Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry: Adequacy of Australia's biosecurity measures and response preparedness

Question No: IQ22-000005

Hearing Date: 10 August 2022

Division/Agency: Biosecurity Operations Division (BOD)

Topic: Number of passengers who crossed the foot mats

Hansard Page: 4

Question Date: 10 August 2022

Question Type: Spoken

Senator Canavan asked:

CHAIR: Since the 27 [h] July, how many passengers from Indonesia have arrived in Australia,and what proportion of those went through the foot mats?
Mr Hunter: Since late afternoon on 27 July, all passengers—to my knowledge, except probably one or two—have now crossed the foot mats. If you just give me a moment, I can get the number of passengers that I'd estimate have crossed those mats.
CHAIR: You can take that on notice, if you like, and possibly tell us later, so we can keep moving on.

Answer:

From 27 July to 11 August 2022, around 51,000 travellers arriving directly from Indonesia have crossed the foot mats.

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Agriculture, Fisheries and Forestry Portfolio

Inquiry: Adequacy of Australia's biosecurity measures and response preparedness

Question No: IQ22-000006

Hearing Date: 10 August 2022

Division/Agency: Biosecurity Operations Division (BOD)

Topic: Date Minister requested foot mats

Hansard Page: 5

Question Date: 10 August 2022

Question Type: Spoken

Senator Ciccone asked:

Senator CICCONE: When did the minister, Minister Watt, first request that the mats be rolled out?
Mr Metcalfe: We'll just check on the precise date.

Answer:

The Minister asked the Department of Agriculture, Fisheries and Foretry to expedite the consideration of foot mats on 13 July 2022.

Rural and Regional Affairs and Transport References
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Agriculture, Fisheries and Forestry Portfolio

Inquiry:	Adequacy of Australia's biosecurity measures and response preparedness
Question No:	IQ22-000007
Hearing Date:	10 August 2022
Division/Agency:	Biosecurity Animal Division (BAD)
Topic:	List of food products permitted
Hansard Page:	8-9
Question Date:	10 August 2022
Question Type:	Spoken

Senator McDonald asked:

Senator McDONALD: I'm sorry to interrupt you, but I will only have a few minutes left. Perhaps on notice, you could table those lists of food products that are able to be brought in, either commercially or through travellers. I guess it just returns me to my question: if we've identified that food products coming with travellers are the high risk—that's why we're doing the 100 per cent scanning of post products; that's why we've banned dairy products commercially—why are we not just making it very easy for our biosecurity officers and saying: 'There is no food. You will not go hungry in Australia; you just can't bring anything in'?

Dr Martin: As I said, most—certainly with meat products—are not permitted and you do have to declare those. If you don't, as recently happened, then you can have a heavy fine. There are a few very highly processed products that are permitted for personal use, and we're reviewing those.

Senator McDONALD: May I ask that that list be a very urgent list of what is allowed, because, again, food has been identified, through all the hearings I have been to, as the most likely import risk for FMD and ASF. I'm just seeking a sense of urgency on all food being banned or at least identifying a very good reason why you would not be banning everything that comes in for personal use.

...

Dr Martin: With commercial imports, when Indonesia notified that it had lumpy skin disease, those products—unless they were treated to an extent that the virus was no longer of concern, those permits were suspended or revoked. There were a couple remaining dairy type products which have been suspended or revoked, when foot-and-mouth disease was notified. So we have very strict import requirements for meat and meat products and dairy, and it very much depends on your country disease status. And if you aren't free of certain diseases then it means the product has to be very highly processed, to ensure that those viruses of concern are inactivated.

CHAIR: Thank you. It's probably captured by Senator McDonald's question, but if you could, perhaps, certainly make sure you include there, in that list, the remaining dairy products that can come from FMD countries.

Answer:

Imported products:

The Department of Agriculture, Fisheries and Forestry conducts risk assessments for the purpose of determining the biosecurity risk associated with bringing or importing animal-derived goods into Australia. If the estimated unrestricted risk does not achieve Australia's Appropriate Level of Protection (ALOP), sanitary measures are considered to mitigate the risk. These measures are applied through the imposition of conditions for the goods brought or imported into Australia. Conditions are applied in two ways;

- through publication of conditions in the *Biosecurity (Conditionally Non-prohibited Goods) Determination 2021;* or

- through import conditions imposed through the granting of an import permit.

Where risk management measures (or combination of measures) that reduce the biosecurity risk to achieve Australia's ALOP have not been identified, import is not permitted.

The granting of an import permit involves an individual assessment of the goods and their associated biosecurity risk. Where risk management measures exist that can sufficiently reduce the risk to achieve Australia's ALOP, an import permit containing those conditions may be granted.

Conditions listed in the *Biosecurity (Conditionally Non-prohibited Goods) Determination 2021* are imposed without requiring an import permit. These are known as alternative conditions. Goods for personal use, including foods entering with travellers, are often brought or imported under these alternative conditions. The full list of animal derived goods can be found in the **Goods Determination -** Part 2 Conditionally non-prohibited goods.

Meat and meat products and dairy products for human consumption which may currently be brought or imported with travellers, without the need for an import permit, are listed in **Appendix A.** The specific import conditions for these products can be found in **Appendix B.**

In response to the outbreak of foot-and-mouth disease (FMD) in Indonesia in May 2022, the department suspended import permits for several dairy-based goods. Details of all changes to import conditions and import permits are detailed in response to IQ22-000033.

Dairy products which may still be brought or imported into Australia from countries not recognised by the department as free from FMD which require an import permit are outlined in **Appendix C**, along with their associated import conditions.

Where risk management measures (or combination of measures) that reduce the biosecurity risk to achieve Australia's ALOP have not been identified, import is not permitted.

It is not lawfully possible to ban the import of all food products on the basis of preventing FMD where those products are not susceptible to carrying FMD.

APPENDIX A – Meat and meat products and diary products which may be brought or imported with travellers, without the need for an import permit

Meat and meat products
Meat-based flavouring product
Meat or meat products from New Zealand
Pâté (whether or not egg is included as an ingredient) or foie gras
Pork crackling or pork rind
Meat floss
Meat jerky or biltong, other than meat jerky or biltong derived from porcine animals
Natural casings derived from bovine, caprine, ovine or porcine animals
Retorted meat products
Dairy products
Lactose or any derivative of lactose (other than lactose, or a derivative of lactose, that is intended for animal consumption, veterinary therapeutic use or use as fertiliser);
Dairy products (including infant formula)
Cheesecakes, cooked biscuits, cooked breads, cooked cakes or cooked pastries
Dairy-based beverages
Chocolate
Clarified butter oil or ghee

APPENDIX B – Alternative conditions for meat and meat products and dairy products for human consumption purposes

Meat and meat products

Alternative conditions—meat and meat products	
Column 1 Goods	Column 2 Alternative conditions
Meat-based flavouring product	The goods: (a) have been commercially manufactured and packaged; and (b) do not contain any discernible pieces of meat; and (c) are for personal use
Meat or meat products from New Zealand, other than goods that are, or that contain: (a) pork; or (b) avian meat	Either: (a) the goods: (i) were produced from animals in New Zealand; and (ii) are clearly labelled on the outermost of the largest packaged unit with the date of processing, the name and address of the place of production, and "Product of New Zealand"; or (b) the goods: (i) are clearly labelled as a product of New Zealand; and (ii) are for personal use
Meat or meat products from New Zealand that are, or that contain: (a) pork; or (b) avian meat	All of the following: (a) the animals from which the goods were derived were of Australian or New Zealand origin; (b) the animals from which the goods were derived were processed in premises under the supervision of the Ministry of the government of New Zealand with responsibility for primary industries; (c) the goods have been retorted; (d) the goods are accompanied by a health certificate stating the matters referred to in paragraphs (a) to (c)
Pâté (whether or not egg is included as an ingredient) or foie gras	All of the following: (a) the goods are shelf-stable; (b) the goods are for personal use; (c) the quantity of the goods is not more than 1 kilogram or 1 litre
Pork crackling or pork rind	The goods: (a) are shelf-stable; and (b) are for personal use
Meat floss	The goods: (a) have been commercially prepared; and (b) are for personal use
Meat jerky or biltong, other than meat jerky or biltong derived from porcine animals	All of the following: (a) the goods are shelf-stable; (b) the goods are for personal use; (c) the quantity of the goods is not more than 1 kilogram; (d) if the goods are not from avian meat—the goods have been manufactured in an FMD-free country
Natural casings derived from bovine, caprine, ovine or porcine animals	All of the following: (a) the animals from which the goods were derived: (i) were born, raised and slaughtered in one or more countries, each of which is a listed country for natural

Alternative conditions—meat and meat products	
Column 1 **Goods**	**Column 2** **Alternative conditions**
	casings derived from bovine, caprine, ovine or porcine animals; and (ii) were found to be free from contagious and infectious disease at ante-mortem and post-mortem veterinary inspections, conducted under official veterinary supervision; and (iii) were slaughtered at least 30 days before the day the goods are brought or imported into Australian territory; (b) the goods were not exposed to contamination before being exported; (c) each package containing the goods states the identification or veterinary control number of the establishment at which the casings were packed; (d) the goods are accompanied by a health certificate stating the matters referred to in paragraphs (a), (b), and (c)
Meat or meat products, other than meat or meat products to which column 1 of another item in this table applies	Either: (a) the goods: (i) have been retorted and the container in which the goods were retorted has not been opened since the goods were retorted; and (ii) contain less than 5% by weight of meat; and (iii) are shelf-stable; or (b) the goods: (i) have been commercially manufactured and packaged; and (ii) have been retorted and the container in which the goods were retorted has not been opened since the goods were retorted; and (iii) are shelf-stable; and (iv) are for personal use

Dairy products

Alternative conditions—dairy products	
Column 1 **Goods**	**Column 2** **Alternative conditions**
Dairy products, other than: (a) infant formula; or (b) dairy products intended for use as stockfeed	Any of the following: (a) the goods: (i) have been commercially prepared and packaged; and (ii) were manufactured in an FMD-free country; and (iii) are for personal use; (b) the goods: (i) are shelf-stable; and (ii) are in a quantity of not more than 1 litre or 1 kilogram; and (iii) are for personal use; (c) if the goods contain one or more packets (for example, a box containing a cake mix)—the total dry weight of the components of the goods (other than added water) contains less than 10% of dairy products
Infant formula	Any of the following: (a) the goods: (i) have been commercially prepared and packaged; and (ii) were manufactured in FMD-free countries only; and (iii) are for personal use;

Alternative conditions—dairy products

Column 1 Goods	Column 2 Alternative conditions
	(b) all of the following: (i) the goods have been commercially prepared and packaged; (ii) the goods are for personal use; (iii) the person bringing in the goods is accompanied by one or more infants; (c) all of the following: (i) the goods have been commercially prepared and packaged; (ii) the goods are for personal use; (iii) if the goods are not brought in as baggage—the quantity of the goods is not more than 1 kilogram or 1 litre; (iv) if the goods are brought in as baggage—the quantity of the goods is not more than 5 kilograms or 5 litres; (d) the goods contain less than 10% by dry weight (other than added water) of dairy products
Commercial dairy products from New Zealand, other than dairy products intended for use as stockfeed	The goods: (a) are brought in or imported directly from New Zealand; and (b) are made of ingredients that originated in, and were produced, processed and manufactured in, Australian territory or New Zealand only
The following goods: (a) cheesecakes; (b) cooked biscuits, cooked breads, cooked cakes or cooked pastries containing uncooked dairy fillings or toppings	The goods: (a) were manufactured in an FMD-free country; and (b) are for personal use
Dairy-based beverages	The goods: (a) include tea, coffee or flavouring as an ingredient; and (b) are shelf-stable; and (c) are for instant use; and (d) are for personal use
Chocolate	The goods have been commercially prepared and packaged
Clarified butter oil or ghee	The goods have been commercially prepared and packaged
Lactose or any derivative of lactose (other than lactose, or a derivative of lactose)	[Exempt from alternative conditions]

***APPENDIX C – Dairy products for human consumption from FMD affected countries
requiring an import permit***

Dairy products for human consumption requiring an import permit:

Retorted dairy:
   a. Prior to the importation of goods into Australian territory, a valid import permit issued by
       the Department of Agriculture, Fisheries and Forestry is required.
An import permit may be obtained by submitting an import permit application to the department
(use the 'Apply Now' button at the bottom of this page).
   b. These conditions allow for the import of retorted goods excluding bird's nest, products
       containing discernible pieces of egg and goods imported in a refrigerated container (set
       below 10°C).
         1. The goods must be retorted, commercially sterile and shelf stable at ambient
             temperature.
         2. The goods must have been hermetically sealed in a container before being heat
             treated to a minimum core temperature of 100°C, obtaining an F_0 value of at
             least 2.8.
         3. The final product must be imported in the hermetically sealed (airtight)
             container in which it was retorted.
         4. The goods must not contain transmissible spongiform encephalopathy risk
             material.
         5. The goods are not bird's nest or contain discernible pieces of egg.
         6. The goods must not be imported in a container refrigerated below 10°C.
   c. The goods must meet biosecurity requirements.
To demonstrate compliance with this requirement you must present the following on a Health
certificate:
Either:
         1. The product does not contain any bovine derived material (other than dairy
             ingredients, gelatine and/or collagen derived from hides and skins), or
         2. All bovine materials (other than dairy ingredients, gelatine and/or collagen from
             hides and skins) were sourced from animals born, raised and slaughtered in
             countries assessed by FSANZ and assigned a category 1 or 2 BSE risk rating.
             [Country/ies must be listed on the health certificate provided]
[The health certificate must indicate the option that applies]
AND
Either:
         3. The product does not contain any ovine or caprine derived material (other than
             dairy ingredients), or
         4. The ovine and caprine material (other than dairy ingredients) does not include
             offal (and protein products derived from offal) from animals over 12 months of
             age which originated from countries or zones not considered free from scrapie.
[Offal includes skulls including brains, eyes, spinals cord, tonsils, thymus, spleen, distal ileum,
proximal colon, lymph nodes, adrenal glands, pancreas, liver or bone marrow.]
[The health certificate must indicate the option that applies]
AND
         5. A statement that the final product has been retorted, and during the retorting
             process the product was heated to a minimum core temperature of 100 °C,
             obtaining an F_0 value of at least 2.8.
         6. A statement that the final product is imported in the hermetically
             sealed (airtight) container in which it was retorted. The hermetically sealed
             container is stamped or embossed with a permanent mark with:
2.1. the identification number of the manufacturing establishment
2.2. the batch code.
   d. The goods must meet biosecurity requirements.
To demonstrate compliance with this requirement you must present the following on a Health
certificate or Government endorsed manufacturer's declaration:

1. A statement that the goods are not bird's nest, and
2. A statement that the goods do not contain discernible pieces of egg.
   e.   The retorted goods must not be imported in a refrigerated container.

To demonstrate compliance with this requirement you must present the following on a [Bill of Lading](#):

Evidence that the goods have not been imported in a container refrigerated below 10°C.

   f.   These goods or any derivatives must not be distributed, sold or used for:
1. animal consumption
2. environmental purposes (including use as bioremediation product or fertiliser)
3. growing purposes, or
4. veterinary therapeutic use.

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Agriculture, Fisheries and Forestry Portfolio

Inquiry: Adequacy of Australia's biosecurity measures and response preparedness

Question No: IQ22-000008

Hearing Date: 10 August 2022

Division/Agency: Australian Chief Veterinary Office

Topic: List of significant changes in notifications for FMD

Hansard Page: 11-12

Question Date: 10 August 2022

Question Type: Spoken

Senator Colbeck asked:

Senator COLBECK: Thanks, Chair. I have a couple of follow-up questions from the briefing we had last week in relation to FMD countries. You've given us a list of countries that have FMD present or are regarded by the WOAH as having FMD. Is there a difference between having FMD present and an FMD outbreak, and a notification process? Is there a difference in those two things?

Dr Cookson: There is a process within the World Organisation for Animal Health where countries either officially report their status—that's the list of the 68 countries that noted that foot-and-mouth disease was present. When a status changes, so when it's the reoccurrence of a disease or a change in the distribution of a disease, then countries are required to also report those changes. They will be reported for the period of the last 12 months. That's where you will see some differences in how those countries are reporting to the World Organisation for Animal Health.

Senator COLBECK: A country might be regarded as having FMD but there's a requirement to report if they have an active outbreak?

Dr Cookson: There's a requirement to report if it's a substantial change to their current status. For example, that would be when they have been regarded as having foot-and-mouth disease contained to a zone and the disease may be reported outside of that zone They would then report that change in distribution to the World Organisation for Animal Health. On a routine basis, if the disease is endemic you may find that there will be some smaller outbreaks of disease, but if it's within an area that has already been confirmed to have the disease that won't necessarily be reported to the World Organisation for Animal Health.

Senator COLBECK: The outbreak in Indonesia is effectively a significant change in the activities of the disease in that jurisdiction?

Dr Cookson: That's correct. Indonesia had previously been officially recognised by the World Organisation for Animal Health as FMD free, so when FMD was detected within Indonesia they then had to notify the World Organisation of Animal Health of that change.

Senator COLBECK: The UK is not on that list at the moment, so they are regarded as FMD free following their outbreak in the early 2000s and having eradicated it?

Dr Cookson: Yes, that's correct.

Senator COLBECK: Can we get a list of significant changes in notifications over, say, the last decade? Is it possible to pull that together, please?

Dr Cookson: Yes, we can take that on notice.

Answer:

1. The World Organisation for Animal Health (WOAH) is the global authority on animal health. Its 182 members are required to regularly report their status for foot-and-mouth disease (FMD).

Official status

2. WOAH members may elect to obtain an official FMD status. This status is based on the submission of detailed technical information which is reviewed by WOAH.

3. The official FMD status for **six countries** has changed over the last 10 years:

Country	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Indonesia	dark green	dark green	dark green	dark green	dark green	dark green	dark green	dark green	dark green	red
Mauritius	dark green	dark green	dark green	red	red	red	red	red	red	red
Paraguay	red	red	red	red	red	light green	light green	light green	light green	light green
Peru	light green	light green	light green	light green	light green	dark green	dark green	dark green	dark green	dark green
South Korea	light green	light green	light green	red	red	red	red	red	red	red
Suriname	red	red	red	red	red	dark green	dark green	dark green	dark green	dark green

dark green	Officially free **without** vaccination
light green	Officially free **with** vaccination
red	Not officially free

4. The above table does not include changes in official FMD free <u>zones</u> within countries. These zones are generally contained within countries with long-standing FMD presence, therefore they do not substantially influence the country's overall risk profile.

Self-reported status

5. Independent from official recognition, all WOAH members are required to self-report their status for FMD every six months. They are also required to make an immediate notification should there be a sudden or unexpected change in the FMD situation within their country. The quality of reporting for individual countries is variable and depends on a range of factors, including their surveillance and laboratory capability.

6. In addition to the countries noted above, the self-reported FMD status of **26 countries** has changed in the past 10 years:

Country	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Angola	light green	light green	red	red	red	light green				
Armenia	light green	light green	red	light green	light green	light green	light green	light green	light green	
Bahrain	yellow	red	red	light green	light green	light green	light green	light green	light green	
Chad	red	light green	light green	red	red	light green	light green			
Chinese Taipei	red	light green	red	light green	light green	light green	light green			
Colombia	light green	light green	light green	light green	red	red	light green			
Eritrea	light green	red	red	red	red	red	red	red		
Guinea-Bissau	light green	red	yellow	red	red	red	red			
Israel	red	red	light green	light green	red	red	red		red	red
Jordan	light green	light green	light green	light green	red	light green	light green	light green	red	red
Kazakhstan	red	light green	light green	light green	light green	light green	light green			red
Kuwait	light green	light green	yellow	red	light green	light green	light green	light green	light green	
Kyrgyzstan	light green	red	light green	light green	light green	light green	light green			
Libya	red	red	light green	light green	light green	light green	red	red	red	red
Malawi	light green	light green	red	red	red	red	red	red	red	red

2

Country	1	2	3	4	5	6	7	8	9	10
Mongolia	red	red	red	red	red	red	green	white	red	red
Morocco	green	green	red	green	green	green	red	white	white	white
Mozambique	green	red	red	red	red	red	red	red	red	red
Rwanda	yellow	green	white	green	red	green	white	red	red	red
Senegal	green	red	red	red	yellow	red	red	white	white	white
Sierra Leone	green	green	green	green	green	red	red	red	red	red
Tajikistan	red	green	green	green	white	white	green	white	white	white
Tunisia	green	red	red	red	red	red	red	white	white	red
United Arab Emirates	red	red	green	red	red	red	red	green	red	white
Venezuela	red	green	green	green	green	green	white	white	white	white
Zambia	green	green	red	red	red	red	red	red	red	red

Colour	Meaning
green	Self-reported absent
orange	Self-reported suspected
red	Self-reported present
white	No data available

Australian assessment

7. The Department of Agriculture, Fisheries and Forestry maintains a list of countries that the Director of Biosecurity is satisfied are free from FMD. This is relevant to the implementation of import conditions via the Goods Determination and Import Permits which specifically refence this list.

