be viewed as an admission of the presence of FMD within a country. This contributed to the abolition within the European Union of general vaccination of cattle in 1992, increasing the vulnerability of cattle to the disease. The implication is that although it may be optimal for an individual country exporting animal products to be assigned vaccine-free status by the OIE, it may not be optimal from a global perspective. That is, any discouragement of vaccine use may increase the rate of outbreaks across the globe.

Given the concern of trade sanctions, a standard procedure in countries with FMD free-without-vaccination status, when responding to an outbreak, is to vaccinate and destroy all livestock within a defined radius of the outbreak. In such circumstances, OIE restores vaccine-free status after 3 months from the last case, enabling the possibility of resumption of international trade.

Barnett et al. (2015) explore the possibility of OIE restoring vaccine-free status in the event of a vaccinate-to-live strategy. The authors believe that with improved vaccines and sufficient post-outbreak surveillance, this is feasible. They cite the benefits arising from 'ethical concerns with respect to social values, the environment, animal welfare and global food security' (Barnett et al., 2015, p. 367). The improved mental health impacts on farmers and other residents in disease-affected regions would be additional benefits (Mort et al., 2005).

The present study aimed to estimate the contributions to welfare losses of a hypothetical FMD outbreak in Australia. GlobeTERM also captures the impacts of trade sanctions on importing countries. This framework enables us to consider whether an optimal response at a national level may differ from that of a global perspective.

# 2 | MODEL DESCRIPTION

GlobeTERM is a dynamic, multicountry CGE model that includes subnational bottom-up detail. It is a multicountry version of the multiregional single-country TERM model (Horridge et al., 2005) documented in Wittwer (2022). The master database of GlobeTERM contains 74 sectors and 525 regions in 150 national regions. The GlobeTERM data rely heavily on the GTAP database for national detail (Corong et al., 2017), which relies on Comtrade data to estimate international trade matrices (downloadable from https://comtradeplus.un.org).

Subnational detail for Australia relies on various ABS sources.[3] The initial year of the database is 2017. Since the time path of managing outbreaks and of international trade responses is critical in modelled outcomes, the model in this study is run at quarterly intervals.

For project-specific applications, we aggregate GlobeTERM for computational convenience, to retain sectors and regions of interest. The aggregated database includes beef cattle and sheep (CattleSheep); dairy cattle; pigs, poultry and other livestock (Other livestock); other agriculture; fibre crops; fodder; wool; forestry and fishing; mining; beef products; other meat products; other food and beverages; dairy products; other manufactures; utilities; construction; wholesale and retail trade; accommodation and food; transport; communications; business services; public administration and defence; health and education; and ownership of dwellings. That is, the aggregation retains cattle and sheep, other livestock and dairy cattle as separate primary industries, and beef products, other meat products and dairy products as separate downstream sectors.

The regional aggregation includes 11 regions, including 4 Australian regions and 7 countries or country group. The Australian regions are Warrnambool and South West Victoria SA4, the Rest of Victoria, Queensland–Western Australia and the Rest of Australia. Other regions include important destinations for Australian animal products. They are China–Hong Kong, Europe, Japan, Korea, the UK, Indonesia and the United States. This representation enables us to examine country-specific trade sanctions in response to a hypothetical FMD outbreak.

The theory of GlobeTERM is similar to that in national dynamic CGE models such as MONASH (Dixon & Rimmer, 2002). In GlobeTERM, each industry selects inputs of labour, capital and materials to minimise the costs of producing its output. The levels of output are chosen to satisfy demands, and demands reflect prices and incomes. Industries within the model alter investment in line with movements in rates of return on capital. Investment flows are linked formally to capital stocks. Another dynamic feature is that trade balance flows enter the formula for net foreign liabilities. Households follow a linear expenditure system of demand subject to a budget constraint. However, instead of a commodity being produced by a single national industry, in this aggregation of GlobeTERM the commodity is produced by an industry in each region within Australia. Instead of the model being confined to production functions and household and government demands within a single country, GlobeTERM also models the economies of Australia's major export destinations for livestock products. That is, the industries of other countries in the model also produce each commodity. Each of the national economies depicted in the model is connected by trade matrices. Therefore, the impact of trade sanctions on a given national origin within an importing country depends largely on the share of that source in the importing country's use of that commodity. In turn, the impact on Australia's exports of trade sanctions in a particular destination depends on that region's initial share of the Australian market. In structure, GlobeTERM is a multicountry version of TERM, the theory of which is elaborated in Wittwer and Horridge (2018). It is similar to a multicountry model such as GTAP (Corong et al., 2017), but extends the model by including subnational Australian regions.

In GlobeTERM, the degree of inter-regional factor mobility assumed between subnational regions is much higher than the degree of international mobility normally assumed between countries. Labour is imperfectly mobile between subnational regions, but assumed to be immobile between countries. This implies that a weakening of a particular region's labour market within Australia will result in a combination of falling real wages and migration to other subnational regions or rising local unemployment in response (see Wittwer et al., 2005). In early periods, real wages adjust slowly. Over a longer time horizon, capital is also mobile between regions and countries. This is because investment in each subnational region and country within the model is driven by rates of return. The assumption within the model is that foreign borrowing in part

[3]https://www.copsmodels.com/archivep.htm item TPGW0196 includes sources used in preparing Australian regional detail. The main source of subnational data in other countries in GlobeTERM is Eurostat, not relevant to this specific application.

funds additional investments. Therefore, if a particular country's capital stocks increase relative to base, they are likely to be accompanied by an increase in that country's net foreign liabilities relative to base.

GlobeTERM is run in two modes: forecasting and policy. In forecasting mode, the model projects into the future based on trend growth in employment and macroeconomic variables. This produces detailed forecasts for industries and regions. In policy mode, it produces deviations from forecast paths in response to shocks such as, in this study, disruptions due to a disease outbreak, changes in technologies and the demands of trading partners. Though GlobeTERM includes many equations, familiar economic concepts and a small number of assumptions are sufficient to explain key simulation results.

Countries in the Rest of World group (i.e. countries/regions not listed above) are removed from the aggregated database. This means that detail concerning production, usage and trade is retained for the 11 regions in the aggregation. International and subnational trades in this aggregation appear in the 'domestic' slices of trade matrices in the database and in associated equations. Imports from the Rest of World group appear in the 'import' slices of relevant trade matrices and equations. Exports from all regions to the Rest of World are assigned an export column in the use matrix of each region. The model excludes production and usage in the Rest of World and excludes trades in which both origins and destinations involve the Rest of World.

## 3 | SCENARIOS

The modelling is based on the following hypothetical. A foot and mouth outbreak is reported in Victoria. For 72 h, following the state government's guidelines, there is a livestock standstill. This will entail inconvenience and some costs, maybe around $10 million, based on the annual transport margin for Australia in the CGE database of $950 million. The outbreak is identified on a farm in the Warrnambool–South West SA4 region of Victoria. Thereafter, authorities assign a 5-km exclusion zone around the farm of the outbreak. The Warrnambool–South West region includes around 12,000 $km^2$ of grazing land (ABS, 2018). The area of the exclusion zone is 78 $km^2$, which therefore accounts for a small fraction of the region's grazing activity.