8. The list is available here:
https://www.agriculture.gov.au/biosecurity-trade/policy/legislation/fmd-free-country-list

9. Should a country apply for inclusion on this list they need to undergo an individual assessment. As a prerequisite they must be recognised by WOAH as officially free from FMD without vaccination. The next step would be submitting specific responses to a questionnaire provided by the department to the relevant competent authority in the county. Further verification, such as an in-country visit by department officials, would also likely be necessary before a country would be recognised for inclusion on the list.

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Inquiry:	Adequacy of Australia's biosecurity measures and response preparedness
Question No:	IQ22-000009
Hearing Date:	10 August 2022
Division/Agency:	Biosecurity Animal Division (BAD)
Topic:	Number of extension officers across state, territory and federal governments
Hansard Page:	13
Question Date:	10 August 2022
Question Type:	Spoken

Senator Canavan asked:

CHAIR: I'll have to do this quickly, because I want to stick to time—I'm using up Senator Colbeck's time—but I do have questions about the Matthews review. I know that was some time ago, but, after reading it, I'm not convinced that we have made progress in some areas. In particular, the Matthews review seemed to identify that we really don't have the resources, if there were an outbreak, to go through the disease eradication. There's a quote from Mr Matthews:

… (The Team's assessment is that because an FMD outbreak could be of at least an order of magnitude more demanding than any previous animal disease outbreak, state, national and industry resources could quickly be overwhelmed.)

My estimate here, and my perception, is that in the last decade or so since this report we've got fewer extension officers at the state level. Do we have the resources? Have we done an audit of whether we have got the people on the ground to take charge of the destruction and the restrictions on movement that are necessary to control an outbreak?

Dr Parker: Senator, you're asking how long's a piece of string, but let me just take a step back. I think we've clearly recognised that there are a range of services that are going to be required in an outbreak situation. The secretary appointed me to my role for exactly that reason. When it became increasingly obvious that there would be even more requirements, the secretary announced an increase in focus across the department, and the minister recently announced a joint task force between DAFF and EMA to address exactly the issues you are raising, to work with emergency services and with health departments—with a whole range of people—and to come up with a plan within the next month about what that looks like and where there are gaps. So I think you raise a very good point, and it is something that the government, through the minister, was very focused on, and it is something that we're very focused on, recognising that we can manage the biology, if you like, or the biosecurity component. But for example, in a stock standstill, which would be the first thing that occurred, you would need significant resources from the police and emergency services to help in ensuring that that's able to be enforced. So it's definitely an issue, it's definitely something we're focused on and it's definitely something the government's focused on.

Mr Metcalfe: Senator, I'll just very quickly add that it's a very good point. You may be aware, from media reports, that all agriculture ministers around Australia met two or three weeks ago now. This was a major area of focus for them; indeed, I think pretty well every state is now looking at its own preparedness arrangements. We do have the AUSVETPLAN and other well-documented escalation procedures, but the reason that Minister Watt set up this task force was precisely to answer the question and to engage with the states and territories for the reasons you've outlined.

CHAIR: Thank you for that. Could you take on notice how many extension officers, for want of

a better word, we have across the country—across state, territory and federal governments?

Mr Metcalfe: We'd need to ask each jurisdiction to assist us with that, Senator—

CHAIR: Well, if you could take on notice—I think it would be a worthwhile audit to have, even if you can't release it to us, so I'll leave that with you.

Mr Metcalfe: I imagine that the task force that's working on this will be engaged in that sort of activity, so we'll certainly do our best to provide you with the best information, but it is very much in that area—that on-the-ground response, as we saw with the human pandemic, with COVID—where the states actually have the lead responsibility and where the Commonwealth's role is support, coordination and, quite often, funding.

CHAIR: Thank you, Secretary.

Answer:

The Department of Agriculture, Fisheries and Forestry does not hold information on the number of extension officers in the states and territories. However, as noted in Dr Parker's response to your question, the joint department and Emergency Management Australia task force is looking into the human resources needed to respond effectively to a foot-and-mouth disease outbreak in Australia.

Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry:	Adequacy of Australia's biosecurity measures and response preparedness
Question No:	IQ22-000010
Hearing Date:	10 August 2022
Division/Agency:	Biosecurity Animal Division (BAD)
Topic:	FMD modelling
Hansard Page:	14-15
Question Date:	10 August 2022
Question Type:	Spoken

Senator Roberts asked:

Senator ROBERTS: Thank you for that. That's good clarification and very useful. Under what scenarios would we use vaccines?

Dr Parker: Again, a widespread outbreak in a number of different states could well necessitate the use of vaccines.

Dr Martin: And I can add that there's been some modelling done, and I think some of that work is published; if it is, we'll provide it.

...

Senator ROBERTS: Thank you very much. After we've seen the modelling from Imperial College London and the Doherty institute with regard to human vaccines and the spread of coronavirus, or COVID, in Australia, I'm very curious to know who did the modelling for us and whether they have modelled all of the scenarios, including the infestation of feral animals.

Mr Metcalfe: We will take it on notice to provide you with that.

Senator ROBERTS: Wonderful. Thank you.

Answer:

- Epidemiological models can be used to investigate the likely spread of disease for different outbreak scenarios and the effectiveness and cost-efficiency of control strategies including vaccination, particularly in the absence of contemporary Australian experience as for foot-and-mouth disease (FMD).

- From 2011-15 an epidemiology group associated with the Quadrilateral Animal Health Emergency Management Group (including representation from governments in Australia, Canada, New Zealand, the United States and the UK) carried out a modelling study comparing a range of vaccination strategies for a simulated FMD outbreak in livestock.

- In 2014-15 the Department of Agriculture, Fisheries and Forestry and University of Sydney carried out a study to model FMD outbreaks in northwestern Australia. Domestic cattle and feral pig populations were represented.

- From 2017-21 the department partnered with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Centre of Excellence for Biosecurity Risk Analysis (CEBRA) on a series of modelling studies using a variety of outbreak scenarios and control strategies for FMD in livestock in Australia including the use of vaccination. This work was conducted as part of the FMD Ready project https://research.csiro.au/fmd/ and used the Australian Animal Disease Spread model https://aadis.org.au/ .

- Published findings from these studies are provided as attachments.

Modelling foot-and-mouth disease transmission in a wild pig–domestic cattle ecosystem

MP Ward,[a]* MG Garner[b] and BD Cowled[a]

Objective   To use simulation modelling to predict the potential spread and to explore control options for a foot-and-mouth disease (FMD) incursion in a mixed wild pig–domestic cattle ecosystem in northern Australia.

Design   Based on aerial surveys, expert opinion and published data, the wild pig and grazing cattle distributions were simulated. A susceptible–infected–resistant disease-spread model was coded and parameterised according to published literature and expert opinion.

Methods   A baseline scenario was simulated in which infection was introduced via wild pigs, with transmission from pigs to cattle and no disease control. Assumptions regarding disease transmission were investigated via sensitivity analyses. Predicted size and length of outbreaks were compared for different control strategies based on movement standstill, surveillance and depopulation.

Results   In most of the simulations, FMD outbreaks were predicted to be ongoing after 6 months, with more cattle herds infected than wild pig herds (median 907 vs 22, respectively). Assuming only pig-to-pig transmission, the infection routinely died out. In contrast, assuming cattle-to-cattle, cattle-to-pig or pig-to-cattle transmission resulted in FMD establishing and spreading in more than 75% of simulations. A control strategy targeting wild pigs only was not predicted to be successful. Control based on cattle only was successful in eradicating the disease. However, control targeting both pigs and cattle resulted in smaller outbreaks.

Conclusions   If FMD is controlled in cattle in the modelled ecosystem, it is likely to be self-limiting in wild pigs. However, to eradicate disease as quickly as possible, both wild pigs and cattle should be targeted for control.

Keywords   Australia; cattle; foot-and-mouth disease; simulation model; wild pigs

Abbreviations   CI, confidence interval; CSF, classical swine fever; FMD, foot-and-mouth disease; GIS, geographic information system; PI, prediction interval; R_0, basic reproduction number

When an infection is shared between domestic livestock and wildlife, the spatial and temporal interface between them is a dynamic feature and includes both direct and indirect contact. The interface commonly occurs at physical contact points where both populations access communal resources, for example, watering points.[1] Although some studies have attempted to estimate contact rates between livestock and wildlife,[2] factors that drive disease transmission between livestock and wildlife populations inhabiting the same landscape are not well understood.[3,4] The presence of an alternate host species is expected to increase the rate and extent of regional disease spread and might lead to disease persistence when otherwise it would die out in a single species.

Wild pigs and wild boar (both *Sus scrofa*) are infected by a range of diseases that also infect domestic livestock, including serious transboundary animal diseases such as foot-and-mouth disease (FMD), classical swine fever (CSF) and African swine fever. Australia is free of these diseases, with government and industry investing in prevention and preparedness to ensure that any incursion will be managed effectively and efficiently. The presence of infected wild animal populations (particularly wild pigs and deer) in FMD outbreaks in temperate countries is a fear because it could complicate both control and eradication efforts, and the demonstration of freedom.[5] Despite this concern, relatively little is known about the probability of disease transmission between domestic and wild animal populations. Simulation modelling provides a means for making informed judgments about disease control in the absence of detailed empirical data.

In Australia, national response plans to the incursion of an exotic disease such as FMD recognise that wild (feral) pigs might be infected and might act as a reservoir of infection.[6] Optimal planning requires a good understanding of disease ecology across livestock and wild pig populations, especially at the livestock–wildlife interface. In the absence of the occurrence and analysis of real epidemics in Australia, disease modelling studies can assist contingency planning.

Some modelling to investigate the role of wild pigs in FMD outbreaks has been conducted previously in Australia.[7–9] Some results indicated that FMD would transmit rapidly through wild pig populations and that culling of impractically high proportions of wild pig populations would be required to induce disease fadeout.[7] Subsequently, there have been calls for the eradication of wild pigs from Australia,[10,11] although largely impractical in remote landscapes in northern Australia. Modern modelling approaches are providing new insights to infection dynamics.[5,9,12] This provides an opportunity to study the livestock–wildlife interface, using potential epidemics of FMD in wild pig and cattle populations in Australia. Such approaches can improve response plans by providing disease managers with a good understanding of the potential role of wild pigs in the establishment, maintenance and spread of diseases such as FMD should they be introduced. In this study, we used simulation modelling to investigate

*Corresponding author.
[a]The University of Sydney, Faculty of Veterinary Science, 425 Werombi Road, Camden, New South Wales 2570, Australia; michael.ward@sydney.edu.au
[b]Department of Agriculture, Canberra, Australian Capital Territory, Australia

the potential spread and control of FMD in a mixed wild pig–domestic cattle ecosystem in the Kimberley region of northern Australia.

Materials and methods

Study area

The study area covered approximately 10,000 km[2] and comprised six pastoral leases in the Kimberley region of northern Western Australia (Figure 1). This is a large, remote and sparsely populated region where cattle are raised under extensive grazing systems. Pigs were introduced by European settlers during the late 19th century and subsequently became wild.[13] The area has a tropical monsoonal climate (mean annual rainfall 484 mm, range 163–907) and hot temperatures (mean daily maximum temperature 30–39°C, range 18–46°C).

Aerial survey

In August 2010, aerial surveys of the study area were conducted (designed using Distance 6.0[14] automated algorithms and distance sampling[15] and mark-resight (double observer)[16] methodology) to determine the abundance and distribution of wild pigs and to assess group sizes of cattle. The results were combined with previous population estimates for cattle and pigs[17–19] and leaseholder information to develop population distributions for disease-spread modelling.

Transects were flown in a north–south direction at 50 m above ground level and a speed of approximately 45 kph in an R44 helicopter. Surveys were undertaken during 1 week in August 2010 in the first 3 h after sunrise (≈ 0600 hours) and the last 3 h before sunset (≈17:30 hours). Areas around major permanent water sources (the Fitzroy and Margaret rivers) were searched for up to 4 km to include likely wild pig home ranges.[3,12 20] The study area was searched using systematic random transects to cover areas of expected high and low density.[21 22]

Figure 1. Map of the location of an area in north-west Australia selected to investigate, via disease outbreak simulation modelling, the potential spread of a foot-and-mouth disease incursion in a population of extensively managed cattle and wild pigs.

Animals were enumerated by subtised recordings using a modified keyboard linked to a portable notebook laptop running specialist aerial survey recording software (Aerial Survey Logger; S. McLeod and J. Tracey, Vertebrate Pest Research Unit, NSW Department of Primary Industries, Orange), which includes a continuous GPS track and sighting recording system.[23] Sighting distances were based on vertical sighting poles attached to a cross-beam fixed through the cabin of the helicopter. Transect sightings data, reconciled for the three observers, was imported into Distance 6.0.[14] Data were analysed using distance methods, as recommended by Buckland et al.[21] and mark-resight (double observer) techniques,[24] using the Distance software.

Population at risk

The average cattle density in the west Kimberley region is reported[17] to be 7 cattle/km[2]. For modelling purposes, a spatial data set of cattle herds was synthesised. A herd is defined as a co-mingling group of grazing cattle, which can be considered the basic epidemiological unit for disease transmission purposes in this environment where a single paddock may be extensive. Within the study area, most leases have separate paddocks, which are usually defined by fences and sometimes include geographical features such as rivers. Paddocks are large: on average approximately 33,000 ha, but can range up to approximately 50,000 ha.[17] In general, more than one discrete group of cattle can be found within a paddock; groups are defined by the available water sources within a paddock.

Cattle do not strongly associate with one another and instead exhibit general gregariousness rather than tightly-knit social groups. Cattle exhibit home range fidelity and in arid Australia some cattle may graze up to 9 km from their watering source each day.[25–29]

The cattle population dataset was created based on known densities,[17] property records and aerial survey data. Two of the six leases in the study area essentially have no management of cattle and no paddock structure, with cattle tending to aggregate along the floodplain on these leases. Periodic, ad hoc mustering is practised. The four other leases maintain a number of breeder herds that are placed in paddocks with permanent water. Mustering occurs once or twice yearly between May and October,[17] when weaners are removed from breeder herds and collected into an age or sex cohort.

The total population of cattle in the study region was estimated by multiplying the area of cattle habitat by the average density of cattle (7 cattle/km[2]). The area around water sources was assumed to be habitable and divided into four concentric rings to allow declining cattle densities as the distance from water increases (see behaviour and management section for justification). These rings were 0–2, 2.1–4, 4.1–6 and 6.1–7.5 km from water and were based on previous research,[17] aerial surveys and information provided by producers in the study area. Densities of cattle for each ring were iteratively calculated using the arbitrary function $density = 14 - 2^{\frac{547x}{1000}}$ (where x is distance to water) in order to simulate a population that declines in density as distance to water increases. However, the overall cattle density estimated (7 cattle/km[2]) was maintained, which resulted in densities of 13, 11, 7 and 1 cattle/km[2] for each ring, respectively.

Wild pigs are highly social animals that live predominantly in herds and in close proximity to water sources.[3,4,19,30–33] Previously, Cowled
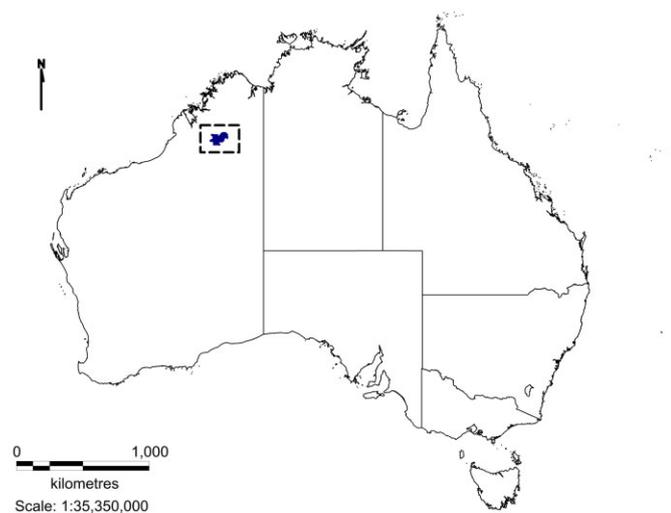
et al. used information from the literature to estimate the distribution of wild pigs in the study area.[31] In the current study, this distribution was modified according to the results of the aerial surveys conducted, which included modified estimates of the overall density of wild pigs in the study area and the maximum distance pigs were observed from major waterways.

Epidemiological parameters (FMD) and model logic

A stochastic, spatially explicit microsimulation model that operates within a geographic information system (GIS) was developed. The model was adapted from an approach previously described for modelling CSF incursions in wild pigs in Australia.[31] A state-transition approach is used to represent the infection process and herds (pigs or cattle) may transition through susceptible–latent–infectious–recovered states. The application was coded in MapBasic® and implemented in Mapinfo® (Pitney Bowes, http://www.mapinfo.com/products/applications/mapping-and-analyticalapplications).

The model takes into account spatial relationships, cattle and wild pig social structures and species ecology and behaviours, including management practices in the case of cattle. Social units (herds) of pigs and cattle are represented individually and all units have an area over which they will move each day (daily home range).

Within the model, pig-to-pig (interherd) transmission can occur when daily home ranges of infectious and susceptible groups intersect, and the daily probability of infection was assumed to be 0.27. In the absence of good data on FMD transmission in wild pigs, this parameter has been estimated from analysis of FMD outbreaks in domestic pigs, notably the large epidemic in pigs in Taiwan in 1997.[34] Cattle-to-cattle (interherd) transmission may occur through the following infection pathways.

1. Shared watering points: assumes that all herds within the same paddock that share a watering point with an infected herd have a daily probability of infection.
2. Proximity: herds within the same paddock that do not share a watering point, but that may come in 'contact' (as measured by intersecting daily home ranges) also have a probability of infection.
3. Indirect contact: fomite transmission between cattle herds on the same lease associated with normal management practices.
4. Cattle movements: seasonal movements that mix and move cattle (e.g. turn-off, weaning).

With no experience of FMD in this environment, it is impossible to precisely set parameters for these pathways. The daily probability of infection for these pathways was assumed to be 0.14, 0.05, 0.001 and 4.75, respectively, based on previous research and expert opinion[35,36] taking into account local environment and management factors. For example, indirect contact between cattle herds on the same lease will be mainly associated with vehicle movements (bore runs) with an estimate of one indirect contact per herd per week and probability of transmission in this environment considered as very low (0.01). For cattle movements, we assume that during mustering, one infected herd will come in contact with five other herds sufficiently close that FMD transmission could occur. Because mustering is likely to involve close contact between individual animals, we assumed a 95% probability of transmission if a herd is infected.

Transmission of infection from infectious pig herds to susceptible cattle herds, and from infectious cattle herds to susceptible pig herds, may occur when daily home ranges intersect, in proportion to the area of home range intersection, time since the source herd was infected (within-herd prevalence) and size of the source and exposed herds. The risk of infection is higher from pigs to cattle than from cattle to pigs because pigs excrete larger amounts of virus than cattle and cattle are highly susceptible to infection by inhalation compared with pigs.[37] The assumed daily probability of infection was 0.13 and 0.01, respectively.

Periods of cattle and pig herd latency, infectiousness and immunity were modelled as triangular statistical distributions, as previously described by Ward et al.,[35] based on expert opinion.