In order to eradicate FMD, animals in the exclusion zone are vaccinated to die. Within the affected SA4 region, there are 5.8 million sheep and lambs, 299,000 dairy cattle and 546,000 beef cattle. Using a conversion to DSE (dry sheep equivalent) of 13.5 per head for dairy cattle and 10 for beef cattle, this equals almost 15.3 million DSE (ABS, 2022). Assuming that the exclusion zone consists of 80% grazing and 20% cropping land and that its carrying capacity is equal to the average of the entire region, almost 80,000 DSE ($=0.8\times78/12{,}000\times15.3$ m) are destroyed within the exclusion zone. If the exclusion zone has the same livestock composition as the entire region, around 30,000 sheep, 1550 dairy cattle and 2840 beef cattle would be destroyed, implying vaccination costs of $172,000 at $5 per head. Within GlobeTERM, a shock to capital stocks in the livestock sectors in Warrnambool–South West of minus 0.5% depicts livestock destruction. Bradhurst et al. (2019) provide indicative vaccination costs of around $5 per head. Neither these nor the 3-day livestock standstill costs are included in the modelling. Similarly, the costs of emotional stress and trauma among farmers and the local community are excluded from the analysis. Any estimates could be included as side calculations to welfare impacts computed using Equation (6).

Other supply-side shocks in GlobeTERM include an extraordinary temporary reduction in livestock sector investment in all of Victoria. Although sharply depressed short-term expectations concerning returns from livestock production would reduce endogenous investment relative to base, the assumption is that livestock movement restrictions and trade sanctions imply a temporary collapse in investment beyond that of the default theory of the model. In addition, the downstream processing sectors for beef, other meat and dairy products respond to depressed demand

**TABLE 1** Australian animal product annual exports by destination, initial (AUS$m).

| | Europe (1) | China–HK (2) | Japan (3) | Korea (4) | UK (5) | Indonesia (6) | USA (7) | RoWorld (8) | Total (9) |
|---|---|---|---|---|---|---|---|---|---|
| CattleSheep | 1 | 333 | 160 | 1 | 4 | 1321 | 25 | 1183 | 3028 |
| Other livestock | 51 | 706 | 33 | 8 | 5 | 10 | 57 | 164 | 1034 |
| Wool | 376 | 2057 | 10 | 81 | 10 | 0 | 5 | 329 | 2868 |
| BeefProds | 530 | 1230 | 3120 | 1814 | 207 | 324 | 2196 | 2600 | 12,021 |
| OthMeatPrds | 23 | 27 | 49 | 12 | 1 | 7 | 16 | 255 | 390 |
| DairyProds | 26 | 647 | 688 | 118 | 4 | 168 | 34 | 1080 | 2765 |
| Total | 1008 | 5000 | 4060 | 2033 | 231 | 1829 | 2332 | 5611 | 22,104 |
| % | 4.6 | 22.6 | 18.4 | 9.2 | 1.0 | 8.3 | 10.6 | 25.4 | 100 |

by reducing operating capacity. With GlobeTERM, this is depicted as a temporary reduction in the productivity of downstream processing capital.

On the demand side, two sets of equations depict the impact of trade sanctions. Table 1 shows the annual export sales of animal products from Australia in the initial database. The first seven columns show exports to regions endogenous in this aggregation of GlobeTERM. The model depicts the trade matrix for these regions plus the four subnational regions of Australia.

Equation (1) below shows the substitutability between these seven regions and Australian regions. In percentage change terms, $x_{cod}$ is the quantity of commodity $c$ demanded by destination $d$ from origin $o$; $p_{cod}$, the corresponding price; $x_{cd}$, the overall (origin-composite) demand; and $p_{cd}$, the composite price. The variable $a_{cod}$ is an origin-specific taste variable and $\sigma_c$, a CES parameter.

$$x_{cod} - a_{cod} = x_{cd} - \sigma_c . \left(p_{cod} + a_{cod} - p_{cd}\right) \tag{1}$$

Equation (2) shows $p_{cd}$ as the value-share ($S_{cod}$) weighted sum of effective origin-specific prices.

$$p_{cd} = \sum_o S_{cod} . \left(p_{cod} + a_{cod}\right) \tag{2}$$

To depict trade sanctions, we wish to impose origin-specific demand shifts. The origin-specific taste variable in Equation (1) is not suitable due to interaction terms within the substitution component of the equation. An additional equation, in which the origin-specific preference term $a_{cod}$ becomes endogenous, enables us to ascribe origin-specific shocks directly:

$$t_{cod} = a_{cod} - \sigma_c . \left(a_{cod} - a_{cd}\right) \tag{3}$$

In Equation (3), $t_{cod}$ is an origin-specific twist term.

An export demand equation depicts the Rest of World group (i.e. Column (8) in Table 1), whose economies are exogenous to the model:

$$x_{cn} - f_{cn} = \gamma_c . \left(p_{cn} - \phi\right), \tag{4}$$

where $x_{cn}$ is the export quantity of commodity $c$ originating in nation $n$, $f_{cn}$ is an export demand shifter, $\gamma_c$ is the export demand elasticity (a negative number) and $\phi$ is the nominal exchange rate between regions within the model and the Rest of the World (i.e. the numeraire of the model). We can depict the banning of commodity $c$ from origin $o$ in destination $d$ by ascribing shocks to $t_{cod}$

and trade sanctions in countries outside the model using $f_{cn}$. These shocks approach but do not equal −100%.[4]

Some FMD outbreaks have adverse impacts on tourism, notably in the UK (Blake et al., 2003). The contribution of tourism to the UK economy is much larger than the livestock contribution. Quarantine checks imposed on incoming visitors to the UK are less stringent than those in Australia. In the UK, tourism sites and livestock products are adjacent; there are more tourists, and tourism attractions are distributed over a much smaller area than in Australia. There is little comparison with Australia, where livestock production occurs on dispersed holdings that are usually remote from tourism sites. The relatively large contribution of livestock to the Australian economy has ensured that quarantine measures have remained reasonably stringent, with elevated concerns following outbreaks in near neighbours, as was the case following the 2022 outbreak in Indonesia. The protocols such as a 5-km exclusion zone in the hypothetical Warrnambool–SW Victoria case are likely to have limited and short-lived impacts on tourism.

This study includes three variants of the FMD outbreak. In the first, trade sanctions are imposed in the quarter of the outbreak and lifted fully in the second quarter after the elimination of FMD from Australia. The second variant is identical to the first except for China–Hong Kong, which keeps trade sanctions in place for 5 years after the elimination of the disease in Australia. In the third variant, all importing nations keep trade sanctions in place for 5 years after the elimination of the disease.

## 3.1 | Variant 1: Full resumption of trade in the second quarter after FMD is eliminated

Trade sanctions induce a terms-of-trade decline, namely a fall in the price of exports relative to the price of imports. Unlike a partial equilibrium model, a general equilibrium framework depicts a short-term link between terms of trade and employment. This arises from the assumption that real wages adjust sluggishly and that capital is fixed in the short term, except in those sectors in which utilisation falls due to a collapse in demand. We divide real wages into two terms:

$$w/p_c = (w/p_g) * (p_g/p_c) \tag{5}$$

In Equation (5), $w$ is the nominal wage; $p_c$, the CPI; and $p_g$, the GDP deflator. The marginal product of labour, $w/p_g$, is a function of the capital-to-labour ratio. In the short term, there is limited real wage adjustment as the labour market weakens due to trade sanctions. But the term $p_g/p_c$ falls as the price of exports falls relative to the price of imports, because GDP includes exports but not imports and consumption includes imports but not exports (in period y1q3, $p_g$ is −2.8% and $p_c$ −2.1% relative to base). Therefore, with real wages falling only 0.17% below base in the quarter of the outbreak, the marginal product of labour $w/p_g$ rises and with it the capital-to-labour ratio. Capital in each sector in the short run is either fixed or falls due to temporarily idle capital and destroyed livestock, which implies that employment falls at the regional and national levels (Figures 1 and 2).

Shocks imposed at the sectoral level depress both sales and prices of livestock and downstream products. Although the outbreak is confined to the Warrnambool–SW Vic region, there are also adverse impacts on livestock sectors in the Rest of Australia (Figures 3 and 4). This is a consequence of bans on Australian products imposed fully by importers in the

[4]More specifically, $t_{cod}$ and export demand shocks ($f_{cn}$ in Equation (4)) in the first quarter of the outbreak are −90% and then −70% in the second quarter. Therefore, until lifting of sanctions commences, foreign demands for Australian livestock products are 97% below base.


**FIGURE 1** Warrnambool–SW Vic labour market, variant 1 (per cent deviations from base).

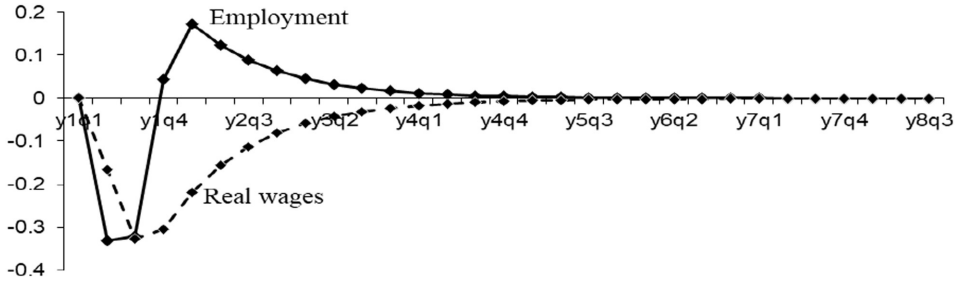


**FIGURE 2** Australian labour market, variant 1 (per cent deviations from base).

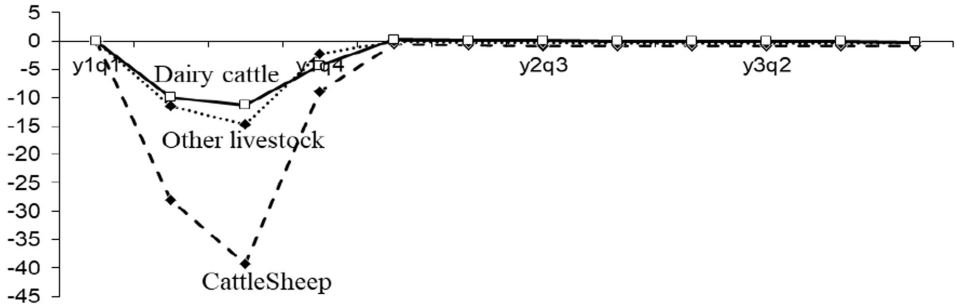


**FIGURE 3** Warrnambool–SW Vic livestock output, variant 1 (per cent deviations from base).

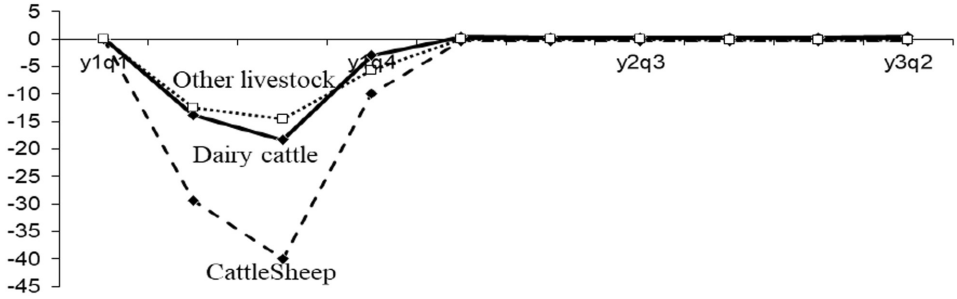


**FIGURE 4** Aust national livestock output, variant 1 (per cent deviations from base).

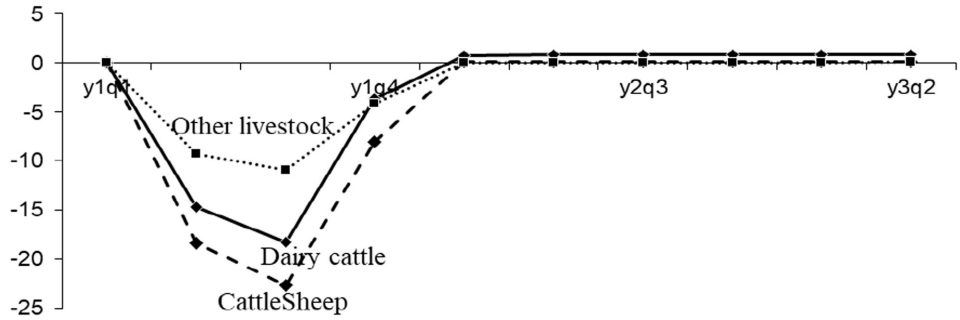


**FIGURE 5** Aust livestock producer prices, variant 1 (per cent deviations from base).

quarter after the detection of the outbreak (y1q3 in the figures that follow). Trade sanctions are extended to include Australian wool. China, for example, imposed import bans on South African wool in 2019 (Jeffrey, 2019) and again in 2022 following FMD outbreaks in the latter (Sgqolana, 2022).

All industries within the model have a production function, $Q=f(K, L, \text{Lnd}, 1/A)$, where $Q$ is the level of output; $K$, capital stocks; $L$, labour; Lnd, the fixed land endowment; and $1/A$, underlying technology. Around 80% of output losses within the Warrnambool–SW Vic's livestock sectors arise from a reduction in labour inputs: Employment in the region in Cattle and sheep production falls to 56% below base in the quarter after the outbreak (i.e. y1q3). The direct impact of destroyed livestock is smaller. The lifting of sanctions commences in the succeeding quarter (y1q4) with completion by y2q1. Both livestock employment and output return to near-base Australian regions in y2q1 (Figures 3 and 4).

Figures 5 and 6 show that producer prices fall sharply with the imposition of trade sanctions and are restored to near base as sanctions are lifted. In downstream sectors, the most severe impacts are on beef products and wool, in which exports account for large shares of total Australian output. Figure 7 shows Australia's downstream output impacts.