Control and surveillance

The model simulates control measures consistent with Australia's veterinary emergency control plan (AUSVETPLAN) for FMD.[6] This involves quarantine of infected premises and area movement restrictions, tracing of animal movements and surveillance, and culling of infected and exposed animals on infected and dangerous contact premises. Vaccination is unlikely to be considered in this remote area with low stocking rates. In the event that wild animals are found to be infected, a wildlife population reduction program would be applied.[38]

Control of FMD outbreaks in cattle in temperate countries involves three measures: all direct cattle movements and indirect contact cease after the index case is discovered, surveillance through stock inspections is implemented and stamping out (destruction and disposal of cattle on infected premises) is carried out. We assumed all infected cattle herds would be detected. The time from onset of clinical signs to reporting was modelled as a triangular statistical distribution (7, 10, 14 days). We assumed that it would take 1 day to muster and cull cattle in an infected paddock. Because of the very large size of pastoral holdings in the study region, we assumed that only cattle in paddocks where infection is found would be destocked. Disease control in wild pigs is based on a control zone of 10-km radius around infected herds that have been detected. Within this zone, pig herds are culled, based on the likelihood that individual groups are sighted and culled. We assumed the probability of sighting and culling pig herds in the control zone to be 80%.[39] A 10-km surveillance zone is applied outside the control zone and sampling of herds in the surveillance zone is also undertaken. If new infected cattle or pig herds are detected, then control and surveillance activities are expanded appropriately.

Simulations (sensitivity analyses, experiments and scenarios)

We considered initial infection of wild pigs with subsequent transmission within the pig population and between the pig and cattle populations (mixed species infection) to be the most plausible way FMD would be introduced and spread in this region and accordingly this was our 'reference scenario'. To investigate the importance of the multi-host system, the potential spread of disease in pig populations only and in cattle populations only (single-species infection) were simulated separately. To start a simulation, FMD virus was introduced to a randomly selected wild pig or cattle herd. Infection was then allowed to spread for 6 months with no control implemented and 200 simulations were used for all scenarios.

Given the uncertainty around FMD transmission in this setting (FMD has never occurred in this region), a sensitivity analysis of the transmission probabilities was undertaken by halving and doubling the baseline parameter estimates.

In a second set of studies, the effectiveness of control measures was evaluated in a mixed species outbreak using the reference scenario (FMD randomly introduced into the pig population, with transmission from pigs to cattle and cattle to pigs permitted). Disease was assumed to be detected 30, 60 or 90 days after introduction. The effects of targeted control of pigs only, cattle only and pigs plus cattle were separately considered. Again, the model was run for 6 months with 200 simulation runs in each case.

Outcome measures

The mean proportion of FMD introductions in which disease established (still spreading at 6 months), the mean number of infected herds at 6 months, the mean incidence rate (number of herds infected per day), the mean total area infected (km^2) at 6 months and the mean cumulative incidence were calculated for both wild pig and cattle herds. Prediction intervals (PI) were calculated for outcomes to provide an indication of variability in results. This was achieved by ranking each outcome in each scenario for all 200 model runs; the 95% PI was then the 10th and 190th ranked values.

Results

Aerial survey

During the aerial surveys that were carried out in August 2013, 1263 cattle herds were observed. The median herd size was 4 (Q1–Q3: 2–10), with a range of 1 to approximately 1000 cattle. Cattle herd sizes observed during aerial surveys resembled a Poisson or negative binomial distribution with a mean of 1, although over-dispersion was also evident. Cattle herd sizes were arbitrarily simulated using a Poisson

distribution (20% of herds, mean = 1), a uniform distribution (0.5% of herds 1–1000) and a BetaPert distribution (79.5% of herds, lowest = 1, most likely = 3, highest = 40) to derive a probability distribution that visually resembled that observed during the aerial survey. These herds were then randomly distributed across the study area (Figure 2), although care was taken to distribute them in concentric rings around waterways according to the densities derived before. The study area was estimated to contain approximately 79,400 cattle in 8231 functional herds in 84 paddocks covering the six pastoral leases.

Overall, a total of 208 wild pigs in 48 groups were counted in the aerial survey, an estimated density of 0.62–1.68 wild pigs/km^2. Assuming 1 pig/km^2 of suitable habitat for the aerial survey area (6818 km^2), a total of 1190 pigs located in 275 functional herds (Figure 3) was used in disease-spread modelling.

Baseline model simulations

In the mixed species infections, outbreaks of FMD were predicted to establish and still be spreading at 6 months in 75–81% of introductions, with larger outbreaks being seen when disease was introduced via the pig population (reference scenario) (Table 1). A typical example of a disease outbreak simulation is shown in Figure 4. Smaller outbreaks were seen in the single-species scenarios. In the cattle-only scenario, FMD was also likely to establish and spread, with infection still active at 6 months in 62% of runs. In contrast, in the pig-only scenario, FMD inevitably died out without intervention. The median survival time was only 19 days (95% PI, 12–52). In 64.5% of runs, the infection did not spread beyond the initial infected herd, compared with 4.5% of runs in the cattle-only scenario.
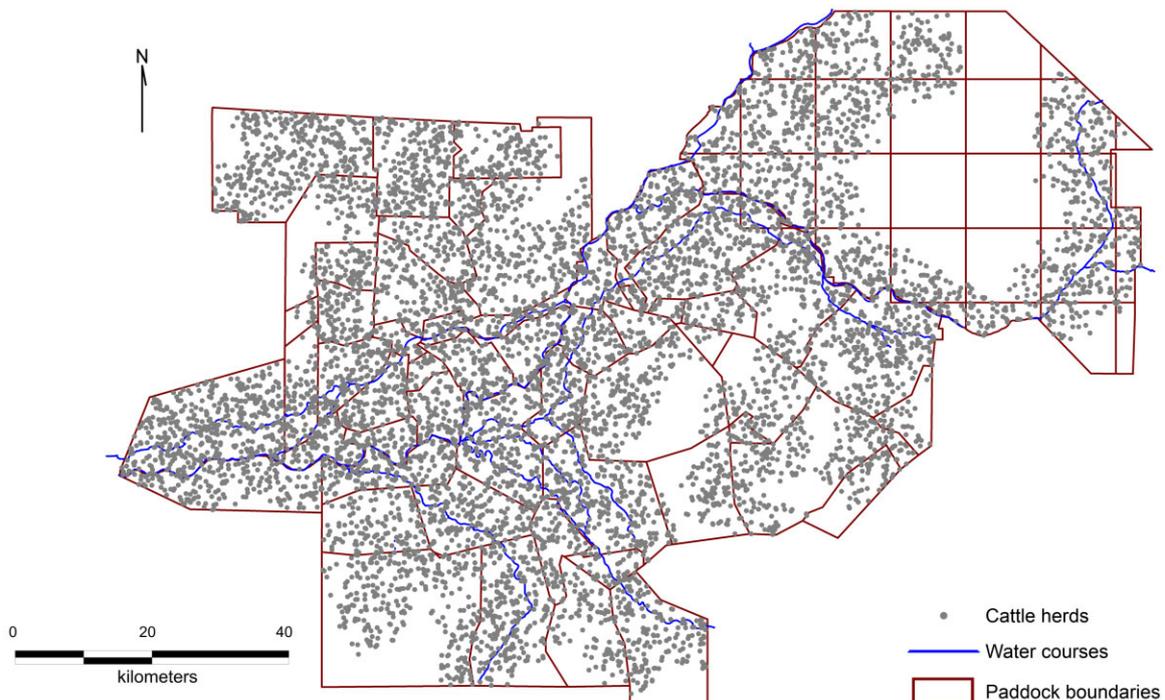
Figure 2. Map of study region showing pastoral leases, paddocks and simulated distribution of cattle herds. Note: for one lease the paddock boundaries were unavailable and 10 × 10 km grid cells were used to distribute the cattle population.
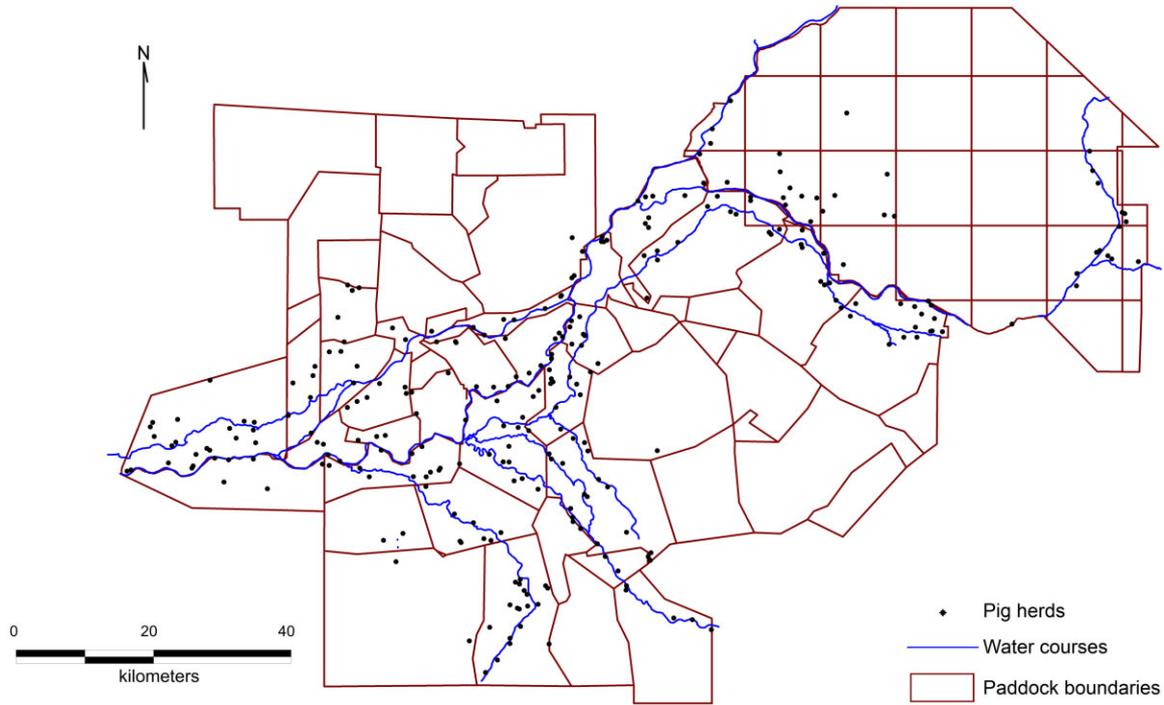
Figure 3. Map of study region showing the distribution of simulated wild pig herds. Note: for one lease the paddock boundaries were unavailable and 10 × 10 km grid cells were used to distribute the pig population.

Table 1. Predictions from a model simulating infection of extensively managed cattle and wild pigs by foot-and-mouth disease virus in north-west Australia, based on different assumptions regarding intra- and interspecies disease transmission

Experiment	Outbreaks[a]	Cattle			Pigs		
		Herds infected[b]	Area infected[c]	Cumulative incidence[d]	Herds infected	Area infected	Cumulative incidence
Pig-to-cattle*	81	2941 (0–6000)[e]	5634 (0–9259)	35.7 (0–72.9)	87 (1–186)	3205 (0–5634)	31.5 (0.3–67.6)
Cattle-to-pig	75	2373 (1–5658)	4645 (0–8724)	28.9 (0.1–68.7)	79 (0–170)	2506 (0–5501)	28.5 (0–61.8)
Cattle-to-cattle	62	1223 (1–5001)	2585 (0–7945)	14.9 (0–60.7)	–	–	–
Pig-to-pig	0	–	–	–	1 (1–4)	0 (0–3)	0.4 (0.4–1.5)

No disease control was assumed and the model was simulation for 200 iterations for 180 days for each experiment.
*Reference scenario (initial infection of wild pigs with subsequent transmission within the pig population and between the pig and cattle populations, and no disease control).
[a]Proportion (%) of all simulations in which a single point introduction leads to disease transmission still occurring at 6 months. [b]Total number of herds infected throughout the simulation. [c]Area (km^2) of a minimum convex hull (MCH) established around every infected herd throughout the epidemic. NB: MCH requires at least three points. [d]Proportion (%) of herds infected, the total number of infected herds ÷ total herds in contiguous population. [e]Median (95% prediction interval).

The largest outbreaks in both cattle and pigs (herds infected and cumulative incidence) and area infected occurred in the reference scenario (Table 1): a median of 2941 (95% PI, 1–5658) cattle herds were predicted to be infected across an area of 5634 km^2 (95% PI, 0–9259). Cumulative incidence of infection for cattle herds was 35.7% (95% PI, 0–72.9). In addition, there was a median of 87 (95% PI, 1–186) pig herds infected with a cumulative incidence of 31.5% (95% PI, 0.3–67.6). Mixed species infection initiated in the cattle population was slightly smaller. For cattle only outbreaks, fewer herds were infected: median cumulative incidence 14.9% (95% PI, 0–60.7). In contrast to the mixed and cattle-only scenarios, for the pig-only outbreaks there was very little spread: median cumulative incidence 0.4% (95% PI, 0.4–1.5).

Sensitivity analyses

Not surprisingly, increasing the value of the epidemiological transmission parameters for the reference scenario resulted in a greater proportion of epidemics establishing: 91% compared with 81% for the
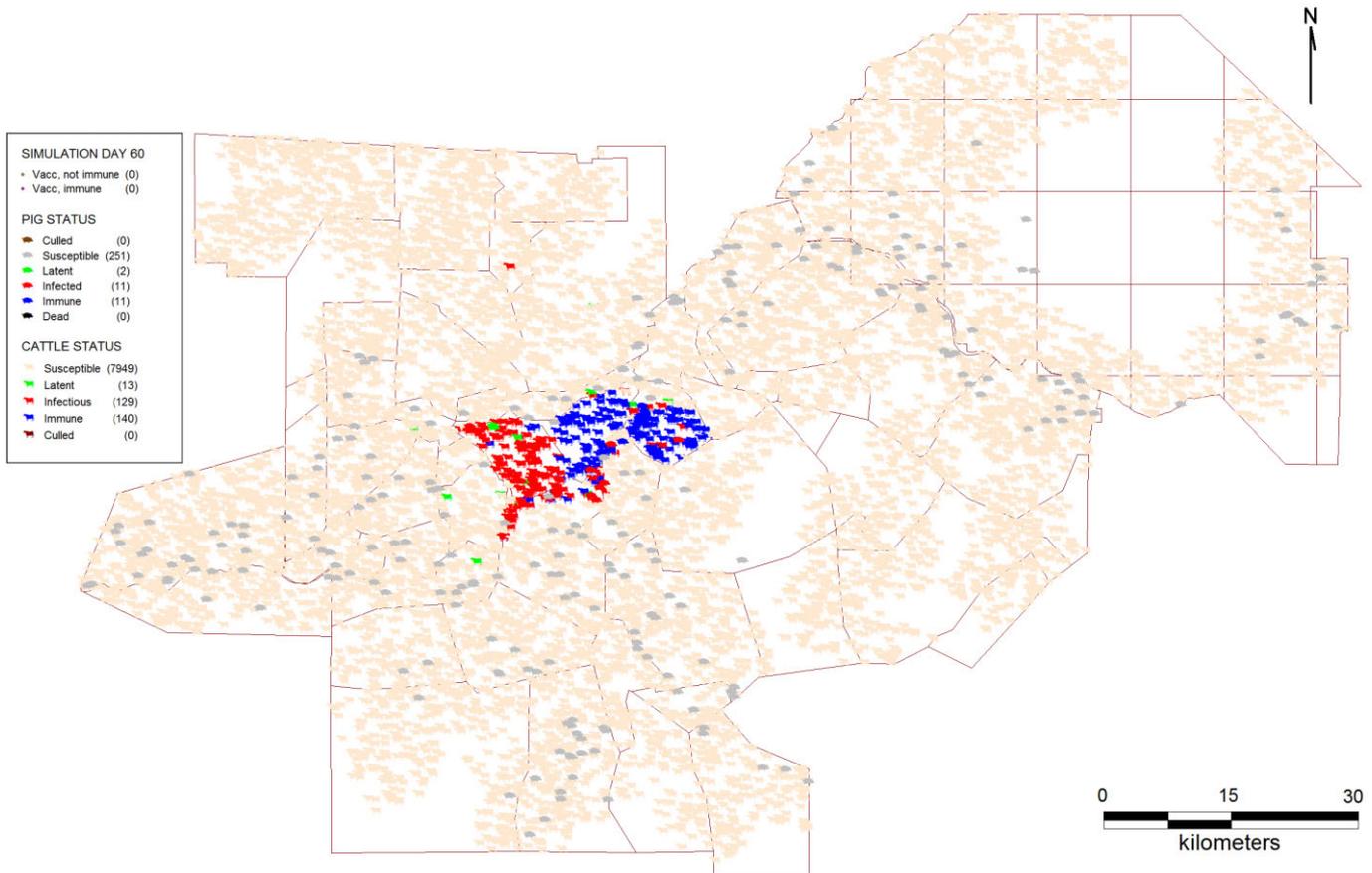
Figure 4. An example of a disease outbreak simulation of foot-and-mouth disease incursion in a population of extensively managed cattle and wild pigs in north-west Australia.

Table 2. Predictions from a model simulating infection of extensively managed cattle and wild pigs by foot-and-mouth disease virus in north-west Australia, based on different assumptions regarding intra- and interspecies disease transmission

Experiment	Outbreaks[a]	Cattle			Pigs		
		Herds infected[b]	Area infected[c]	Cumulative incidence[d]	Herds infected	Area infected	Cumulative incidence
Baseline transmission	81	2941 (0–6000)[e]	5634 (0–9259)	35.7 (0–72.9)	87 (1–186)	3205 (0–5634)	31.5 (0.4–67.6)
Half transmission	57	626 (0–4093)	1055 (0–6662)	7.6 (0–49.7)	12 (1–118)	263 (0–4218)	4.3 (0.4–42.7)
Double transmission	91	5902 (0–7419)	8469 (0–10469)	71.7 (0–90.1)	183 (1–222)	5098 (0–6923)	66.5 (0.4–80.7)

Sensitivity analysis of the reference scenario (FMD introduction in a randomly selected pig herd, transmission between pig herds, pig herds to cattle herds and between cattle herds, and no disease control) was performed by halving and doubling the baseline transmission.
[a]Proportion (%) of all simulations in which a single point introduction leads to disease transmission still occurring at 6 months. [b]Total number of herds infected throughout the simulation. [c]Area (km²) of a minimum convex hull (MCH) established around every infected herd throughout the epidemic. NB: MCH requires at least three points. [d]Proportion (%) of herds infected, the total number of infected herds ÷ total herds in contiguous population. [e]Median (95% prediction interval).

baseline parameters (Table 2). It also resulted in a larger epidemic size, particularly for the predicted number of herds infected and size of area infected (1.5–2.1 fold increases). Conversely, decreasing transmission parameters reduced the proportion of epidemics that established and spread (57%), and reduced the number of infected herds and size of the area infected (Table 2).

Control measures

A control strategy targeting wild pigs only was not predicted to be successful. Assuming FMD was detected 30 days after introduction, in a control program focused only on wild pigs, but involving cattle, 39% of outbreaks would still be active at 6 months (Table 3). A control program focused on cattle only, or including both cattle and pigs,

Table 3. Predictions from a model simulating infection of extensively managed cattle and wild pigs by foot-and-mouth disease virus in north-west Australia, using three different disease control strategies: culling pigs only, cattle only or cattle and pigs using the reference scenario (FMD introduction in a randomly selected pig herd, transmission between pig herds, pig herds to cattle herds and between cattle herds, and no disease control)

Metric	Control strategy		
	Pigs only	Cattle only	Cattle and pigs
Probability of eradication[a]	60.9%	100%	100%
Time to eradication (days)[b]	111 (52–174)	49 (31–105)	42 (31–74)
Control area (sq km)[c]	146 (6–359)	335 (60–1079)	283 (55–1021)
Cattle herds culled	–	349 (83–941)	329 (71–902)
Total cattle culled	–	3332 (730–9986)	3264 (730–8529)
Pig herds culled	20 (3–49)	–	20 (0–71)

The model was simulation for 200 iterations for 180 days for each scenario and disease detection was assumed to occur at day 30. Note that disease died out before 30 days (without any intervention) in 21 out of 200 runs.
[a]Number of simulations where disease was eradicated divided by total simulations. [b]Days until outbreak controlled: number of days from introduction until there are no infected cattle or pigs left (or if infection still present at 180 days, outbreak uncontrolled). [c]Area (km²) of a minimum convex hull established around every infected herd throughout the epidemic.

always resulted in eradication within 6 months. Compared with control targeting pigs only, targeting both pigs and cattle resulted in larger control areas, a similar number of pig herds culled but a greater likelihood of eradicating the disease (100% compared with 61%) with an average 69-day reduction in the time needed to control an outbreak (Table 3). Compared with control targeting cattle only, targeting both pigs and cattle resulted in shorter outbreaks (on average a 7-day reduction), fewer cattle herds culled and a smaller control area (Table 3). Even with delayed detection (at 60 days and 90 days), a control strategy in which both cattle and pigs were targeted minimised the time to eradication and number of cattle culled (data not shown).