Figure 8 shows the impact on income-side GDP in the Warrnambool–South West region. Real GDP falls to around 1.6% below based on the two quarters directly affected by the outbreak. The region's base period real GDP is AUS $6.1 billion annually. Therefore, a fall of 1.6% in regional real GDP is equivalent to AUS $24.4 million (=0.016×0.25×$6100 m) lost income in one quarter. Trade sanctions reduce the value of livestock output and downstream products. In response, food processing sectors throughout Australia reduce their operating capacity temporarily. The decline in effective capital relative to base in Figure 7 arises from a combination of destroyed livestock and reduced food processing operating capacity. Employment in the region falls by 2.2% relative to base (130 full-time equivalent or FTE jobs). Base labour costs in the region are $3.2 billion, giving a contribution to GDP of minus AUS $17.6 million (=0.022×0.25×$3200 m), thereby accounting for around three-quarters of regional output losses in the quarter.

The Warrnambool region in which the outbreak occurs accounts for only 0.4% of national GDP. The region makes only a small contribution to overall national losses in the scenario. At the national level, effective capital falls below base in the two periods of the outbreak due mainly to reduced food processing operating capacity, but the main short-run impact is in the labour market. Employment falls to 0.33% below base (more than 40,000 FTE jobs) in the first period of the outbreak (Figure 9), driven by a trade sanctions-induced fall in the terms of trade (see Figure 13), as the weakened labour market is dominated by employment adjustment. With the recovery in Australia's export markets for animal products, employment rises above base by as much as 0.17% (around 20,000 FTE jobs) in period y2q1. In recovery, labour demand

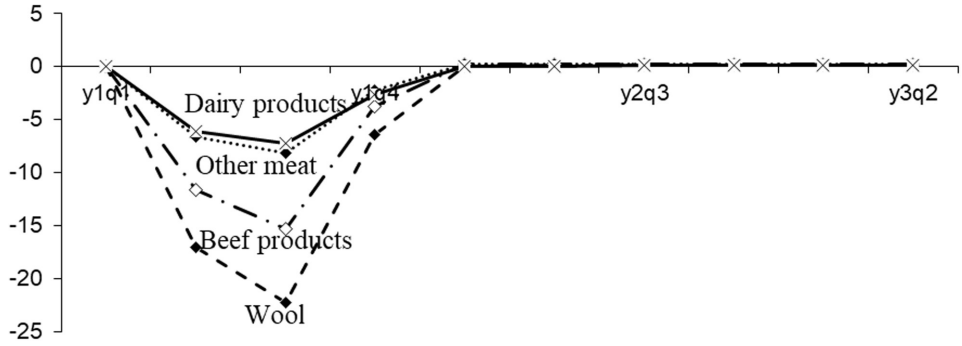


**FIGURE 6** Aust downstream producer prices, variant 1 (per cent deviations from base).

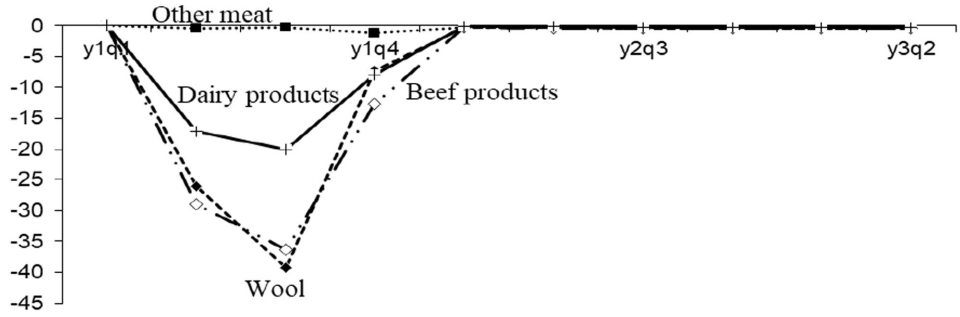


**FIGURE 7** Aust downstream outputs, variant 1 (per cent deviations from base).

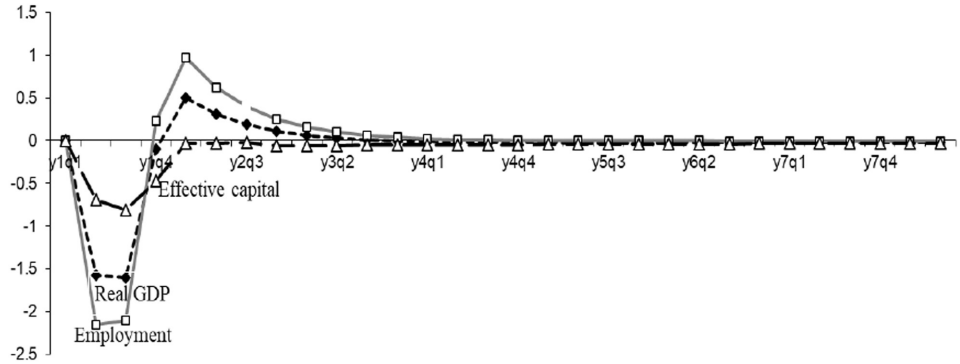


**FIGURE 8** Warrnambool–SW income-side impacts, variant 1 (per cent deviations from base).

exceeds labour supply, which imposes upward pressure on real wages. Real wages flatten when excess labour demand has been choked off (Figure 10).

With trade sanctions removed entirely by the fourth quarter (y2q1) following the outbreak, Australia's terms of trade return to base. The temporary loss in national spending power arising from the terms-of-trade loss forces aggregate household consumption below base (Figure 11). Whereas real GDP falls by only 0.22% below base in period y1q3, aggregate consumption is