Discussion

This study demonstrated that a different disease pattern will occur in a two-species disease ecosystem compared with each species considered in isolation. Considering wild pigs in isolation, FMD inevitably died out in a relative short time frame (weeks) in the Kimberley environment. This is not surprising, given the relatively small number and limited distribution of pig herds (based on aerial surveys, we estimated that there were 1190 pigs in the study area) compared with cattle (approximately 79,400 grazing cattle). In the cattle-only scenario, the disease was more likely to establish and spread, although there was a 38% probability that it would die out within 6 months. However, when wild pig–cattle interactions were taken into account, outbreaks were invariably larger and disease more likely to persist. The findings suggest that if FMD is controlled in cattle, it is likely to be self-limiting in wild pigs, which has important implications in terms of disease response and resource management in this remote region.

In the event of an FMD incursion in this wildlife–livestock ecosystem, simulation results suggest that it is the cattle population that determines the outcome. The likely reasons for this include cattle existing in the study area at higher densities, being more dispersed, having larger home ranges (because this species is less reliant on watercourses) than the wild pig population and being moved large distances

during routine management practices. Because of the interconnectedness of the cattle population, disease could be sustained, thus allowing regular spillover of infection to the wild pigs that share this landscape.

Disease control focusing on depopulation of wild pigs was predicted to lead to only slightly smaller outbreaks compared with the uncontrolled situation (reference scenario). There was only a 61% probability of FMD being eradicated with a pig-only control program. In contrast, control only in cattle always led to eradication, suggesting that pigs at the density observed in our study area would act as a spillover species for FMD. However, control of both pigs and cattle resulted in the shortest time to eradication. Thus, if time to eradication is a driving force in the response to an incursion (i.e. to regain FMD-free status and resume trade), then both species need to be included in the disease management plan. If there are limited resources available, then focusing on controlling FMD in cattle is likely to be the preferred approach in the first instance. Once this has been achieved, assessing the disease status of the wild pig population would then become a priority.[40] Although the role of wild pigs in the spread of disease in this ecosystem might be minor, an equally important issue is the demonstration of disease freedom once an incursion has been controlled. The cost–benefit of controlling the wild pig population in such scenarios also needs to be assessed.

Previous disease-spread modelling of CSF in this population of wild pigs found that disease was likely to spread quickly.[31] However, in that study, higher wild pig densities (based on expert opinion) were assumed. In the current study, we used lower density values based on an aerial survey. The different findings from the two studies suggest that the optimal approach to managing an exotic disease incursion involving wild pigs is likely to be very sensitive to the distribution and density of the pig population. If this is the case, then a key component of the response should be to determine the distribution and abundance of the local wild pig population (also recognising that wildlife populations can change quickly in response to weather and other seasonal events and the availability of natural resources). Based on

distribution and abundance estimates, an optimal response strategy can then be developed. It should be noted that the response will also depend on the nature of the disease. In the case of CSF, a persistent carrier state in pigs exists, but this is not the case for FMD. This also needs to be taken into account when assessing the role a species may play in maintaining and spreading disease.

The sensitivity analysis of the simulation model used in this study identified (as expected) the critical importance of understanding within- and between-species transmission. We assumed that the daily probability of infection occurring, given that two wild pig herds (infectious and susceptible) come into contact, was 0.27 when the infectious group is fully infectious. It should be noted that the actual parameter value is weighted by within-group prevalence of the infectious group, so that it is initially low when the herd is first infected, increases as the disease spreads within the herd and falls as individual animals become immune. The actual average daily value over the full infectious period was 0.10 in our simulations. In essence, if two pig herds' home ranges intersect on any given day, the average daily probability that transmission would occur is approximately 10%. This value will vary with the stage of infection in the infectious herd. Also, transmission based on the intersection of home range assumes both direct and indirect contact; that is, the temporal component of actual daily movement within a herd's home range is ignored. Retrospective analysis of model output of pig-only runs (n = 50) indicated that, based on the number of newly infected herds during the simulations, the daily transmission rate was 0.026. Assuming an average 14-day infectious period, this would equate to an interherd basic reproduction number (R_O) of 0.36 (95% confidence interval (CI), 0.23–0.5). Thus, it is not surprising that most simulated epidemics in the pig-only transmission scenario died out. Even doubling the pig-to-pig transmission probability had little effect (results not shown), suggesting that it is a lack of contact between herds in the study area that is important. In fact, the estimated average daily contact rate in our dynamic model (for each simulation, the total contacts that infectious groups had divided by the duration of the outbreak) was 0.225 per day. An infectious herd would have an average of three contacts over its infectious period in this environment, with only approximately 10% chance that transmission would occur (assuming the contacted group is susceptible).

For cattle, retrospective analysis of model output indicated that the daily transmission rate was 0.212 and assuming an average infectious period of 17 days, the estimated R_O was 3.6 (95% CI 3.1–4.1). This value is plausible; for example, Perez et al. estimated that the interherd R_O for the 2001 Argentine FMD outbreak in cattle ranged from 2.4 to 3.8, prior to implementation of control measures.[41] In contrast, we estimated the R_O for FMD transmission between domestic pig herds in Taiwan in 1997[35] (based on 717 herds infected during the first 2 weeks prior to implementation of mass vaccination and an average herd infectious period of 14 days) to be approximately 2.0. This illustrates the unique characteristics of the ecosystem simulated in the current study; the grazing cattle population is likely typical of extensively managed systems throughout the world, whereas disease transmission in the wild pig population is very different to the situation in domestic pig production systems. When these two species are considered within the same wildlife–livestock ecosystem, the spread of FMD predicted by disease modelling can reveal insights that inform disease control policy.

Conclusions

Within the studied ecosystem, the ability of each species to spread and sustain FMD is likely different. Because of management (cattle maintained at much higher density), ecology (cattle can roam further from water sources) and epidemiology (cattle might act as the disease reservoir in this ecosystem), control of the disease in cattle needs to be prioritised. However, to quickly achieve eradication and, importantly, to demonstrate disease freedom, response strategies must include wild pigs. The results of this simulation study puts into perspective the role that wild pigs might play in an incursion of FMD. The eradication of wild pigs will not substantially reduce the risk of FMD outbreaks in such northern Australian ecosystems, but their control remains important after an outbreak occurs.

Acknowledgments

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Evaluating vaccination strategies to control foot-and-mouth disease: a model comparison study

S. E. ROCHE[1]*, M. G. GARNER[1], R. L. SANSON[2], C. COOK[3], C. BIRCH[3],
J. A. BACKER[4], C. DUBE[5], K. A. PATYK[6], M. A. STEVENSON[7], Z. D. YU[8],
T. G. RAWDON[8] AND F. GAUNTLETT[3]

[1] *Epidemiology and One Health Program, Department of Agriculture, ACT, Australia*
[2] *AsureQuality Limited, Palmerston North, New Zealand*
[3] *Animal Health and Veterinary Laboratories Agency, Weybridge, UK*
[4] *Central Veterinary Institute of Wageningen UR, Lelystad, The Netherlands*
[5] *Animal Health Risk Assessment Unit, Canadian Food Inspection Agency, Ontario, Canada*
[6] *Animal and Plant Health Inspection Service, Veterinary Services, Science Technology and Analysis Services, Center for Epidemiology and Animal Health, United States Department of Agriculture, Colorado, USA*
[7] *Faculty of Veterinary Science, The University of Melbourne, Parkville, Victoria, Australia*
[8] *Investigation & Diagnostic Centre and Response Directorate, Ministry for Primary Industries, Wellington, New Zealand*

SUMMARY

Simulation models can offer valuable insights into the effectiveness of different control strategies and act as important decision support tools when comparing and evaluating outbreak scenarios and control strategies. An international modelling study was performed to compare a range of vaccination strategies in the control of foot-and-mouth disease (FMD). Modelling groups from five countries (Australia, New Zealand, USA, UK, The Netherlands) participated in the study. Vaccination is increasingly being recognized as a potentially important tool in the control of FMD, although there is considerable uncertainty as to how and when it should be used. We sought to compare model outputs and assess the effectiveness of different vaccination strategies in the control of FMD. Using a standardized outbreak scenario based on data from an FMD exercise in the UK in 2010, the study showed general agreement between respective models in terms of the effectiveness of vaccination. Under the scenario assumptions, all models demonstrated that vaccination with 'stamping-out' of infected premises led to a significant reduction in predicted epidemic size and duration compared to the 'stamping-out' strategy alone. For all models there were advantages in vaccinating cattle-only rather than all species, using 3-km vaccination rings immediately around infected premises, and starting vaccination earlier in the control programme. This study has shown that certain vaccination strategies are robust even to substantial differences in model configurations. This result should increase end-user confidence in conclusions drawn from model outputs. These results can be used to support and develop effective policies for FMD control.

Key words: Disease spread, foot-and-mouth disease, model comparison, modelling, relative validation, vaccination.

* Author for correspondence: Ms. S. E. Roche, Epidemiology and One Health Program, Department of Agriculture, ACT, Australia.
(Email: sharon.roche@agriculture.gov.au)

INTRODUCTION

Disease simulation models are widely used as decision support tools to aid in planning for disease outbreaks, predicting or assessing outbreaks in real-time and as training tools in simulation exercises [1, 2]. Simulation models can offer valuable insights into the effectiveness of different control strategies and act as important decision support tools by comparing and evaluating outbreak scenarios and control strategies [3 5]. Decision makers need to have confidence that advice based on model outputs is reliable if models are to be used to inform disease control policy. Underlying assumptions and model limitations also need to be made transparent and communicated effectively to decision makers.

Criticism of the use and value of modelling is not uncommon [6, 7]. Careful evaluation of a model is important to ensure it represents the real-life system appropriately, is fit for purpose, and its operation and outputs are transparent and well communicated to decision makers. Part of this evaluation includes model verification, a process that checks whether a model is correctly implemented and matches underlying assumptions and specifications relative to the model concept. This may involve a structured assessment of the programme, checking the model with experts, examining model outputs for 'correctness', and comparing models against others under the same set of starting parameters [5]. A number of studies have used this latter approach [1, 2, 8, 9]. Model validation checks the accuracy of a model's representation of the real system. As explained in Dubé *et al.* [8] 'an infectious disease model is said to be internally valid when its outputs make epidemiological sense given the underlying population dataset and parameters used to initiate the simulations. External validity is assessed when model predictions are comparable with one or more real epidemics.'

Spanning 2005 2010, members of the Quadrilateral Group of countries (QUADS: Australia, Canada, New Zealand, USA) were involved in a study comparing foot-and-mouth (FMD) simulation models [8]. Building on this experience, a new study on the use of vaccination in FMD control was initiated through QUADS, and also included the UK and The Netherlands. The study used a multi-model comparison approach to compare different vaccination strategies in a FMD outbreak based on the UK's 2010 FMD simulation exercise, 'Exercise Silver Birch' [10]. Exercise Silver Birch was chosen as it provided

a plausible multi-focal outbreak and ready-to-use data. Each model was set up and parameterized to represent the scenario. Parameter input values for the models reflected UK settings and FMD contingency plans to ensure consistency between models and their outputs. The study aimed to compare models under a common scenario, and understand how these model differences might influence the effectiveness of vaccination in controlling an FMD outbreak.

The use of vaccination to augment control of an FMD outbreak in a previously FMD-free country is increasingly being recognized as a potentially important component of the response. This is particularly so when standard zoo-sanitary measures have been unsuccessful in eradicating the disease and community concern over the large-scale slaughter of animals has grown, as was seen in the recent Korean [11] and Japanese FMD outbreaks [12]. Recent changes in the international guidelines on regaining FMD-free status following an outbreak have also reduced the time period before countries can regain their FMD-free status when using vaccination [13]. Many countries have or are developing contingency plans and vaccine supply arrangements. However, there is considerable uncertainty as to when and how vaccination should be used, and how vaccinated animals should be managed. For countries with significant exports of livestock and livestock products this is of particular concern, because under the current conditions the presence of FMD-vaccinated animals in the population could be expected to cause market access difficulties [1]. Under a 'vaccinate-to-live' policy, where vaccinated animals remain in the population, FMD-free status can be recovered 6 months after the last reported case, compared to 3 months under a 'stamping-out' policy [13]. Although a 3-month recovery period applies in a 'vaccinate-to-cull' policy, market delays are expected due to the added surveillance requirements for proof of freedom status and delays in removing vaccinates following the outbreak [1]. Consequently, this is an important issue for policy planners and disease managers.

The success of a vaccination programme to control FMD is expected to vary depending on the approach taken, response goals and programme management. A number of recently published articles demonstrate the various vaccination approaches that can be used in the control of FMD [1, 14 16]. For this study, advice was sought from disease managers in the participating countries and directly from chief veterinary officers at the 2012 QUADS Annual Meeting in

Canada. The key factors that were considered for a vaccination programme included the vaccination approach (suppressive *vs.* protective), timing (when vaccination is carried out relative to the date of first detection), species to vaccinate, vaccination zone sizes, deployment methods, and resourcing. These factors were used to develop a series of 12 control strategies suitable for each model's configuration and requirements. A model comparison approach was used to evaluate the effectiveness of the strategies in controlling a FMD outbreak in the UK. The study also aimed to identify and explain any differences in results between models.

MATERIALS AND METHODS

FMD models

Models from five countries participated in the study:

(1) *AusSpread   Australian Department of Agriculture* [4, 17, 18]. AusSpread is a stochastic spatial simulation model that simulates the spread and control of FMD in livestock populations at a regional scale. AusSpread uses the farm as its unit of interest and FMD transmission is modelled through five discrete pathways: farm-to-farm animal movements, local spread (infection of farms within close geographical proximity by unspecified means), indirect contact (via contaminated fomites or animal products), animal movements via saleyards or markets and windborne spread. For FMD control, AusSpread is configured to support the range of mitigations described in Australia's contingency plans for FMD with the effectiveness of these measures dependent on resources [19].

(2) *NAADSM North American Animal Disease Spread Model (NAADSM) Development Team* [20]. NAADSM is a stochastic, spatial, state-transition simulation model designed to simulate the spread and control of highly contagious diseases between herds in a population of susceptible animals. User-established parameters define model behaviour in terms of disease progression; disease spread by direct contact, indirect contact, and windborne dissemination; and the application of control measures such as quarantine, movement restrictions, depopulation, and vaccination. NAADSM has been developed through a continuing international collaboration involving researchers from the USA and Canada, along with

support, involvement, and advice from a broad international pool of subject-matter experts.

(3) *InterSpread Plus (IS+).* IS+ is a spatial and stochastic simulation model of infectious disease in domestic animal populations [21, 22]. IS+ is a state-transition model [23] meaning that the epidemiological units of interest (farm locations) exist in either the susceptible, infected and not-at-risk state at any given time. Similar to AusSpread and NAADSM, IS+ uses a series of user-defined parameters to define the spread of infectious agent from one farm location to another: local spread, windborne spread, and direct and indirect contacts. Control measures such as depopulation, vaccination, and movement restrictions in addition to varying disease surveillance intensity can be simulated, with the ability to carry out each of these activities subject to user-defined resource constraints.

(4) *Exodis.* Exodis-FMD™ is a stochastic, spatial, state-transition simulation model for FMD outbreaks in the UK. Virus transmission is simulated between and within herds, which are represented to an individual species level. User-defined epidemiological parameters are used to describe disease progression and transmission. Control measures for FMD are explicitly included in the model as specified in the UK FMD Disease Control Strategy for Great Britain (Defra, crown copyright 2011). Exodis was developed by Risk Solutions after the 2001 FMD epidemic in the UK, commissioned by the Department for Environment, Food and Rural Affairs (Defra), with the involvement of technical experts.

(5) *The Netherlands model (NL)   Central Veterinary Institute of Wageningen UR* [16, 24]. NL is an individual-based stochastic spatial simulation model that describes FMD virus transmission on two levels: between animals and between herds. Results from vaccination and transmission experiments serve to parameterize the transmission model between animals, whereas the parameters for the between-herd model are estimated from the 2001 FMD epidemic in The Netherlands. The model distinguishes between cattle, sheep and pigs, and takes the relative infectivity and susceptibility of herd types and assortative mixing between herd types into account.

All models simulate the spread of disease between farms; however, the Exodis and NL models also

simulate the spread of disease within farms. The remaining models approximated this process by using prevalence curves for each farm type to represent the varying infection pressure generated by an infected farm over time. The first three models can be described as micro-simulation models where discrete spread pathways are used to simulate FMD transmission including direct animal movements, indirect contact transmission between farms, local spread, and windborne spread. For more details on these models refer to Dubé *et al.* [8]. The NL model uses a single spatial kernel where all transmission routes are aggregated with a probability of transmission depending on the distance between infected and susceptible farms. Exodis takes a hybrid approach using a spatial kernel to represent local spread and indirect contact transmission and separate pathways for windborne spread and direct animal movement transmission.

Three of the models used in this study (AusSpread, IS+, NAADSM) have been used previously in various model comparison studies [2, 8 9]. For the remaining models, this study provided an opportunity to compare models through a relative validation process [9].

Outbreak scenario

Data from the 2010 UK FMD exercise, Exercise Silver Birch, was used as the basis for the study [10]. The exercise was based on a multifocal outbreak with detailed outbreak history and documented spread of disease that could be used by the modelling teams to set up their respective models. The UK provided population data and transmission parameter values. During the set-up phase the capabilities of each model were discussed and parameter estimates and control strategies defined so that each team could configure their model to represent the same set of epidemiological assumptions and inputs. Individual models attempted to follow these settings as closely as possible, but due to model differences it was not always possible to represent the start-up conditions exactly. Where results varied significantly between models these differences are considered in the Discussion.

The study area represented 38 counties in central England and Wales. The population data was derived from the 2006 UK census with almost 65 000 premises comprising dairy, beef, sheep, pigs, and mixed cattle, sheep and pig farms (Table 1).

Disease transmission occurred via direct contact, indirect contact, windborne and local area spread. To simplify matching of the models, long-range windborne

spread was not included, because runs of Exodis during Exercise Silver Birch showed negligible numbers of cases due to that mechanism. The scenario definition used in Exercise Silver Birch included an 18-day delay from introduction until the incursion was detected by veterinary authorities (silent spread phase), by which time there were 20 undetected infected holdings in three separate foci in the study area. At the time of first detection only one infected premise (IP) had been confirmed. For consistency, this scenario was used as the initial outbreak situation for evaluating control strategies. That is, each team set up their model with the infection status and histories of these premises and all subsequent modelling scenarios began by simulating forward from the day of first detection.

Control measures

The simulated control programme was consistent with UK contingency plans [25]. It was assumed that a national livestock movement standstill would be in place for the duration of the epidemic. Control measures included livestock movement restrictions around IPs (with 100% compliance), surveillance and tracing operations, and stamping out of all FMD susceptible livestock on IPs. This approach represented the stamping-out control strategy with no vaccination (SO). Estimates of resources to conduct depopulation, surveillance and vaccination were provided by the UK. Initial estimates were subsequently reduced because they were considered overly optimistic compared to expected capacity of the other participating countries, as well as to take account of recent reductions in government-supported resources in the UK.

Vaccination strategies

To assess the effect of vaccination on FMD control, 11 vaccination strategies were defined based on a number of operational factors and taking into account the contingency plans and policy priorities in participating countries. These factors included the approach to vaccination, timing, size of vaccination zones, species vaccinated, and deployment of vaccination.

The approach to vaccination may be suppressive (SV), where at-risk animals are vaccinated within defined areas around IPs to control the spread of disease and reduce viral excretion, or protective (PV), where at-risk animals in defined areas beyond the immediate surroundings of IPs are vaccinated in advance of potential exposure to protect animals from

Table 1. *UK farm population data used in a simulated outbreak of foot-and-mouth disease in the UK*

| | | Average animal numbers | | |
| | | Cattle | Sheep | Pigs |
Type of holding	No. of holdings			
Dairy	423	60		
Beef	11 993	53		
Pigs*	1773			1052
Sheep	20 138		221	
Mixed beef/sheep/pig	17 325	72	652	13
Mixed dairy/sheep/pig	175	43	294	0
Mixed beef/dairy/pig	8086	161		3
Mixed beef/dairy/sheep/pig	4906	141	0	3
Total	64 819			

* Defined as holdings with >1000 pigs. Holdings with <1000 pigs were classified as mixed based on other species present.

Table 2. *Description of the stamping-out (SO) and vaccination scenarios used in simulated outbreaks of foot-and-mouth disease in the UK*

ID	Vaccination approach	Vaccination zone size (km)	Timing† (days)	Species vaccinated	Retrospective (R) or prospective (P)	Order of vaccine deployment
SO						
V1	SV	3	14	All[a]	P	Random
V2	SV	3	14	All	P	Outside in
V3	SV	3	14	All	P	Large farm size first
V4	SV	3	7	All	P	Outside in
V5	SV	3	28	All	P	Outside in
V6	SV	1	14	All	P	Outside in
V7	SV	5	14	All	P	Outside in
V8	SV	3	14	Cattle only	P	Outside in
V9	PV	3 7	14	All	P	Inside out
V10	SV	3	14	All	R	Outside in
V11	PV	5 10	14	All	P	Inside out

SV, Suppressive vaccination; PV, protective vaccination.
*Cattle, sheep, pigs.
† Delay between first detection in the population and initiation of a vaccination campaign.

infection [19]. The sizes of the vaccination zones evaluated were 1 km, 3 km, or 5 km in radius around IPs for SV, or a band with a 3-km inner radius and a 7-km outer radius for PV. Three delays in initiation of a vaccination programme following the first detection were considered 1, 2 or 4 weeks. Two species-related vaccination approaches were compared: vaccination of all susceptible species or cattle-only. This was based on advice provided by disease managers. Cattle-only vaccination represents the preferred UK approach (F. Gauntlett, personal communication). Under the scenario considered, relatively few pig farms were infected compared to other species and culling was considered to be a more effective approach than vaccination for managing them. Sheep

were considered a lower priority for vaccination due to their lower infectiousness, susceptibility and value compared to cattle. The deployment of vaccine could progress in a random fashion, from the outside of the ring inwards or vice versa, or vaccination of larger farms before smaller farms. The other deployment option was vaccination around all IPs from the onset of the control programme (retrospective) or only around newly declared IPs (prospective).

In total, 12 control strategies (one without vaccination and 11 with vaccination) were assessed (Table 2). The SO strategy was run for comparison and calibration of the models. It should be noted that all vaccination strategies operated in conjunction with standard zoo-sanitary measures including the

culling of all FMD-susceptible animals on IPs. NAADSM could only run six of the strategies due to limitations in the model's ability to simulate the vaccination approach and deployment. For each strategy, 100 iterations were run. Each simulation was run until FMD was eradicated. The following outputs from each model were recorded:

(1) number of IPs;
(2) spatial distribution of IPs;
(3) outbreak duration (number of days from the start of the control programme until the last case is detected plus 21 days). It was assumed it would take 21 days following the last case to complete all decontamination, disposal, surveillance and vaccination activities;
(4) number of vaccinated farms.

A list of the key parameter inputs for disease spread and control measures are provided in Table 3.

Statistical and spatial analyses

The size of predicted outbreak areas for each iteration of each model for the 12 strategies (one SO and 11 vaccination strategies) were quantified by plotting the point locations of predicted IPs using a geographical information system (GIS). A 10-km buffer was created around each point location and contiguous buffered areas dissolved to create predicted outbreak areas. The sizes of the predicted outbreak areas (in km^2) were calculated using GIS.

Strategies were organized into five logical groupings (as shown in Figs 3 7) for comparison. For each strategy group two-way ANOVAs were performed using the predicted number of IPs, the predicted epidemic duration and predicted outbreak area as the outcomes. Model (with five levels) and strategy (with three levels) were included as explanatory variables. Because outcomes from the SO strategy were expected to differ from the vaccination strategies and because it was of interest to identify differences among vaccination strategies, SO was excluded in each of the ANOVA calculations. Each of the outcome variables was log-transformed to ensure that the error values from ANOVAs were homogeneous and normally distributed.

Intensity maps showing the predicted number of infected farms/km^2 were calculated using the spatstat package [26] implemented in R [27]. These analyses were performed using a regular grid of 200×200 cells superimposed over the study area with the standard deviation of the Gaussian kernel (the bandwidth) fixed at 10 km.

RESULTS

Descriptive statistics of the predicted number of IPs, predicted epidemic duration (in days) and the predicted number of vaccinated farms by strategy and model are shown in Table 4. Due to the limited number of strategies completed by NAADSM, results will focus on the other four models, unless available for NAADSM.

For the SO strategy, Exodis generated the largest epidemics in terms of the median predicted number of IPs whereas IS+ generated the smallest (Table 4). The NAADSM and NL models generated epidemics with the widest variation. Vaccination (strategies V1 V11) reduced the predicted number of IPs, epidemic duration, and variability in the outcome compared to the SO strategy (Fig. 1), with the proportional reduction in each outcome varying across each of the five models. The spatial distribution of predicted IP locations for the SO strategy varied across models (Fig. 2). AusSpread and Exodis predicted three distinct clusters of infection, IS+ predicted two, while the NAADSM and NL models predicted smaller and denser clusters of infection, with one cluster larger than the others. Similar spatial patterns were evident for each of the vaccination strategies; however; the size of the predicted outbreak areas were reduced (data not presented).

Figures 3 7 are box and whisker plots showing the ratio of the predicted number of IPs to the median number of IPs for the SO scenario computed across all models (Figs 3a 7a) and the ratio of predicted epidemic duration to the median epidemic duration for the SO scenario computed across all models (Figs 3b 7b), by scenario groupings. For all five models the order of vaccination random (V1), outside in (V2) or large farms first (V3) did not significantly differ in terms of the predicted number of IPs ($F_{2,1293} = 0.958$, $P = 0.38$, Fig. 3a) and predicted epidemic duration ($F_{2,1293} = 0.697$, $P = 0.50$, Fig. 3b).

All models predicted smaller numbers of IPs when vaccination start was at 7 days post-detection (V4), compared to vaccination start at 14 days (V2) and 28 days (V5) (Fig. 4a). For all models increasing vaccination start to 28 days (V5) increased predicted epidemic duration compared to vaccination start at 7 days (V4) (Fig. 4b).
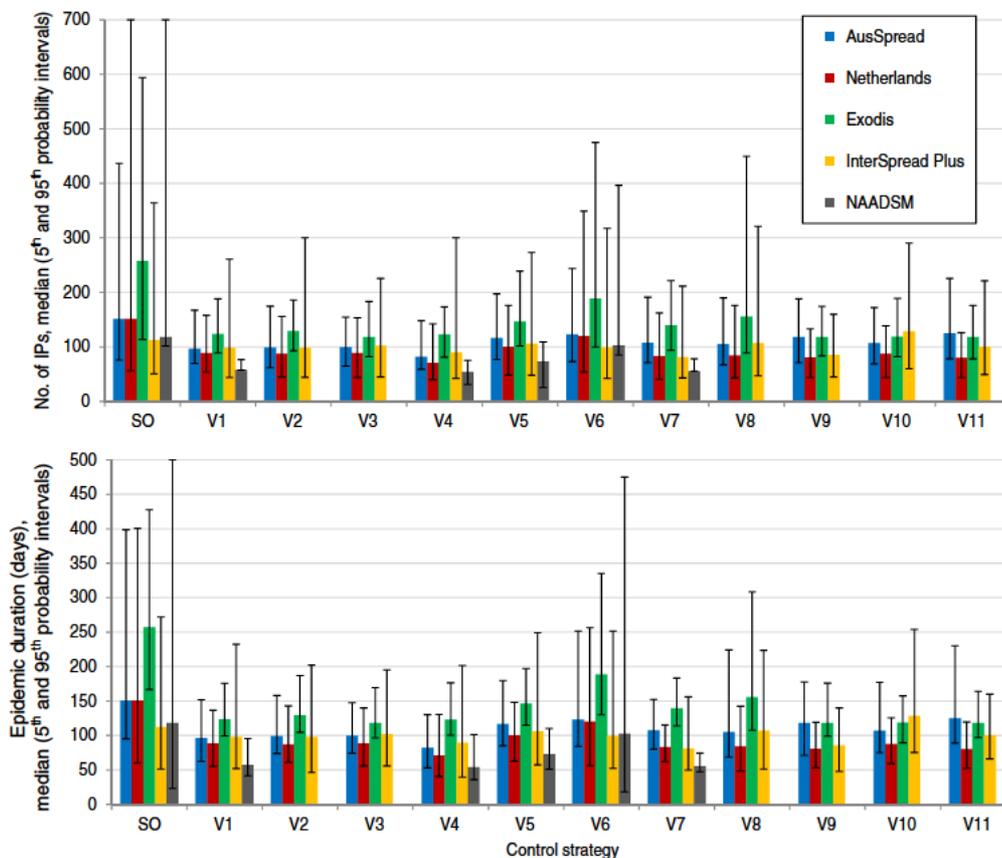
Fig. 1. Predicted median (5th and 95th probability interval) epidemic length and median (5th and 95th probability interval) number of infected premises (IPs) for 12 control strategies in a simulated outbreak of foot and mouth disease in the UK. Models: AU, AusSpread; EX, Exodis; IS+, InterSpread Plus; NA, NAADSM; NL, The Netherlands.
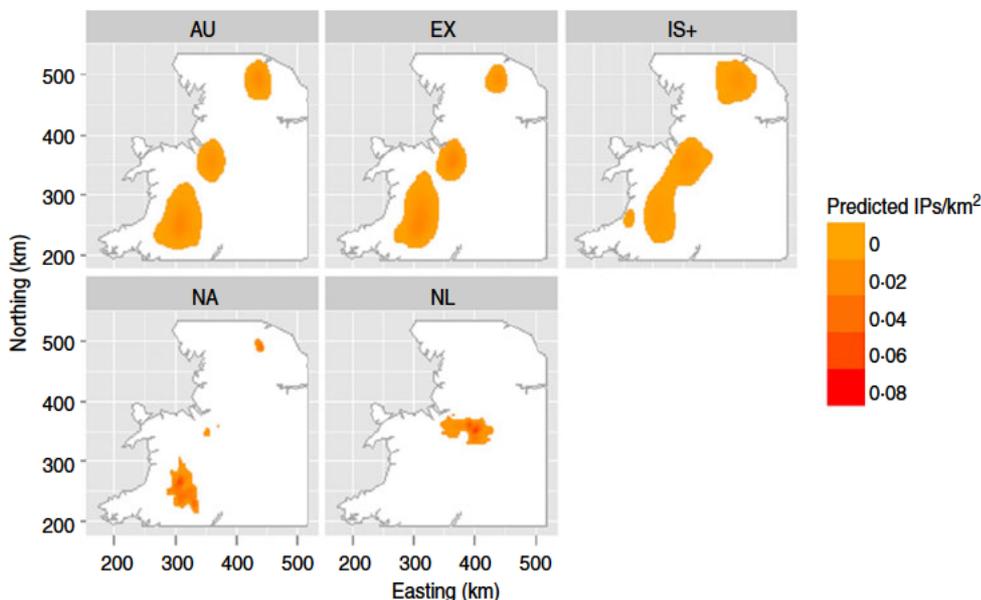

Fig. 2. Intensity of predicted infected premises for the stamping out strategy expressed as the number of infected premises/km² averaged across 100 iterations in a simulated outbreak of foot and mouth disease in the UK. Models: AU, AusSpread; EX, Exodis; IS+, InterSpread Plus; NA, NAADSM; NL, The Netherlands.

Table 3. *Key input parameters used in simulated outbreaks of foot-and-mouth disease in the UK*

| Operation	Parameter	Value	Reference
Spread	Distance (km) for		Birch, pers. comm., 2012 (Exodis manual)
	• local spread	3	
	• indirect spread	80	
	• windborne spread	Varied	
	Latent period (days)	Triangular (2,5,12) or Gamma (shape 3·58, scale 1·56)	Sanson *et al.* [9]
	Onset of clinical signs from start of infectious period (days)	Triangular (0,0,1) except sheep (1,2,3)	
	Daily probability of detection	Cattle 0·6	
		Pigs 0·5	
		Sheep 0·25	
	Infectious period herd level (days)	Triangular	
		Dairy (14,22,35)	
		Pigs (7,15,28)	
		Sheep (15,28,45)	
		Beef (14,26,40)	
Movement controls	Protection zone (PZ) radius [area where stringent movement restrictions apply around infected premises (IPs)]	3 km	Defra [25]
	Surveillance zone (SZ) radius (area where less stringent movement conditions apply around IPs)	10 km	
Surveillance	Surveillance priority	Premises in PZ>trace premises>suspect premises	Birch, pers. comm., 2012 (Exodis manual)
	Number of surveillance visits conducted per premises in PZ	Week 1: 1/day	
		Week 2: 1 every other day	
		Weeks ⩾3: 1/week	
	Number of surveillance teams	Days 1 2: 0	
		Day 3: 2	
		Days 4 5: 60	
		Days 6 7: 89	
		Days 8 12: 180	
		Days 13 32: 313	
		Days ⩾33: 720	
	Time to complete surveillance visit/team/farm (days)	0·5	
	Backward tracing period (days)	14	
	Tracing effectiveness (proportion of contacts able to be correctly traced)	50% indirect	
		85% direct	
	Time to complete trace (days)	Betapert (1,2,4)	

Table 3 (*cont.*)

| Operation	Parameter	Value	Reference
Culling	Maximum time to complete culling/farm	1 day	Birch, pers. comm., 2012
	Number of culling teams	Days 1 2: 0	(Exodis manual)
		Days 3 5: 37	
		Days 6 12: 60	
		Days 13 17: 80	
		Days $\geqslant$18: 105	
	Time to cull one farm/team	2 h set up time $+$ 0·016 h/cow 0·006 h/pig 0·0065 h/sheep	
	Average number of dangerous contact premises generated per IP	2·34	
Vaccination*	Maximum time to complete vaccination/farm	1 day	
	Number of vaccination teams	Days 1 6: 0	
		Days 7 13: 50	
		Days 14 20: 100	
		Days $\geqslant$21: 150	
	Time to vaccinate one farm	1 h $+$2 min/animal	
	Duration of immunity (days)	Betapert (180,210,240)	
	Time to gain full immunity (days)	Triangular (4,5,6)	
	Farm level susceptibility following vaccination (%)	Days 1 3: 100	
		Day 4: 75	
		Day 5: 50	
		Day 6: 0	
	Reduction in transmission if farm infected at time of vaccination (%)	50	