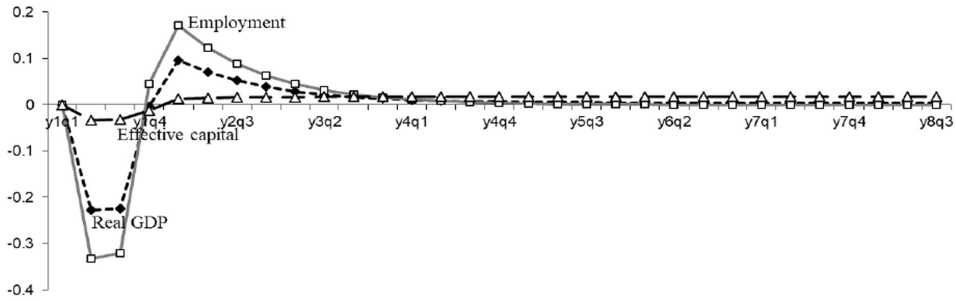


**FIGURE 9** National income-side impacts, variant 1 (per cent deviations from base).

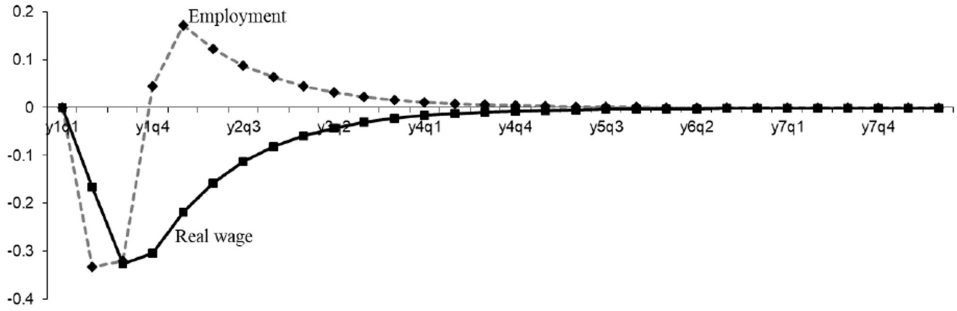


**FIGURE 10** National labour market, variant 1 (per cent deviations from base).

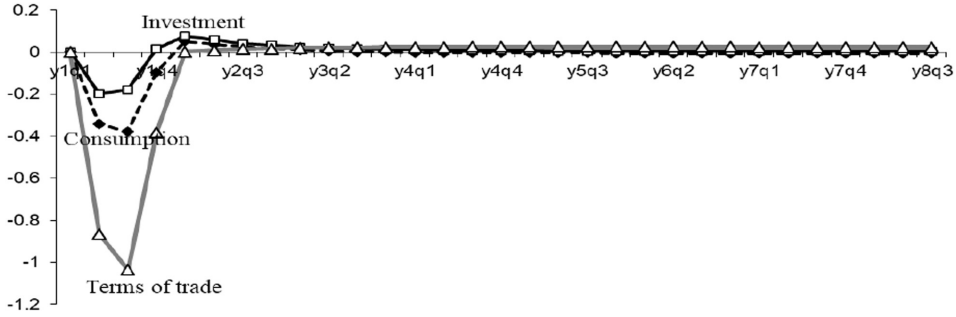


**FIGURE 11** National aggregate consumption, investment and terms of trade impacts, variant 1 (per cent deviations from base).

0.4% below base due to the terms-of-trade decline. In addition, as shown in Table 1, the trade deficit worsens. That is, the impact of FMD on lost spending power is substantially greater than the impact on output, as measured by real GDP.

Household demands follow the standard form:

$$x_{h,c} - q = \varepsilon_c(c - q) + \sum_b \left(\eta_{bc} . p_{h,b}\right) + a_{h,c} - \sum_k \left(S_{h,k} . a_{h,k}\right) \quad (6)$$

In Equation (6), in percentage change terms and dropping the regional subscript, $x_{h,c}$ is the quantity of household consumption of commodity $c$, $q$ the number of households, $p_{h,b}$

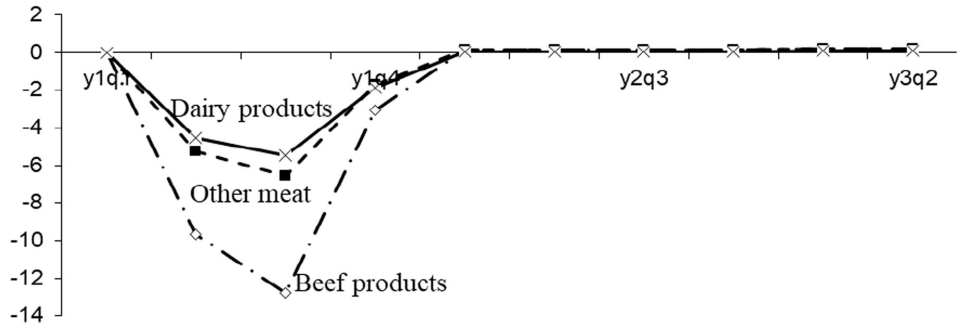


**FIGURE 12** Aust consumer prices, livestock products variant 1 (per cent deviations from base).

the consumer price for commodity $b$, $a_{h,c}$ a preference shifter and $S_{h,k}$ household expenditure shares. The summed preference shifts in the last term ensure that overall preference shifts sum to zero, so as not to violate the budget constraint. The matrix of price elasticities is $\eta_{b,c}$ and $\varepsilon_c$ the expenditure elasticity.

For each product, consumer price decreases are demagnified relative to producer price decreases (comparing Figures 6 and 12). This reflects transport, retail and wholesale margins, which account for significant shares of consumer prices, and change little as producer prices fall.

Figure 11 shows that real aggregate consumption falls to 0.38% below base in Australia in y1q3. In the same period, there is a decline in the CPI in Australia relative to base of 2.1%, so that aggregate nominal consumption falls by almost 2.5%. The expenditure elasticity of beef products, for example, is 0.5 so that the expenditure effect contributes −1.25% to the change in domestic consumption. In y1q3, the consumer price for beef products falls by 13% relative to base. Since consumption increases by 3.1% (Figure 13) relative to base in this period, this infers that the own-price elasticity is around −0.32% (=(3.1 to −1.25)/−13).

Different assumptions concerning household behaviour would alter industry outcomes to a small extent. If beef products are substitutable with other meat, consumption of the former would increase at the expense of the latter, given relative price impacts (Figure 12), and improve slightly the outcome for beef producers during the period of trade sanctions at the expense of nonbeef meat producers. Agriculture Victoria notes:

> FMD is not a food safety concern. It cannot be transmitted to humans through consuming commercially produced meat, milk or dairy products.[5]

If consumers fear that FMD is hazardous to human health, which has been the case for bovine spongiform encephalopathy (BSE),[6] a negative taste shift could be imposed on beef products, making the outcome for Australian producers worse than modelled. Reports of livestock culling may also harm the image of meat sectors and induce a negative taste swing against all meat consumption. Each of these impacts in the short term, at least, would be second-order relative to a ban on imports of beef products from Australia in major destinations, given that more than 40% of domestic production is exported (the database of the model shows exports of AUS$12 billion and output of AUS$29 billion) and that exports temporarily are almost wiped out.

[5]https://agriculture.vic.gov.au/biosecurity/animal-diseases/general-livestock-diseases/foot-and-mouth-disease/foot-and-mouth-disease-frequently-asked-questions#h2-1. Accessed 16 June 2023.

[6]See https://www.foodstandards.gov.au/industry/bse/Pages/default.aspx.

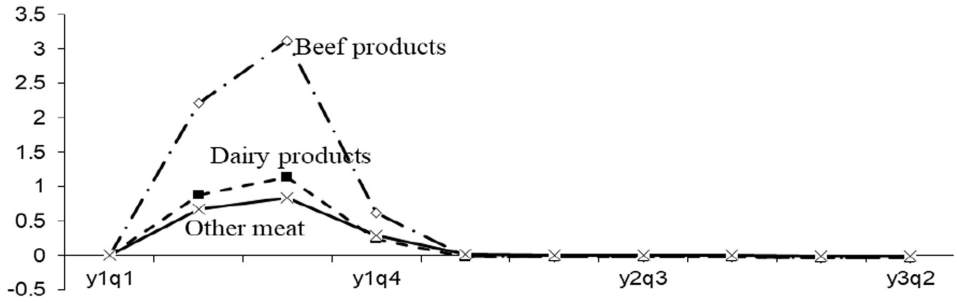


**FIGURE 13** Aust consumption, livestock products variant 1 (per cent deviations from base).

To put into the perspective, the economic impact of increased domestic consumption, annual consumption of beef products, other meat and dairy products in the base period for Australia are AUS $6.2 billion, AUS $2.5 billion and AUS $5.6 billion, respectively. We calculate the increase in consumer surplus as $\mathrm{VAL}\times(-p+(0.5\times-p\times q))$, where VAL is the initial quarterly consumption and $p$ and $q$ the percentage changes (divided by 100) in consumer prices and quantities. The respective increases in consumer surplus in this quarter equal AUS $201 million, AUS $41 million and AUS $77 million, totalling AUS $320 million. This compares with the impacts for y1q3 shown in Table 1 of a direct terms-of-trade loss of AUS $1 billion, and an overall welfare loss of AUS $4.6 billion. Interstate trade sanctions may worsen the national welfare outcome by diminishing the AUS $320 million positive contribution to welfare of lower consumer prices, whereas substitution will, in partial equilibrium terms, transfer some producer surplus losses to other commodities, with little net impact on welfare. The modelling does not account for any delay in the resumption of milk production after the lifting of sanctions, which would also worsen the welfare outcome to some extent.