* Resources for vaccination do not compete with those for surveillance and culling operations.
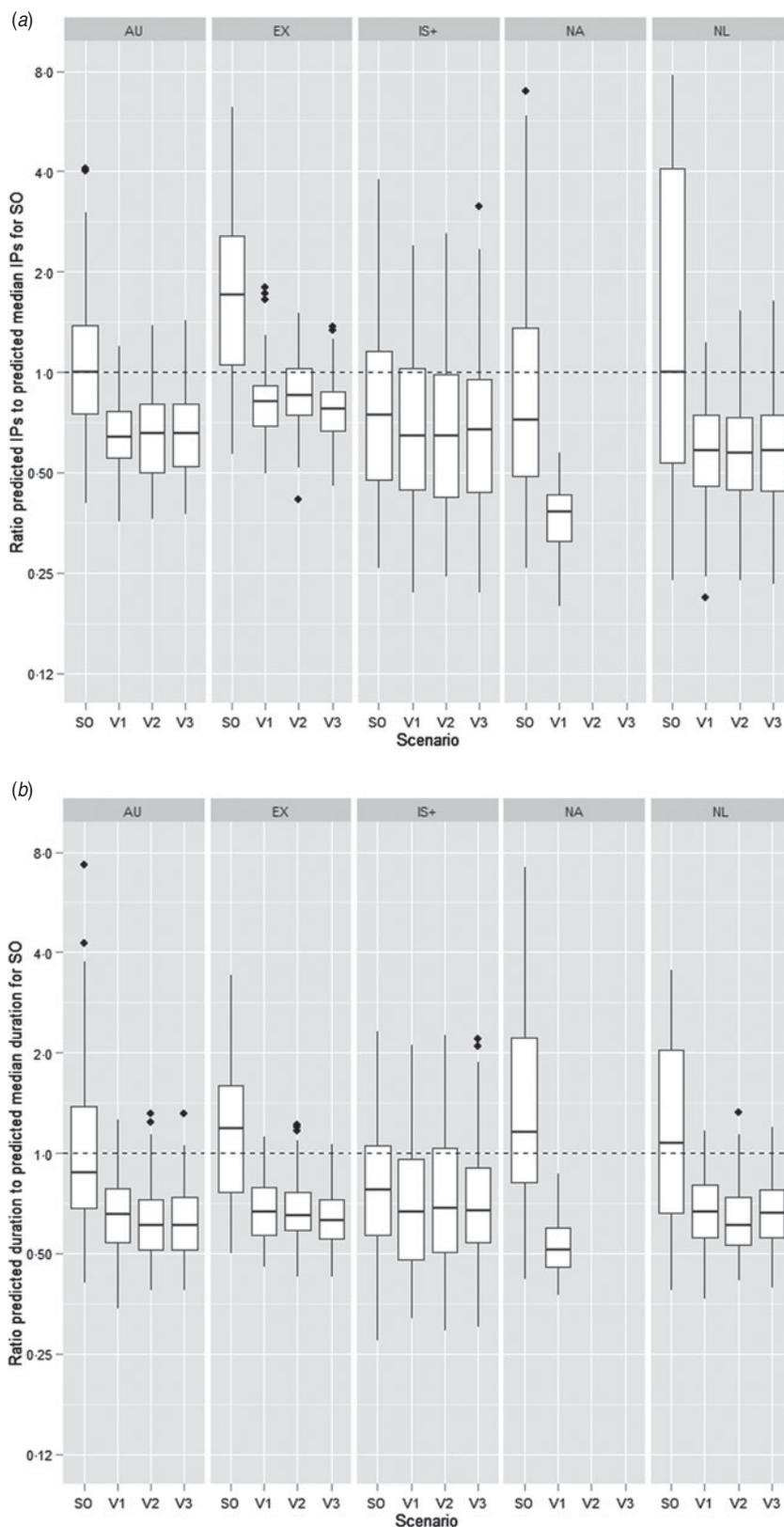
Fig. 3. Box and whisker plots showing: (*a*) the ratio of the predicted number of infected premises (IPs) to the median number of IPs for the stamping out (SO) scenario and (*b*) the ratio of the predicted epidemic duration to the median epidemic duration for the SO scenario when vaccination is deployed randomly (V1), outside in (V2) or on large farms first (V3) in a simulated outbreak of foot and mouth disease in the UK. Models: AU, AusSpread; EX, Exodis; IS+, InterSpread Plus; NA, NAADSM; NL, The Netherlands.
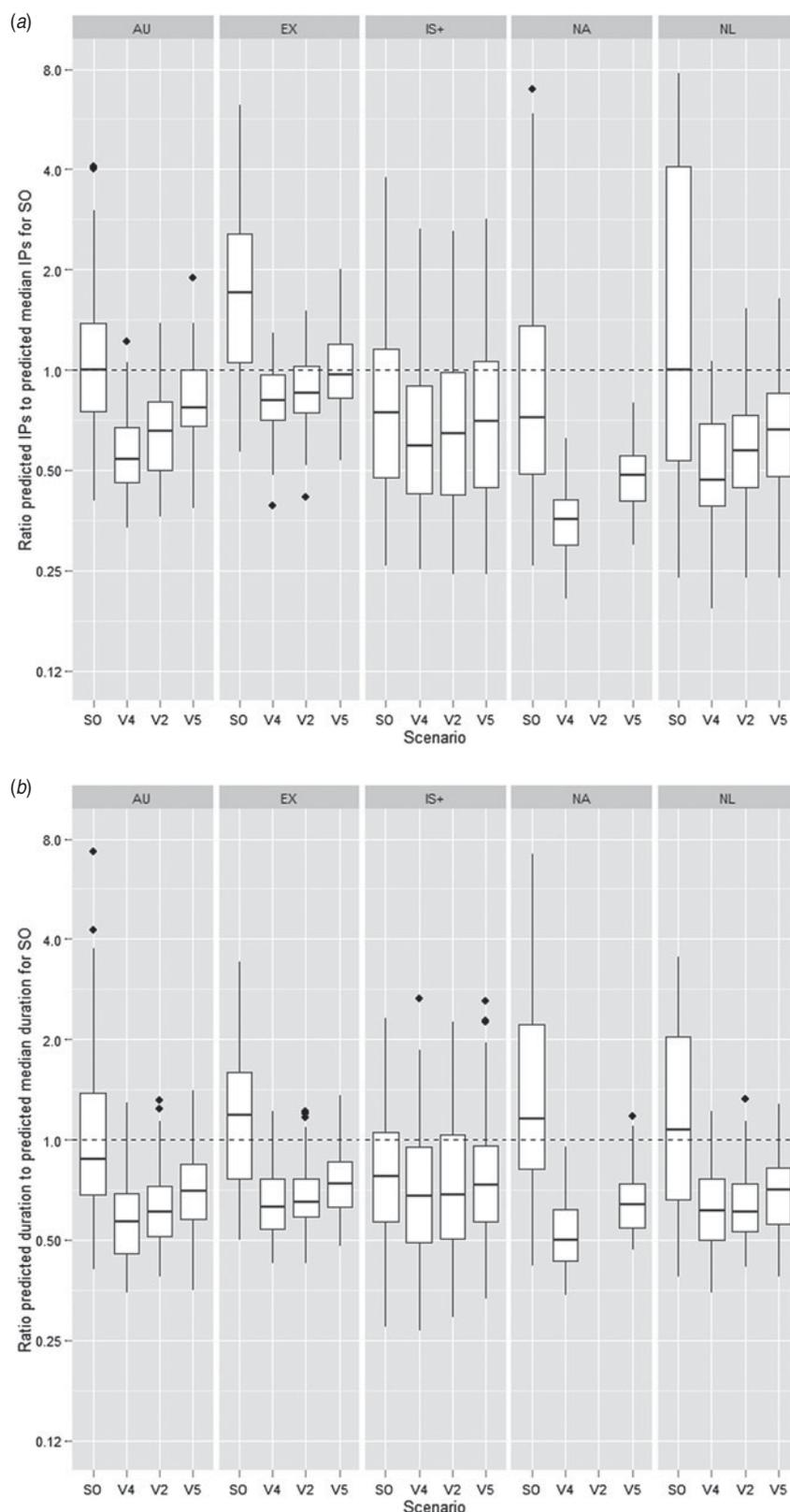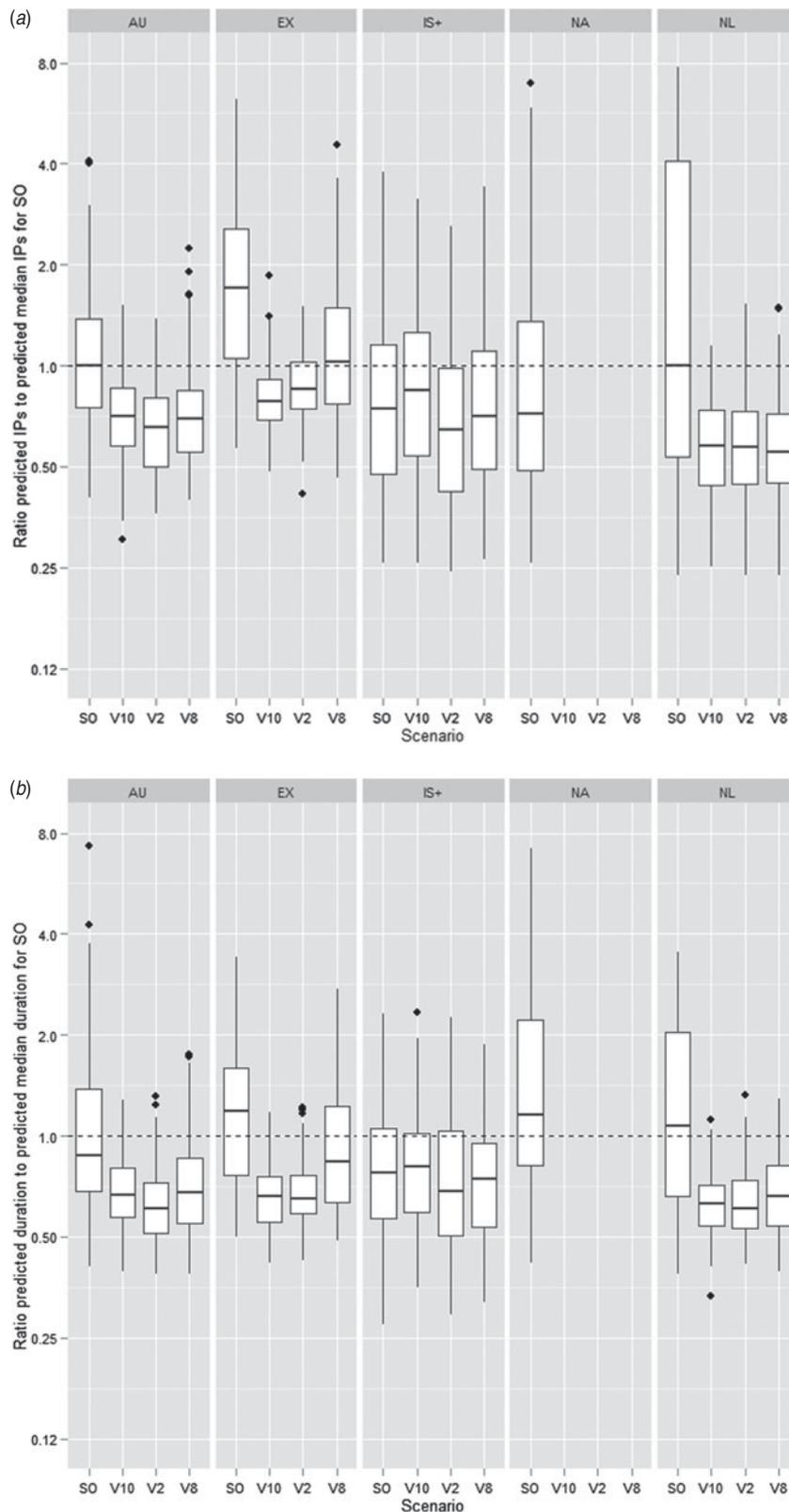
Fig. 4. Box and whisker plots showing: (*a*) the ratio of the predicted number of infected premises (IPs) to the median number of IPs for the stamping out (SO) scenario and (*b*) the ratio of the predicted epidemic duration to the median epidemic duration for the SO scenario when vaccination is started 7 days (V4), 14 days (V2), and 28 days (V5) into the control programme in a simulated outbreak of foot and mouth disease in the UK. Models: AU, AusSpread; EX, Exodis; IS+, InterSpread Plus; NA, NAADSM; NL, The Netherlands.
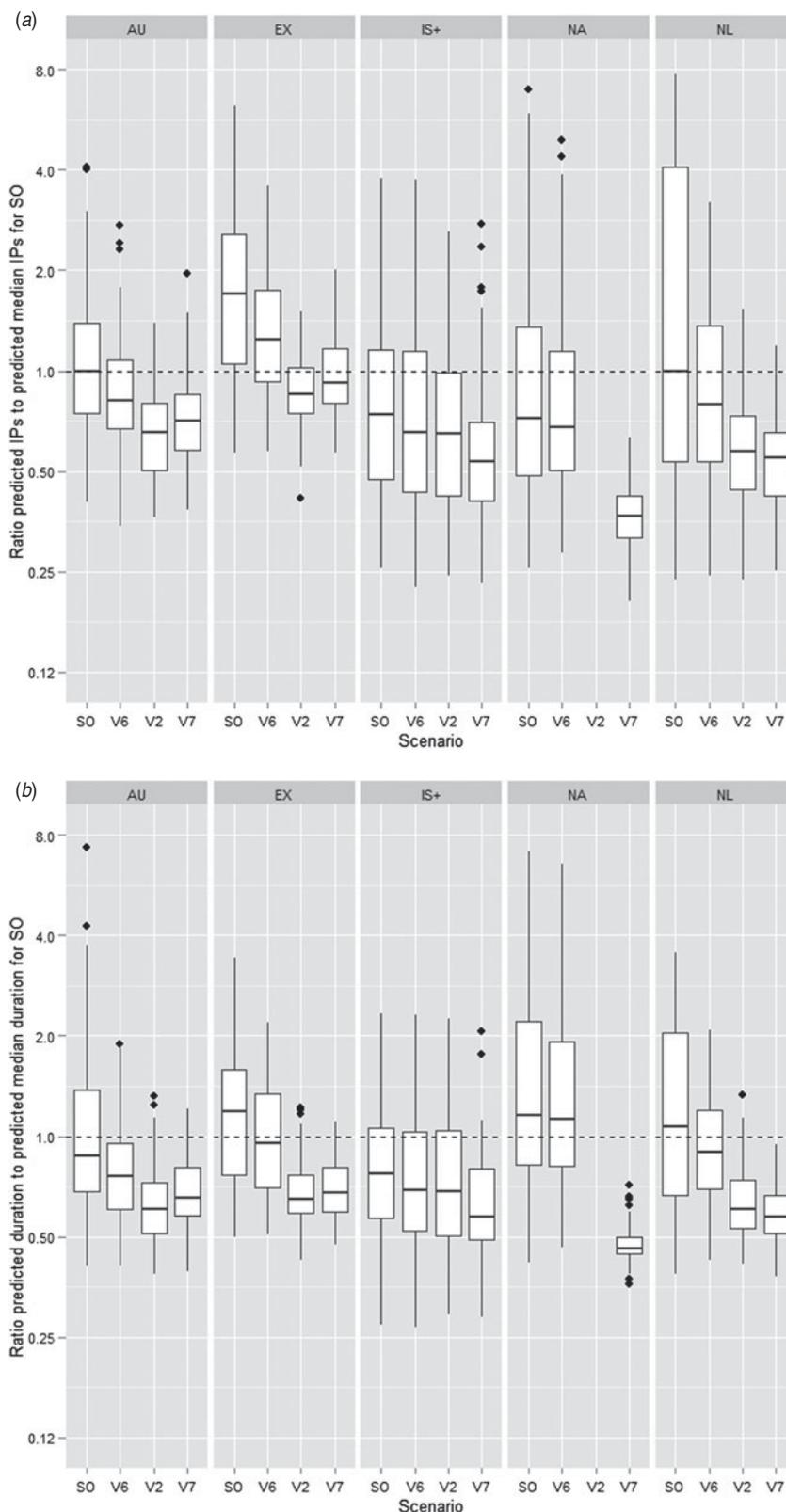
Fig. 5. Box and whisker plots showing: (a) the ratio of the predicted number of infected premises (IPs) to the median number of IPs for the stamping out (SO) scenario and (b) the ratio of the predicted epidemic duration to the median epidemic duration for the SO scenario when vaccination radii of 1 km (V6), 3 km (V2), and 5 km (V7) are used in a simulated outbreak of foot and mouth disease in the UK. Models: AU, AusSpread; EX, Exodis; IS+, InterSpread Plus; NA, NAADSM; NL, The Netherlands.
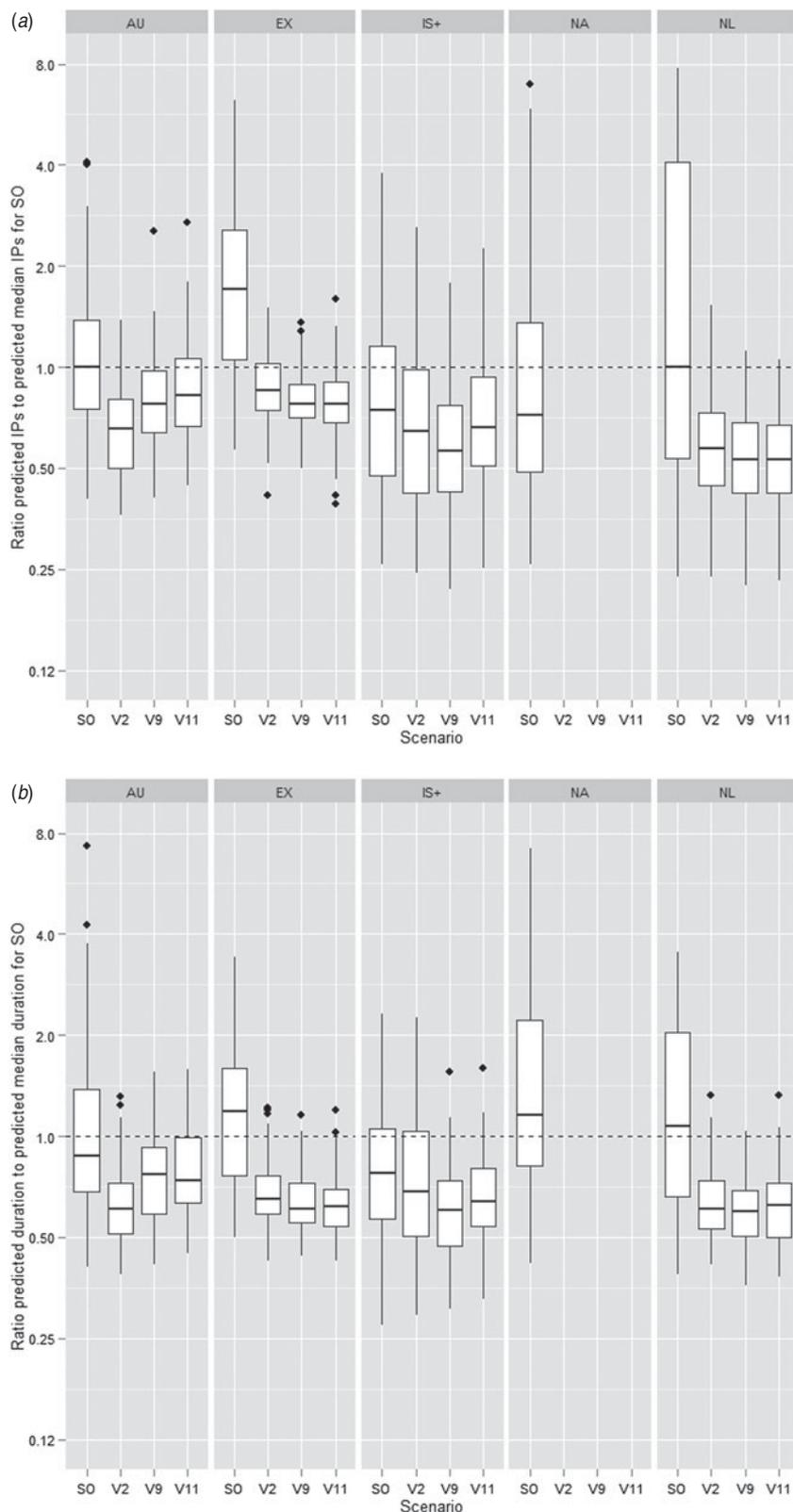
Fig. 6. Box and whisker plots showing: (*a*) the ratio of the predicted number of infected premises (IPs) to the median number of IPs for the stamping out (SO) scenario and (*b*) the ratio of the predicted epidemic duration to the median epidemic duration for the SO scenario using a suppressive approach (V2) compared to a protective approach 3 7 km (V9) or 5 10 km (V11) from identified infected places in a simulated outbreak of foot and mouth disease in the UK. Models: AU, AusSpread; EX, Exodis; IS+, InterSpread Plus; NA, NAADSM; NL, The Netherlands.

Fig. 7. Box and whisker plots showing: (*a*) the ratio of the predicted number of infected premises (IPs) to the median number of IPs for the stamping out (SO) scenario and (*b*) the ratio of the predicted epidemic duration to the median epidemic duration for the SO scenario when all susceptible species are vaccinated (V2) compared to vaccinating only cattle (V8), and when retrospective vaccination is used (V10) in a simulated outbreak of foot and mouth disease in the UK. Models: AU, AusSpread; EX, Exodis; IS+, InterSpread Plus; NA, NAADSM; NL, The Netherlands.

Table 4. *Results for the predicted number of infected premises, epidemic duration, and number of vaccinated farms for the control strategies used in a simulated outbreak of foot-and-mouth disease in the UK*

Strategy	Model	Infected premises (*n*)	Epidemic duration (days)	Vaccinated farms (*n*)
		[median (5th and 95th probability interval)]		
Stamping out	AU	151 (76 436)	132 (76 379)	
	NA	118 (50 1071)	181 (86 944)	
	IS+	113 (51 364)	116 (55 275)	
	NL	151 (56 1005)	160 (69 410)	
	EX	258 (114 594)	179 (88 349)	
V1 (3 km random)	AU	97 (70 167)	98 (64 153)	1169 (727 2044)
	NA	58 (41 77)	77 (61 115)	803 (676 974)
	IS+	98 (44 261)	100 (54 234)	1129 (426 3525)
	NL	89 (54 158)	100 (67 148)	1644 (704 3049)
	EX	124 (89 188)	100 (76 152)	1770 (1157 2671)
V2 (3 km outside in)	AU	99 (62 175)	91 (66 150)	1245 (758 2444)
	IS+	98 (44 300)	103 (51 207)	1141 (423 3922)
	NL	87 (45 156)	91 (65 147)	1515 (652 2870)
	EX	129 (93 186)	98 (73 155)	1775 (1083 2754)
V3 (3 km large farm priority)	AU	100 (65 155)	91 (66 139)	1190 (757 1874)
	IS+	102 (45 225)	101 (55 194)	1290 (418 3267)
	NL	89 (44 153)	100 (67 151)	1602 (632 2941)
	EX	118 (82 183)	95 (73 146)	1691 (1054 2774)
V4 (7 day start to vaccination)	AU	82 (59 148)	85 (56 133)	1233 (875 1968)
	NA	54 (39 75)	75 (57 123)	817 (658 1011)
	IS+	90 (42 300)	102 (52 214)	1266 (601 4367)
	NL	71 (40 142)	92 (61 151)	1430 (768 3103)
	EX	123 (81 173)	95 (72 148)	1993 (1409 2758)
V5 (28 day start to vaccination)	AU	117 (77 197)	105 (74 168)	984 (358 1981)
	NA	73 (50 109)	96 (74 133)	854 (691 1197)
	IS+	106 (48 273)	110 (61 253)	1041 (95 3227)
	NL	100 (48 176)	106 (69 154)	1222 (275 2692)
	EX	147 (102 239)	111 (79 161)	949 (330 2081)
V6 (1 km vaccination zone)	AU	123 (73 244)	114 (75 242)	247 (131 555)
	NA	103 (55 396)	169 (85 541)	268 (159 662)
	IS+	99 (42 317)	104 (57 256)	214 (59 832)
	NL	120 (54 349)	135 (71 271)	398 (108 1317)
	EX	189 (100 475)	144 (85 290)	397 (208 1033)
V7 (5 km vaccination zone)	AU	108 (71 191)	98 (71 143)	2802 (1821 4797)
	NA	56 (38 78)	69 (61 88)	1573 (1353 1963)
	IS+	81 (43 211)	86 (55 161)	2060 (812 6124)
	NL	83 (41 162)	86 (65 118)	2834 (1287 5544)
	EX	140 (94 221)	102 (76 145)	3406 (2292 5162)
V8 (3 km cattle only vaccination)	AU	105 (67 190)	102 (66 221)	880 (547 1541)
	IS+	107 (47 321)	112 (56 228)	1315 (362 4195)
	NL	84 (43 176)	100 (64 158)	942 (346 2037)
	EX	156 (89 450)	126 (78 279)	1352 (805 2596)
V9 (3 7 km protective vaccination)	AU	118 (71 188)	116 (69 175)	4485 (2719 6851)
	IS+	86 (45 160)	91 (53 145)	3062 (1296 6331)
	NL	81 (44 133)	90 (62 128)	4324 (2070 7157)
	EX	118 (84 174)	91 (72 149)	4747 (3490 6543)
V10 (3 km retrospective)	AU	107 (69 172)	100 (68 170)	1525 (962 2579)
	IS+	129 (60 290)	121 (68 246)	1802 (798 3914)
	NL	88 (44 139)	94 (66 132)	1838 (973 3122)
	EX	119 (82 189)	99 (70 138)	1987 (1443 2934)

Table 4 (*cont.*)

Strategy	Model	Infected premises (*n*)	Epidemic duration (days)	Vaccinated farms (*n*)
		[median (5th and 95th probability interval)]		
V11 (5 10 km protective vaccination)	AU	125 (78 225)	111 (75 216)	7528 (4725 11 574)
	IS+	100 (49 221)	96 (62 156)	5509 (3122 10 997)
	NL	80 (44 126)	94 (66 133)	6495 (3350 10 183)
	EX	118 (78 176)	93 (72 139)	6348 (4334 7405)

AU, AusSpread; NA, NAADSM; IS+, InterSpread Plus; NL, The Netherlands; EX, Exodis.

All five models predicted that a 1-km radius vaccination zone (V6) was less effective than a 3-km radius vaccination zone (V2), (Fig. 5*a*, *b*). In all models except IS+, increasing the radius of the vaccination zone to 5 km (V7) produced little or no benefit in terms of a reduction in the predicted number of IPs or a reduction in predicted epidemic duration. For all models, a 3-km vaccination radius (V2) resulted in, on average, between four and five times the number of vaccinated farms compared with a 1-km vaccination radius (V6) and half the number of vaccinated farms compared to a 5-km vaccination radius (V7) (Table 4).

For the suppressive (V2) and protective (V9) vaccination strategies, the predicted number of IPs varied across models (Fig. 6*a*). Compared to SV (V2) all models except AusSpread predicted smaller numbers of IPs for the PV strategy (V9). For all models, more than twice the numbers of farms were vaccinated when the PV approach was used since vaccination areas were larger than those used with SV (Table 4). There was no benefit in increasing the PV radius from 3 7 km (V9) to 5 10 km (V11) with all models predicting similar numbers of IPs (Fig. 6*a*).

Compared to retrospective vaccination (V10), AusSpread and IS+ predicted a smaller number of IPs when a prospective vaccination (V2) strategy was applied. Exodis predicted a larger number of IPs whereas the NL model predicted similar numbers of IPs (Fig. 7*a*). The differences in predicted numbers of IPs across scenarios were statistically significant ($F_{2,1194} = 6.49$, $P < 0.01$).

Vaccination of cattle only (V8) did not significantly increase the predicted number of IPs compared to vaccination of all species (V2) in all models except Exodis. Exodis predicted a greater number of IPs and epidemics of longer duration for V8 compared to V2 (Fig. 7*a*, *b*). Predicted epidemic durations were similar across strategies V10, V2 and V8 for AusSpread, IS+ and NL models.

DISCUSSION

Modelling the use of vaccination as an adjunct to the control of FMD has been a widely published topic in the recent scientific literature [1, 14 17]. The take-home message from many of these studies is that the decision to vaccinate and choice of vaccination strategy will depend on the nature of the outbreak, availability of resources, and socioeconomic factors such as trade and public opinion. While the findings from modelling studies can provide guidance to disease managers on when and how to vaccinate, they also need confidence in the modelling tools when making these decisions. In this study we sought to explore the situations under which vaccination may be of benefit in a FMD outbreak and used five modelling platforms to test how various approaches to vaccination performed in a UK setting.

Under the UK scenario examined in this study, it was clear that vaccination used in conjunction with SO resulted in significantly smaller epidemics than for SO alone. Not only was the median size of an outbreak smaller, but all models also showed that the probability of more severe epidemics was significantly reduced under the vaccination strategies compared to SO on its own. These findings support the value of vaccination as an adjunct to zoo-sanitary measures in FMD control [28]. Vaccination can limit local disease spread around IPs, and despite the delay in development of immunity, can be effective in helping to contain an outbreak. This is particularly the case when disease is widespread or fast spreading, or when authorities anticipate significant resource issues [14, 17, 29, 30]. Backer and co-workers [16] modelled FMD transmission in a dense livestock region in The Netherlands and concluded that vaccination or pre-emptive ring culling was needed as an adjunct to standard control measures. Similar findings have been seen in modelling studies of FMD outbreaks in Denmark [1] and Australia [17].

All models showed that the earlier vaccination is implemented in a control programme the more effective it is likely to be in reducing the size of an outbreak. For this study, the earliest period before vaccine would be available for deployment in the UK was assumed to be 7 days [31]. Our findings are consistent with other modelling studies that show the length of time before vaccination is used in the field is critical to its effectiveness [15, 32]. Porphyre *et al.* [15] showed that a daily delay in using vaccination linearly reduced its effectiveness in terms of numbers of IPs, duration of epidemics, and numbers of vaccinated animals in the population.

Another common finding across the models was that among the vaccination zone sizes simulated, 3-km vaccination zones around IPs resulted in the most benefit in terms of minimizing epidemic size, duration and number of vaccinated farms in the population. Increasing vaccination zone size to 5 km did not always reduce epidemic size or duration but required the vaccination of approximately twice the number of vaccinated farms in the population. It is important to appreciate the assumptions applied in this study: that a national livestock movement standstill was in place for the duration of the control programme and that there was 100% compliance with movement controls of livestock. This means that effectively local and indirect spread were the most important mechanisms by which disease transmission could occur. In the models this is implemented either by spatial kernels (Exodis, NAADSM and NL models) or distance bands (AusSpread, IS+) that are parameterized so that a large number of the new infections tended to occur within 3 km of an IP [33], and the further a susceptible farm is from an IP the less likely it is to become infected. Given this, it is probably not surprising that vaccinating in 3-km rings around IPs proved to be effective with little benefit seen in vaccinating beyond these areas. If farms over a wider area are at risk of infection, then the use of wider rings might need to be considered. Three out of four models suggested that PV was associated with smaller outbreaks than SV, although at the cost of vaccinating more farms in total. Available resources for vaccination may have also influenced these outcomes. Some models (e.g. AusSpread and Exodis) implemented vaccination in strict accordance with the UK resource settings (Table 3) based on animal numbers on farms, with multiple teams allocated to large farms to ensure vaccination would be completed in a single day. As a result, using larger

vaccination zones such as 5-km suppressive rings or 5-km protective bands, a backlog of farms waiting to be vaccinated could build up which would take some time to clear. This had the potential to reduce the benefits of vaccination. By contrast, other models used a simpler approach based on average numbers of farms able to be vaccinated per day.

Three of four models predicted that a cattle-only vaccination strategy was as effective as vaccinating all susceptible species. For these models epidemics were similar between strategies with less farms requiring vaccination under the cattle-only approach. This translates into significantly fewer animals vaccinated as many farms were mixed so only a proportion of the animals on these farms required vaccination. The value of such a strategy is that it significantly reduces the total number of animals vaccinated without compromising the size or length of the epidemic. Similar findings have been reported elsewhere [32]. There are clear advantages to using this strategy as less vaccine is needed and fewer resources are required to vaccinate stock and manage vaccinated animals over the post-outbreak phase. Restrictions in trade and management of vaccinated animals following a FMD outbreak have historically limited the use of vaccination. FMD-free status can be recovered 3 months after the last reported case under SO or a 'vaccinate-to-cull' strategy, where vaccinates are removed from the population, or 6 months if vaccinated animals remain in the population and surveillance to demonstrate absence of FMD circulation is undertaken [13]. In a vaccination strategy where fewer animals are vaccinated, removal of vaccinated animals or post-outbreak surveillance will be simpler and less expensive.

This study provided a means to compare different models and to assess if control strategies produced similar outcomes. This approach provides a relative validation methodology that can enhance end-user confidence in model outputs [2, 8]. For a disease manager it can be disconcerting when different models generate different outcomes for the same type of study scenario. Where the findings are consistent, irrespective of the model used, one can have greater confidence that the outcome is not an artefact or consequence of a specific modelling team's conceptual approach or implementation. From this perspective there is value in model diversity, particularly given differences in modelling objectives, data availability and approaches to parameterization. On the other hand, where differences do occur it is important to understand why these have occurred, recognizing

that all models will have their individual strengths and limitations. Provided these are made clear, the user is then in a better position to assess the findings in terms of his or her particular context.

In our study the process of relative validation was not a trivial one, and Sanson *et al.* [9] provides a good discussion of the challenges in parameterizing and comparing different models. Developing parameters that align with each model's requirements forced each of the modelling teams to assess the way core functions were implemented in their models, and generated some useful insights. For example, partial immunity on mixed farms that house cattle and sheep in a cattle-only vaccination strategy was modelled differently between models. In AusSpread, Exodis and NL models, cattle and sheep populations on a mixed farm are discrete populations and vaccination can be implemented separately, so that mixed farms acquire a partial immunity. In IS+ partial immunity was not fully implemented in the version of the model used, and mixed farms defaulted to a susceptibility equal to the most susceptible animals on the farm, which would be the unvaccinated species. Therefore, in IS+ cattle-only vaccination only benefited cattle-only farms, where there would be full immunity applied.

All models except NL predicted three clusters of infection that reflected diffusion-like spread from the three focal points of the starting scenario. The NL model predicted only a single cluster of infection that coincided with the highest animal density. This was because the transmission kernel extends over large distances, with higher infection probabilities at shorter distances, resulting in scattered but density-driven transmission patterns. NAADSM predicted large uncertainty intervals in epidemic size and duration for the SO strategy, which was attributed to the time to detection remaining constant throughout the epidemic, whereas time to detection diminished over time in some of the other models. The study also suggests that resources for vaccination and the way these are managed are likely to be issues particularly when larger vaccination zones are considered.

Vaccination may not always provide benefits over SO depending on the nature of the epidemic and availability of resources to control it. Vaccination may compete with SO activities for resources and interfere with the effectiveness of SO when resources are limited [17]. In well-resourced outbreaks or areas with low livestock density SO may be more effective than vaccination as the time to develop immunity is longer

than the period to complete culling operations [14, 34]. In this study, the findings regarding the effectiveness of vaccination were sensitive to the human resource settings and the way control measures were implemented in the individual models. An example of this is the way models represent surveillance and vaccination. The UK assumptions about the resource capacity to cull, vaccinate and perform surveillance activities and the speed at which this capacity is reached are unlikely to be accurate for countries with larger farm sizes and more extensive production systems such as Australia, Canada and USA. Vaccination and culling operations were assumed to be completed on each premise within 24 h. In geographically large countries farm sizes can be significantly larger and completion of these activities within 24 h is likely to be very optimistic. The implications of this 24-h assumption need to be explored further. In addition, should resource availability in the early stages of an outbreak in the UK be reduced further, the effectiveness of SO and the relative effectiveness of vaccination strategies could change.

The decision to vaccinate and choice of strategy will ultimately depend on the nature of the epidemic, available resources to control it, and objectives of the control programme. A policy of eradication and minimization of the number of animals culled may warrant a different control policy to that of eradication in the quickest time. Time out of markets may drive the choice of control measures where the management of vaccinated animals in the population post-outbreak may prolong market access due to OIE guidelines on the time to regain FMD-free status [13]. Of additional consideration, beyond the scope of this study, are the implications of post-outbreak surveillance and proof of freedom on farms that were both vaccinated and exposed to infection [24]. When considering control costs and export losses, vaccination may not always be the most cost-effective approach [1, 14].

Despite the differences in absolute numbers of IPs or epidemic durations between models, the individual models tended to demonstrate similar patterns of effectiveness between the vaccination strategies evaluated. All models predicted that vaccination as an adjunct to standard zoo-sanitary measures resulted in smaller epidemics compared to SO alone. In general, it was also clear that there were advantages in vaccinating cattle-only rather than all species, using 3-km vaccination rings immediately around IPs, and starting vaccination earlier in the control programme.

Although these patterns may not hold true in other study scenarios or for other countries with different animal demographics and resources, the study highlights that certain control strategies are robust despite different model configurations. These findings can be used to support and develop more effective policies for FMD control.

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DECLARATION OF INTEREST

None.

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Evaluating vaccination strategies to control foot-and-mouth disease: a country comparison study

T.G. Rawdon[1], M.G. Garner[2], R.L. Sanson[3], M.A. Stevenson[4], C. Cook[5], C. Birch[5], S.E. Roche[2], K.A. Patyk[6], K.N. Forde-Folle[6], C. Dubé[7], T. Smylie[8] and Z.D. Yu[9]

[1]Diagnostics and Surveillance Services Directorate, Ministry for Primary Industries, Upper Hutt 5140, New Zealand; [2]Department of Agriculture and Water Resources, Epidemiology and One Health Program, Canberra City ACT 2016, Australia; [3]AsureQuality Limited, Palmerston North 4440, New Zealand; [4]Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Parkville Victoria 3010, Australia; [5]Animal and Plant Health Agency (APHA), Weybridge, UK; [6]United States Department of Agriculture, Science Technology and Analysis Services, Veterinary Services, Animal and Plant Health Inspection Service, Colorado, USA; [7]Animal Health Risk Assessment Unit, Canadian Food Inspection Agency, Ontario, Canada; [8]Foreign Animal Disease Section, Canadian Food Inspection Agency, Ontario, Canada and [9]Readiness and Response Services Directorate, Ministry for Primary Industries, Wellington 6140, New Zealand

Abstract

Vaccination is increasingly being recognised as a potential tool to supplement 'stamping out' for controlling foot and mouth disease (FMD) outbreaks in non endemic countries. Infectious disease simulation models provide the opportunity to determine how vaccination might be used in the face of an FMD outbreak. Previously, consistent relative benefits of specific vaccin ation strategies across different FMD simulation modelling platforms have been demonstrated, using a UK FMD outbreak scenario. We extended this work to assess the relative effectiveness of selected vaccination strategies in five countries: Australia, New Zealand, the USA, the UK and Canada. A comparable, but not identical, FMD outbreak scenario was developed for each country with initial seeding of Pan Asia type O FMD virus into an area with a relatively high density of livestock farms. A series of vaccination strategies (in addition to stamping out (SO)) were selected to evaluate key areas of interest from a disease response perspective, includ ing timing of vaccination, species considerations (e.g. vaccination of only those farms with cat tle), risk area vaccination and resources available for vaccination. The study found that vaccination used with SO was effective in reducing epidemic size and duration in a severe out break situation. Early vaccination and unconstrained resources for vaccination consistently outperformed other strategies. Vaccination of only those farms with cattle produced compar able results, with some countries demonstrating that this could be as effective as all species vac cination. Restriction of vaccination to higher risk areas was less effective than other strategies. This study demonstrates consistency in the relative effectiveness of selected vaccination strat egies under different outbreak start up conditions conditional on the assumption that each of the simulation models provide a realistic estimation of FMD virus spread. Preferred outbreak management approaches must however balance the principles identified in this study, working to clearly defined outbreak management objectives, while having a good understanding of logistic requirements and the socio economic implications of different control measures.

Introduction

Criticism of the use of disease models to inform control policies during an outbreak is not uncommon. Several reports highlight the problems associated with using non validated mod els to direct disease control during the outbreak of foot and mouth disease (FMD) that occurred in the UK in 2001 [1, 2]. This experience serves as a salutary warning and reinforces the importance of careful model evaluation and active demonstration of model validity [1]. Decision makers must have confidence in the reliability of model predictions if they are to be used to inform disease control policy. Confidence and clarity are particularly important during an animal disease emergency response when political pressures and scrutiny are highest [2]. Recognising these issues, members of the Quadrilateral (Quads) Group of countries (Australia, Canada, New Zealand and the USA) together with other collaborators (UK, Ireland and The Netherlands) have engaged in joint studies comparing FMD simulation mod els. In the absence of detailed and accurate data from a range of epidemics that would allow external validation of model predictions, a process of multi model comparison has been devel oped. This approach has been useful as a means of comparing models to not only ensure their internal validity, but also to assess model predictions for consistency and to provide confidence in outputs through a process termed 'relative validation' [3 5].

Various modelling studies have shown that certain vaccination strategies may offer a benefit over standard stamping out (SO) approaches for FMD control and eradication in non endemic countries [5 9]. Analyses of the recent, large scale epidemics of FMD that occurred in Korea [10] and Japan [11] concluded that early adoption of vaccination enhanced the speed of disease control and eradication attempts.

Much of the recent FMD modelling work has focused on the use of vaccination in individual countries where farm demographics, movement patterns, response management and resources were fixed. Recent work by Porphyre *et al.* [12] showed that in Scotland there could be variability in the effectiveness of disease control strategies in different areas of the country, with vaccination being most effective in the southern counties where the risk of severe outbreaks is highest.

Despite indirect evidence of its potential value, the use of vaccination as a strategy for controlling FMD epidemics in non endemic countries remains a contentious issue, with little consensus on when vaccination should be used, what factors might trigger its implementation and how resource availability (for example, constraints on the number of vaccine doses available and/or constraints on the number of personnel available to carry out a vaccination program) might impact on how quickly an FMD outbreak is brought under control. Decision makers also need to balance economic and socio cultural factors, including economic effects, public opinion and the implications that vaccination use has on international market access. The outbreaks of FMD that occurred in Europe in 2001 provide a good example of this lack of consensus where, in the UK, farmer groups opposed vaccination, while on mainland Europe, The Netherlands showed little hesitation in employing a suppressive vaccination strategy [2]. Lack of established precedents in individual countries around FMD control and eradication will inevitably result in delays in decision making, which could potentially affect the utilisation and effectiveness of vaccination as an outbreak control option [2, 12].

Previous studies have demonstrated that key measures of the magnitude of an FMD epidemic (the total number of infected places (IPs), outbreak duration and geographical extent of the infected area) simulated with different modelling platforms were comparable when the models were parameterised to represent a defined FMD outbreak scenario [3 5, 9] In studies by Roche and *et al.* [5] and Probert and *et al.* [9], the relative effectiveness of specific vaccination strategies were assessed and similarities were identified when tested on a standardised FMD outbreak scenario set in the UK. Before general conclusions on the effectiveness of vaccination can be drawn, however, it is important to test whether the findings were specific to a given outbreak scenario or are consistent across a range of outbreaks in a range of countries.

The objective of this study was to use FMD simulation modelling to assess the relative gain in epidemic control afforded by augmenting SO with selected vaccination strategies, under different livestock demographics, production systems and movement patterns and country specific policies and resourcing for control. Strategies were designed to quantify the impact of specific aspects of vaccine use in FMD outbreak management, including: the onset of the vaccination programme (timing), the types of farms vaccinated (all farms with susceptible species or cattle farms only), limiting vaccination to high risk zones and the effect of constraints on vaccine resources.

Materials and methods

Outbreak scenarios

FMD modelling groups participating in the Quads collaboration as well as the UK were asked to select a study area within each of their respective countries with high farm and livestock densities. The rationale for this was that if vaccination was not effective under conditions most expected to favour the spread of FMD, it would be unlikely to be effective in other circumstances. Each of the modelling groups was then asked to define a plausible incursion scenario. Infection, with a Pan Asia O type FMD virus, was introduced onto a single farm in each country's defined study area and an FMD outbreak scenario was selected as follows. Australia, the UK and the USA simulated a series of uncontrolled outbreaks ($n = 100$) in their chosen study area. Outbreaks were simulated for 21 days following the date on which the first farm was infected, to produce a 21 day 'silent spread' phase of an outbreak. Using the results of this set of simulations, an iteration at or above the 90th percentile for the number of infected farms at the end of the silent spread phase was selected. New Zealand ran 100 iterations of their model for 21 days with standard detection and SO controls and selected an iteration using the 90th percentile of the number of infected farms at the end of the 21 day period. For Canada, 100 iterations were run to eradication using a standard SO approach and an iteration close to the 90th percentile in terms of the total number of infected premises was selected (Table 1).

The selected 'silent spread' iteration for each country was then used to generate a standardised starting situation for the subsequent vaccination scenario simulations. This approach fixed the silent spread phase to a single (severe) outbreak scenario for each country and therefore removed the variability associated with disease transmission during the pre detection phase. All subsequent modelling began by simulating forward from the day of first detection (Table 1). For each country, disease control measures started on the day of detection.

Each of the modelling teams used details of their own farm and livestock populations (Table 2) and their own estimates of FMD spread parameters that would apply in the respective study areas (Table 1). Control measures were modelled according to each country's FMD contingency plans (Table 3). Response capacity and resource limitations were country specific (Table 3).

Disease spread models

The FMD modelling platforms used were, AusSpread (AS) [13 15], InterSpread Plus (IS+) [16], Exodis FMD [17] and the North American Animal Disease Spread Model (NAADSM [18]). InterSpread Plus was used by both Canada and New Zealand. The modelling platforms are all stochastic, spatial, state transition simulation models which have been developed to simulate FMD transmission and control. Descriptions and operational details of these models are available in each of the references cited above. Roche *et al.* [5] provides a comparison of each of the four models.