Recall that Australia's aggregate consumption falls relative to base after the FMD outbreak (Figure 11). The deviation in welfare (dWELF) at the national level is calculated from the CGE modelling as:

$$\mathrm{dWELF} = \sum_{d}\sum_{t}\frac{\mathrm{dCON}_t^d + \mathrm{dGOV}_t^d}{(1+r)^t} - \frac{\mathrm{dNFL}_z}{(1+r)^z} + \frac{\mathrm{dKstock}_z}{(1+r)^z} \tag{7}$$

In Equation (7), dCON and dGOV are the deviations in real aggregate household and government spending (i.e. current consumption) in region $d$ (summed across all Australian regions) and period $t$; dNFL is the deviation in real net foreign liabilities in the final period ($z$) of the simulation; dKstock is the deviation in the real value of the capital stock in the final period ($z$) of the simulation; and $r$ is the discount rate.

Table 2 shows the main components of the welfare impact for the three periods in which there are substantial trade sanctions. Row (1) shows the direct export revenue loss, the terms-of-trade change multiplied by the value of exports. The national welfare loss will be substantially larger than the export revenue losses from the fall in terms of trade, as the balance of trade goes into deficit relative to base with the loss in export revenue. If we were to exogenise the national balance of trade, the terms of trade would worsen further as export products unaffected by trade sanctions would move along down-sloping export demand curves, thereby lowering their export prices. Row (2) shows the modelled change in current consumption (household plus government). Row (3) shows the balance of trade, which feeds into the formula for net foreign liabilities:

$$\mathrm{NFL}_t = (1+i)^* \mathrm{NFL}_{t-1} - \mathrm{delb}_{t-1} \tag{8}$$

**TABLE 2** Simplified contributions to welfare impact, variant 1 (AUS $m).

| Period | y1q2 | y1q3 | y1q4 | y2q1 |
|---|---|---|---|---|
| (1) Direct TofT loss | −845 | −1010 | −357 | 26 |
| (2) Consumption | −1158 | −1303 | −408 | 102 |
| (3) Balance of trade | −2663 | −3312 | −1086 | 51 |
| (4) Welfare = (2) + (3) | −3821 | −4615 | −1494 | 153 |
| (5) Discounted welfare | −3797 | −4558 | −1467 | 149 |

In Equation (8), present period net foreign liabilities $NFL_t$ is linked to the previous period $NFL_{t-1}$ minus the previous period balance of trade surplus ($delb_{t-1}$), where *i* denotes the nominal interest rate.

In Table 2, Row (4), the quarterly contribution to welfare, sums (2) plus (3). Row (5) discounts the welfare contributions back to the period *y1q1*, using an annual discount rate of 2.5%. The sum of the four periods in Row (5) is minus AUS $9.7 billion. This approximates the modelled welfare outcome from Equation (1) over the simulation period, which is minus AUS $10.0 billion. The computed welfare impact includes additional interest payments whereas Row (4) in Table 1 does not. This exercise illustrates the link between welfare losses and the duration of trade sanctions. In a scenario in which either one or all trading partners delay the restoration of imports of Australian animal products, the welfare losses will be larger.

All nations imposing trade sanctions suffer welfare losses, despite the quick resolution. In the case of China–HK, the welfare loss calculated using Equation (7) is AUS $1.8 billion. The welfare losses in other countries modelled separately (i.e. Japan, Korea, Europe, the UK, Indonesia and the United States) sum to AUS $2.4 billion.

## 3.2 | Variant 2: China–Hong Kong delays the resumption of imports for 5 years

In this variant of the FMD outbreak, all importers of Australian animal products resume full trade by the fourth quarter (y2q1) except China–HK. China–HK resumes imports 5 years after the outbreak is eradicated (y5q3), with full trade by the following quarter (y5q4).

At the national level, there are small differences relative to variant 1. In the recovery period y2q1, employment rises slightly less above base (0.14%, Figure 14, relative to 0.17% in variant 1), reflecting a smaller upswing in demand with China–HK's sanctions still in place. Real wages persist slightly below base as long as China–HK's sanctions remain (Figure 15). With the lifting of sanctions by China–HK, there is a small upswing in employment from quarter y6q3, as real wages move slowly towards base.

Figure 16 shows the impact of this variant on the terms of trade, national aggregate consumption and national aggregate investment. As long as China–HK's trade sanctions remain, Australia's terms of trade persist around 0.2% below base. Aggregate consumption and investment recover to be only slightly below base after the lifting of trade sanctions in all countries other than China–HK. However, as shown in Table 3, the balance of trade remains in deficit relative to base with China–HK's sanctions in place.

Table 2 shows identical outcomes as variant 1 for the first two quarters, followed by worse outcomes in the following two quarters in this variant, as China–HK's trade sanctions persist. The net present value of the welfare outcome for this variant is minus AUS $21.3 billion. In this variant, China–HK's welfare loss enlarges to AUS $11.8 billion while the sum of losses in other

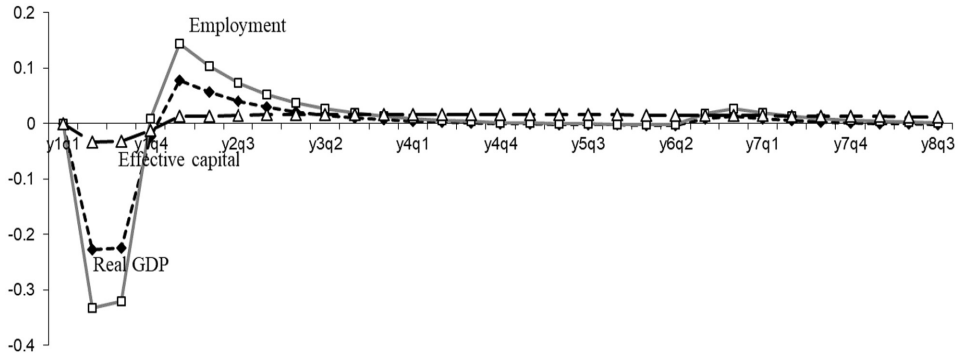


**FIGURE 14** National income-side impacts, variant 2 (per cent deviations from base).

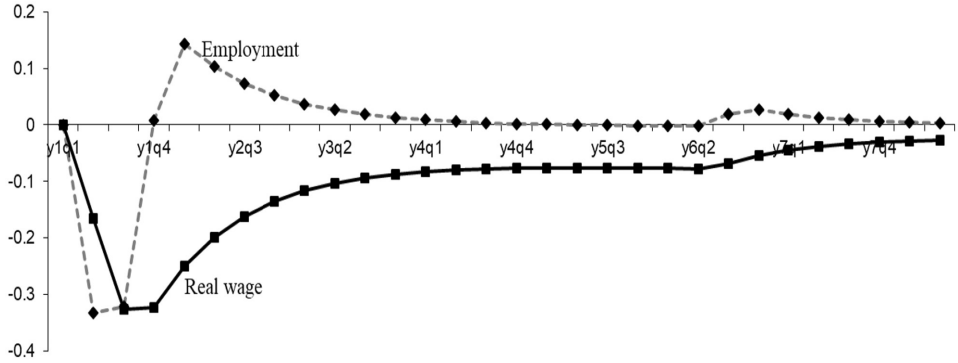


**FIGURE 15** National labour market impacts, variant 2 (per cent deviations from base).

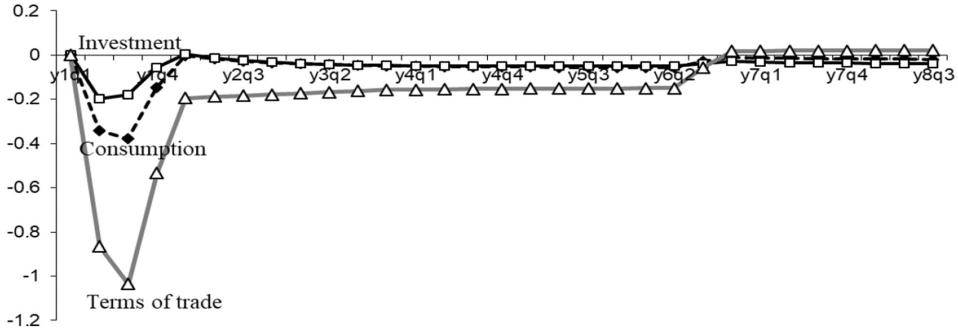


**FIGURE 16** National aggregate consumption, investment and terms of trade impacts, variant 2 (per cent deviations from base).

countries shrinks to \$0.55 billion. That is, other countries have access to relatively cheaper Australian produce as long as China–HK is out of the market.

**TABLE 3** Simplified contributions to welfare impact, variant 2 (AUS $m).

| Period | y1q2 | y1q3 | y1q4 | y2q1 | y2q2 |
|---|---|---|---|---|---|
| (1) Direct TofT loss | −845 | −1010 | −510 | −171 | −165 |
| (2) Consumption | −1158 | −1303 | −569 | −81 | −121 |
| (3) Balance of trade | −2663 | −3312 | −1419 | −334 | −334 |
| (4) Welfare = (2) + (3) | −3821 | −4615 | −1987 | −415 | −455 |
| (5) Discounted welfare | −3797 | −4558 | −1951 | −405 | −440 |


**FIGURE 17** National income-side impacts, variant 3 (per cent deviations from base).

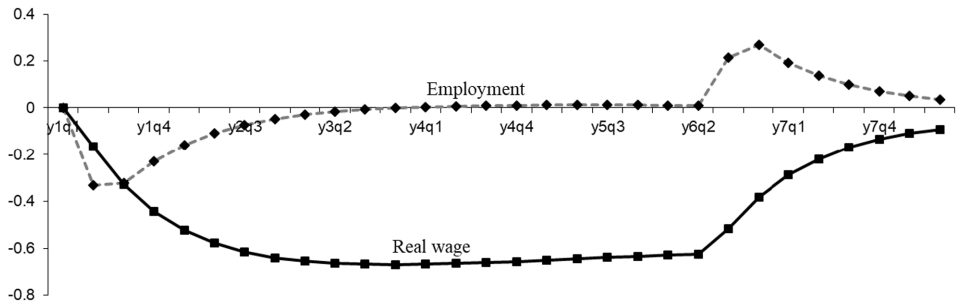


**FIGURE 18** National labour market, variant 3 (per cent deviations from base).

## 3.3 | Variant 3: All importers keep trade sanctions in place for 5 years after FMD eradication

In variant 3, prolonged trade sanctions remain in place for 5 years after FMD eradication, contrary to international guidelines. There is a movement in investment away from livestock production towards other export-oriented activities, such as mining and cropping. Consequently, aggregate national capital rises as output in relatively capital-intensive sectors grows relative to base (Figure 17).

Without an early recovery in the terms of trade, for employment to move back towards base, real wages must adjust downwards, being around 0.6% below base by the time employment adjusts to base levels (Figure 18). Export sectors other than those concerning animal products improve their international competitiveness due to real wages persisting below base. There is a small upsurge in employment and real wages with the eventual lifting of sanctions.

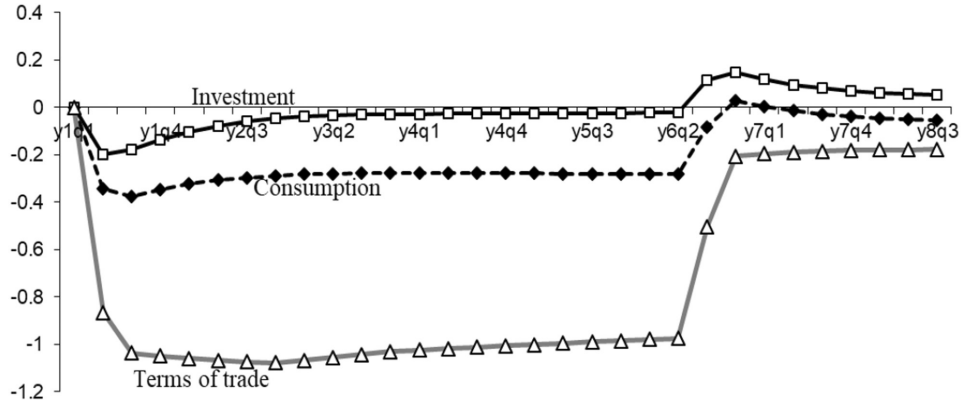


**FIGURE 19** National aggregate consumption, investment and terms of trade impacts, variant 3 (per cent deviations from base).

**TABLE 4** Simplified contributions to welfare impact, variant 3 ($m).

| Period | y1q2 | y1q3 | y1q4 | y2q1 | y2q2 |
|---|---|---|---|---|---|
| (1) Direct TofT loss | −845 | −1010 | −1021 | −1037 | −1050 |
| (2) Consumption | −1158 | −1303 | −1243 | −1136 | −1050 |
| (3) Balance of trade | −2663 | −3312 | −3330 | −3303 | −3277 |
| (4) Welfare = (2) + (3) | −3821 | −4615 | −4573 | −4439 | −4327 |
| (5) Discounted welfare | −3797 | −4558 | −4488 | −4329 | −4194 |

But with the terms of trade persisting below base even with sanctions removed, real wages persist below base.

As export volumes of products other than livestock products increase relative to base, their export prices fall as they move along down-sloping export demand curves. A consequence of this is that when trade sanctions on Australia's animal products are eventually lifted, the terms of trade do not recover fully, at least in the short term, remaining around 0.2% below base (Figure 19). That is, a compositional change in exports relative to base keeps the terms of trade below base.

Without early removal of trade sanctions, welfare losses in Australia accumulate relative to base. Table 4, Row (4) shows that these losses remain in excess of AUS $4 billion per quarter, though later periods will make a slightly smaller contribution to the net present value figure after discounting. A 5-year delay to the restoration of international trade results in a net present value welfare outcome of minus AUS $85 billion.

All countries suffer substantially larger welfare losses than in variant 1. China–HK's welfare loss is AUS $14.3 billion, and the loss in the other six regions sums to AUS $26.4 billion.

## 4 | COMPARISON WITH OTHER STUDIES

Partial equilibrium studies include Garner and Lack (1995) and Tozer and Marsh (2012). These studies exclude interactions between trade sanctions and the macroeconomy. Mahul and Durand (2000) used an input–output model and acknowledged the shortcomings of not using a CGE model. Within GlobeTERM, an early macroeconomic impact of trade sanctions

is a weakened labour market. There is no evidence that importers restrict trade sanctions to the ports or origins closest to the outbreak. Rather, such sanctions are likely to be applied to all products of cloven-hoofed animals originating in the country of the outbreak. Under the assumption of slowly adjusting wages, the harmful impacts of an FMD outbreak spread beyond the region of the outbreak. This implies that multiple outbreaks will not necessarily have many-fold worse outcomes than a single outbreak, at least if the same trade sanctions apply. Once trade sanctions are in place, the real output of GDP outcomes will be several-fold worse than depicted in a partial equilibrium framework. Multiple outbreaks will multiply the direct costs of containment. While these may amount to hundreds of millions of dollars, the economic harm caused by trade sanctions amounts to billions.

Negative terms-of-trade impacts exacerbate output losses, because the spending power arising from a given level of output falls. The most critical driver of welfare outcomes in a CGE framework, at least for a country with highly export-oriented animal products, is the extent and the duration of trade sanctions, not the extent of the initial outbreak. It follows that if there were no trade sanctions in response to an outbreak, outcomes in CGE and partial equilibrium analysis would be closer together.

CGE studies will capture terms-of-trade losses, which are the main contributor to adverse welfare outcomes in hypothetical FMD scenarios in a country with export-oriented animal products. The broad findings of the first variant of the present study align reasonably with the revenue losses reported by Buetre et al. (2013) for a limited outbreak scenario. The third variant of the present study appears to be comparable with the large outbreak scenario reported by Buetre et al. (2013). That study assumed that some markets were closed to Australian produce for up to a decade and also noted that 99% of economic losses arise from revenue losses and 1% from the costs of disease control, consistent with the conclusion here that trade sanctions dominate overall losses.

Boisvert et al. (2012) used multinational GTAP and a single region subnational model to depict an FMD outbreak in the United States in a comparative static setting, while noting that a dynamic, quarterly model would have been helpful. The present application of GlobeTERM combines multinational and subnational detail in a quarterly, dynamic model. US livestock exports account for a much smaller share of domestic production than in Australia. The respective export shares of domestic product for US beef products, other meat products and dairy products are 4.5%, 4% and 1.3% in the GlobeTERM database. The finding of Boisvert et al. (2012) that trade sanctions account for only 8% of US welfare losses reflects these relatively small shares.

One purpose of the present study is to explain the conditionality of welfare losses arising after an outbreak. There is a tendency for government departments and public institutions to report economic losses as a single number without conditionality (see CSIRO, 2023). Given the dominance of lost export revenue relative to disease control costs in overall economic damage, the duration and extent of trade sanctions, rather than the extent of the initial outbreak, dominate losses. There may be a correlation between the extent of an outbreak and the duration of trade sanctions, but is not always so. China's recent sanctions against various Australian products are examples driven by politics rather than other considerations.

The present study also goes further by having a global perspective. Importers of Australian livestock products, as a consequence of trade sanctions, suffer welfare losses. From this, we can infer that an optimal FMD strategy from a global perspective may differ from the optimal strategy of an individual importing nation.

## 5 | DISCUSSION

National terms-of-trade losses arising from trade sanctions far exceed the relatively local direct losses from a small, quickly contained FMD outbreak, given the sales structure of

Australia's livestock products. In the case of an outbreak contained within a small area, vaccination and destruction of affected livestock, though traumatic for locals in an affected region, is equivalent to monetary losses in the tens of millions of dollars. A three-day livestock standstill in an affected state may cost a further $10 million or so. These losses contrast with welfare losses induced by the terms-of-trade decline in the scenarios presented here, which amount to around $4 billion per quarter while trade sanctions remain. Multiple outbreaks across more than one state may magnify direct losses to hundreds of millions of dollars, but trade sanctions cost billions or tens of billions. The benefits of cheaper livestock products for consumers in the affected countries are small relative to losses borne by producers, which are in turn magnified by macroeconomic impacts. Current trading partner responses appear to favour countries with vaccine-free FMD status, in the event of an outbreak, responding with a vaccinate-to-die policy for livestock within a certain radius of the outbreak. This appears as an unsatisfying, second-best response. Barnett et al. (2015) explore the possibility, in part in the context of growing animal welfare concerns, of moving to vaccinate-to-live.

From a global perspective, optimal strategies concerning vaccination lie in the epidemiological as much as if not more than in the economic field. As countries strive to maintain vaccine-free FMD status, they may increase the chance of an outbreak (Blancou et al., 2004). While individual countries may fear the loss of market access if they abandon their vaccine-free status, global economic losses from FMD may diminish with the wider and routine application of vaccines.

While nationalist sentiment might favour trade sanctions, the reality is that consumers pay higher prices for goods if there are import restrictions on some sources. The welfare outcomes for importers of Australian livestock products worsen, the longer that trade sanctions are in place. Part of the issue is that trade sanctions are a blunt instrument, applied to an entire nation even if only one port among many has any risk of FMD carriage. Seitzinger et al. (2022) express a hope that importers will distinguish between ports. It may be excessively optimistic to believe that importers may impose sanctions on individual ports rather than an entire nation. More importantly, these modelled outcomes appear to align with the idea that greater use of vaccines, provided they are not excessively costly to deliver, is likely to be welfare enhancing relative to the current system of according vaccine-free status to major exporters. Even with the relatively quick resolution in variant 1, countries other than Australia suffer welfare losses totalling AUS$4.2 billion. Cost–benefit analysis of a global effort to eliminate FMD may be an important next step in disease research. An example of global eradication of disease through international efforts concerns polio (WHO, 2017).

Beyond improving outcomes in countries that are substantial importers or exporters of animal products, greater efforts to manage FMD in countries where it is endemic may improve welfare in these countries, particularly among the rural poor. Some countries with endemic disease have limited literacy among farmers, poor infrastructure and deficient communications. In these circumstances, there may be many obstacles to successful management of FMD. Other countries with endemic or sporadic status are middle-income countries where efforts to vaccinate livestock and eradicate FMD may yet yield substantial net benefits (McLachlan et al., 2019).

One possible candidate for an internationally funded effort to eliminate the disease is India. The World Bank (2023) projects higher medium-term growth in India than most countries. Raising productivity by diminishing the impact of FMD in rural India may boost farm incomes, raise domestic food supplies and play a role in increasing the nation's demand for international goods and services.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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