Control strategies

Six control strategies were compared: a baseline SO strategy and five strategies where vaccination was used in addition to SO (VS1 5). Details of each of the control strategies are provided in Table 4.

Table 1. Model platform, details of outbreak scenario and details of transmission pathways used for simulated outbreaks of foot and mouth disease in each country

Parameter	Australia	Canada	New Zealand	UK	USA
Model platform	AusSpread [13 15]	InterSpread + [16]	InterSpread + [16]	EXODIS FMD [17]	NAADSM [18]
Outbreak scenario primary case and start up situation (history file) for comparing control strategies	Primary case: FMD virus introduced into small piggery (n = 111 pigs) in the state of Victoria (Fig. 1). History file: Uncontrolled iterations run for 21 days and the 90th percentile largest outbreak selected to start subsequent scenarios. The selected outbreak produced 47 infected farms by the day of first detection (day 21). The FMD outbreak scenario used for this study was adapted from previous work [7].	Primary case: FMD virus introduced into a cow calf operation (n = 100 cows) in a cattle dense area of Alberta (Fig. 1). History file: Set of iterations generated using a standard stamping out approach. An iteration close to the 90th percentile in terms of a number of infected premises was selected to start all subsequent scenarios. The selected iteration produced 17 infected farms by the day of first detection (day 28).	Primary case: The incursion represented a plausible introductory risk pathway for NZ with FMD virus seeded into a lifestyle farm with pigs (n = 2). The farm was in northern Taranaki, an area with a high density of dairy farms (Fig. 1). History file: Set of iterations with standard detection and stamping out run for 21 days and the 90th percentile largest iterations was selected to form the basis for the start of all subsequent scenarios. The selected iteration produced 17 infected farms by the day of first detection (day 15).	Primary case: The incursion seeded FMD virus into a commercial piggery (n = 10 000 pigs) in North Yorskhire, a county with a high density of pigs (Fig. 1). History file: Set of 21 day uncontrolled iterations were run across North Yorskhire. After calculating the 90th percentile number of infected farms at day 21, a single incursion scenario producing 36 infected premises by the day of first detection (day 21) was selected as the basis for all further simulations.	Primary case: The incursion seeded FMD virus into a small swine operation (n = 55 pigs) in Texas (Fig. 1). History file: The 95th percentile for a number of infected farms at the end of a series of iterations of 21 day uncontrolled outbreaks was 37. An iteration that produced 37 infected farms by the day of first detection (day 21) was selected as the basis for the start of all subsequent scenarios.
Transmission pathways	Direct contact, indirect contact[a], local area spread[b], airborne spread, saleyard spread.	Direct contact, indirect contact[a], local area spread[b], saleyard spread (airborne spread off).	Direct contact, indirect contact[a], local area spread[b], saleyard spread, milk tanker spread (airborne spread off).	Direct contact, indirect contact[a], local area spread[b] (airborne spread off).	Direct contact, indirect contact[a], local area spread[b].

[a]Transfer of disease from one location to another via humans, contaminated products, non-susceptible animals and equipment, vehicles and other fomites.
[b]Transfer of disease to locations within 3 kms of an infected farm, where the actual source of the infection is not known.

Suppressive vaccination was applied outside in, in 3 km radii rings around new IPs and those IPs identified up to 5 days before the start of vaccination. For Australia, the UK and the USA, vaccination was also applied around farms identified as dangerous contact premises.[1] Vaccination commenced either 10 days (VS1, VS5) or 17 days (VS2, VS3, VS4) into the control program. All species (cattle, deer, small ruminants and pigs) on all farms were vaccinated, except for the VS3 strategy in which farms classified as predominantly cattle were targeted, although all species were vaccinated on these farms if other species were present. In the USA no small ruminant vaccination was carried out for any of the strategies. Resource estimates for vaccination are listed in Table 3. These applied to all scenarios except for VS5 which had an unlimited number of vaccination teams. Vaccine doses were unlimited except for strategies VS1 4 of the Canadian model where the available doses were constrained at 250 000 based on realistic estimates given vaccine bank arrangements at the time of the study.

Vaccination was used in all infected areas except for VS4 in which vaccination was applied to high risk areas only. The high risk areas selected for vaccination were specified by each country and were defined as follows:

- Australia: High risk areas were based on tertiary administrative areas representing the high density, dairying areas in the state of Victoria (R. Paskin personal communication). Three separate high risk areas in the south east, south west and north of Victoria were selected (Fig. 1).
- Canada: The locations of all livestock farms in the province of Alberta were used to create a point location map. The area with the highest density area of livestock farms was identified and used as a zone for vaccination in the model (Fig. 1).
- New Zealand: The point locations of all dairy farms derived from the national farm database AgriBase [19] were used to create a kernel smoothed density map of dairy farms. Two high density areas were identified within the Waikato and Taranaki regions as having ≥0.4 dairy farms per km² (Fig. 1).
- The UK: High risk areas were selected on the population density of susceptible species. The smallest spatial unit of resolution used was the county. Counties containing the highest density of cattle, sheep or pigs were selected as high risk. The data used to calculate the density of animals were based on agricultural census figures for June 2010 (Fig. 1).

[1]Dangerous Contact Premises (DCP): A premise identified as high risk of having been exposed to infection through tracing of a direct or high risk indirect movement.
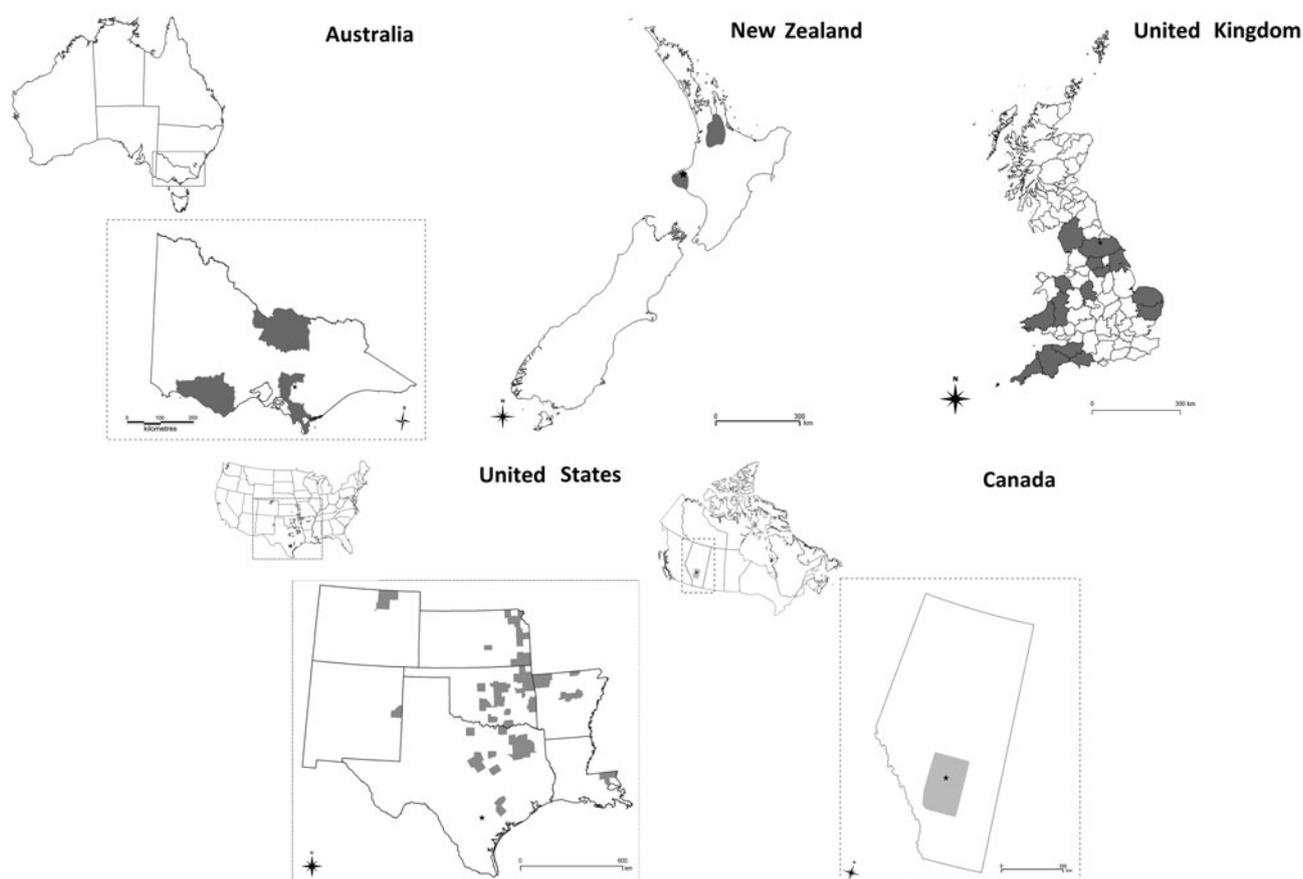
Fig. 1. Map of each country and study area enlargement where applicable. The study area for Australia was the State of Victoria, for Canada the Province of Alberta, for New Zealand and UK the study area was the entire country and for the USA the study area included the states of Colorado, Kansas, New Mexico, Oklahoma, Arkansas, Texas and Louisiana. Grey shading identifies the high risk areas within the study areas selected for vaccination under VS4. In each map the location of the primary case farm is indicated by a black star.

- The USA: High risk areas were based on counties representing the intensive dairying areas. The number of dairies (large and small) per 15 km^2 was calculated for each county, and counties at or above the 90th percentile were designated as high risk areas (Fig. 1).

For each strategy, 100 iterations of each model were run. Each iteration was run until FMD was eradicated. The following outputs from each iteration of each model were recorded: the total number of IPs, the spatial distribution of IPs (that is, the easting and northing coordinate of each IP) and outbreak duration. Outbreak duration was defined as the number of days from the start of the control programme until the last case was detected plus 21 days, as it was assumed it would take 21 days following the last case to complete all depopulation, disposal and decontamination activities. The numbers of animals and farms vaccinated for each iteration were also recorded.

Parameters associated with disease spread and the implementation of baseline SO control measures for each country are provided in Tables 2 and 3, respectively.

Statistical analyses

Descriptive analyses
The predicted total number of IPs, outbreak duration and vaccine usage for each iteration for each scenario for each country were tabulated (Tables 5 and 6). For each country, the predicted total numbers of IPs and outbreak durations for all of the vaccination strategies were pooled and compared with the same measures for the SO strategy alone using the Wilcoxon (Mann Whitney) rank sum test [26, 27].

To generate the graphical outputs (Fig. 2), the median number of IPs for each vaccination strategy for each country was calculated and then rescaled to a number between 0 and 1 by subtracting the value for the lowest median number of IPs and dividing the result by the difference between the largest and smallest medians across the strategies for that country [9]. With rescaling, the best performing control strategy within each country (i.e. the control strategy with the smallest number of IPs) had a score of 0 and the worst had a score of 1. The median outbreak duration and the median number of animals vaccinated for each scenario from each country were scaled using a similar procedure. The scaled median number of IPs for each strategy from each country was then plotted against the scaled median duration and scaled median number of animals vaccinated. This allowed the performance of each control strategy to be compared across a range of response objectives, independent of the raw numerical output of the simulations (Fig. 2).

Multivariable analyses
Frequency histograms were plotted to confirm the total number of IPs and outbreak duration data were consistent with the Poisson distribution. For each country scenario combination, the variance

Table 2. Livestock population and production systems and the number of farms by farm type (mean number of FMD susceptible animals per farm) used in each of the simulated outbreaks of FMD in each country

Details	Australia	Canada	New Zealand	UK	USA
Study area, livestock population and production systems	The study area comprised the state of Victoria with 42 279 farms containing FMD susceptible livestock (Agricultural Census 2011; Figure 1). Seven farm types defined.	The study area comprised the province of Alberta (Fig. 1). Population data was provided in 2012 by the Alberta Agriculture and Rural Development department from their Premises Identification Database. 24 897 farms containing FMD susceptible livestock. Eight farm types defined.	The study area covered New Zealand (Fig. 1). Farm population data was derived from an April 2011 extract from the AgriBase national farms database [19] augmented with any new dairy farms identified through a 2011 extract from the National Animal Identification and Tracing (NAIT) database. A total of 83 067 farms with FMD susceptible livestock. Seven farm types defined.	The study area covered England, Scotland and Wales (Fig. 1). The population data was derived from the 2010 census results with 137 030 premises containing FMD susceptible livestock (Fig. 1). Nine farm types defined.	The study region comprised a group of seven contiguous states in the south central United States: Colorado, Kansas, New Mexico, Oklahoma, Arkansas, Texas and Louisiana (Fig. 1). Farm population data were derived from the 2002 National Agricultural Statistics Service (NASS) Census of Agriculture with 363 989 premises containing FMD susceptible livestock. Twelve production types defined and grouped by five farm types [20].
Dairy farms	7590 (259)	333 (288)	18 417 (424)[a]	21 207 (90)[b]	4330 (396)[c]
Beef farms	7537 (227)	19 761 (224)	Included with 'Mixed farms'	20 778 (13)	283 836 (82)[d]
Sheep farms	4017 (2415)	Included with 'Mixed farms'	Included with 'Mixed farms'	49 997 (111)[e]	61 225 (53)[f]
Pig farms	322 (1452)	401 (2783)	365 (1801)[g]	8690 (324)	11 911 (538)[h]
Mixed farms	5392 (2644)	2795 (554)	39 747 (1129)	36 358 (570)[i]	n/a
Smallholder/ Lifestyle	17 233 (11)	n/a	24 538 (16)	Included above	n/a
Feedlot	188 (362)	1607 (3048)	n/a	n/a	2687 (2579)[j]
Total farms	42 279	24 897	83 067	137 030	363 989

[a] NZ dairy farms category includes milking and grazing dairy farm categories.
[b] UK dairy farms category may have beef cattle present.
[c] US dairy farms category includes small dairy and large dairy categories.
[d] US beef farms includes cow-calf (large), cow-calf (small) and stockers farm categories.
[e] UK sheep farms category is split into upland and lowland sheep farm types and may have pigs present.
[f] US sheep farm category includes both sheep and goat farms.
[g] New Zealand pig farm category includes pig breeder and pig finisher production types.
[h] US pig farms includes swine (large) and swine (small) categories.
[i] UK mixed farms category is split into lowland dairy mixed, lowland beef mixed, upland dairy mixed, upland beef mixed.
[j] US feedlot farm type includes company feedlot, stockholder feedlot, custom feedlot and yearling-pasture feedlot.

of the outcome was greater than the mean, indicative of overdispersion and justifying a decision to use a negative binomial model for the data. We defined y_i as the outcome variable (the predicted total number of IPs for the ith iteration) and set the mean and variance of y_i for the negative binomial as $E(y_i) = \mu_i$ and $var(y_i) \quad \mu_i + \kappa\mu_i^2$ where κ is a dispersion parameter. The mean of the negative binomial regression model is given by:

$$\mu_i \quad \exp(\beta_0 + \beta_1 x_{1i} + \cdots + \beta_m x_{mi} + \epsilon_i) \qquad (1)$$

In Equation 1, β_0 represents the intercept term and $\beta_1 \cdots \beta_m$ the estimated regression coefficients for the m explanatory variables included in the model. The explanatory variables included in each model were: (1) timing of vaccination (a categorical variable with two levels: vaccination start at 10 days and vaccination start at 17 days), (2) species (a categorical variable with two levels:

farms with cattle and farms with any susceptible species), (3) area (a categorical variable with two levels, high risk areas and all areas) and (4) resources (a categorical variable with two levels: standard resources and unlimited resources). Country (a categorical variable with five levels) was included in each model as a fixed effect. To start, all explanatory variables were included in the model. Explanatory variables that were not statistically significant were removed from the model one at a time, beginning with the least significant, until the estimated regression coefficients for all explanatory variables retained were significant at an alpha level of less than 0.05. Model fit was assessed by likelihood ratio tests between successive models as each variable was removed and between the final model and an intercept only model.

A multiple linear regression model was developed to quantify the association between each of the explanatory variables that

Table 3. Stamping out control measures, response capacity and resource limitations for simulated outbreaks of foot and mouth disease in each country

Control measure	Australia	Canada	New Zealand	UK	USA
Stamping out	Control parameter settings consistent with the Australian stamping out response policy [21]: National livestock standstill (72 h); quarantine; zone movement restrictions (3 and 10 km around IPs and DCPs[a]); surveillance (patrol vet 3 km); forward and backward tracing; stamping out (destruction, disposal, decontamination) of all FMD susceptible livestock on IPs and DCPs.	Simulated stamping out policy as defined in the FMD Hazard Specific Plan (FMD HSP) for Canada [22]: Livestock standstill (province level); quarantine; zone movement restrictions (5kms around IPs); surveillance (patrol vet 3 km); forward and backward tracing; stamping out (destruction, disposal, decontamination) of all FMD susceptible livestock on detected IPs and dangerous contact premises (DCPs[10]; IPs taking priority over DCPs).	Simulated stamping out disease control consistent with the New Zealand Standard Model [23]: National livestock standstill (14 days); quarantine; zone movement restrictions (3 and 10 km around IPs); surveillance (patrol vet 3 km); forward and backward tracing; stamping out (destruction, disposal, decontamination) of all FMD susceptible livestock on infected, detected premises.	Simulated control programme consistent with UK contingency plans for stamping out [24]: National livestock standstill (duration of the epidemic); quarantine; zone movement restrictions (3 and 10 km around IPs); surveillance (patrol vet 3 km); forward and backward tracing; stamping out (destruction, disposal, decontamination) of all FMD susceptible livestock on infected, detected premises.	Control parameters for stamping out were defined as described by USDA [25]. Quarantine; zone movement restrictions (10 and 20 km around IPs and each traced direct or indirect contact); surveillance (in 10 km and 20 km zones around IPs and each traced direct or indirect contact); forward and backward tracing; stamping out (destruction, disposal, decontamination) of all FMD susceptible livestock on infected, detected premises.
Vaccination	Vaccination does not compete with other control activities for resources. Vaccination capacity is based on the availability of teams with time to complete vaccination varying with herd type. Capacity for VS1 4 is initially sufficient to vaccinate 10 50 farms per day (Day 1 7), rising to 25 125 (Day 8 20) and maximising at 50 250 farms per day from Day 21 onwards. No vaccination restriction applied for VS5.	No competition between vaccination resource and other response activities. Vaccination conducted by farm vaccinators with sufficient resource to vaccinate 500 farms per day (VS1 VS4). For VS5 it was assumed that up to 5000 farms per day could be vaccinated. The number of doses available was limited to 250 000 for all vaccination scenarios except VS5.	No competition between vaccination resource and other response activities Vaccination resources for VS1 4 sufficient for vaccinating 300 farms per day on Day 1, increasing to 500 farms per day by Day 3. Unlimited personnel resources for VS5 defined as 600 farms per day on Day 1 rising to 1000 per day by Day 3.	Vaccination does not compete with other control activities for resources. Vaccination resource is calculated for individual holdings based on numbers of animals present. Capacity for vaccination is 36 000 animals a day (day 5) rising to 72 000 animals at day 10 and reaching a maximum of 108 000 animals (day 21 onwards). No limits are applied in VS5.	No competition between vaccination resource and other response activities. Vaccination resources sufficient for 100 farms per day by day 24 (10 day start) or by day 31 (17 day start). If vaccination tasks queue up (i.e., they exceed the daily capacity), then dairy receives first priority, followed by swine, feedlot and cow calf.

[a]DCP: Dangerous contact premises. A premises identified as high risk of having been exposed to infection through tracing of a direct or high-risk indirect movement.

Table 4. Details of the five vaccination control strategies for the simulated outbreaks of FMD in each country

Strategy	Vaccination		Farm class[a]	Area	Vaccination resource
	Radius (km)[b]	Start (days)			
VS1	3	10	All	All areas	Limited[c]
VS2	3	17	All	All areas	Limited[c]
VS3	3	17	Cattle	All areas	Limited[c]
VS4	3	17	All	High risk[d]	Limited[c]
VS5	3	10	All	All areas	Unlimited[e]

[a]USA: no sheep or goat vaccination for any strategies.
[b]Vaccination applied outside in for all strategies.
[c]Vaccination team resource limits specific to each country as defined in materials and methods.
[d]This is a country-specific definition as defined in materials and methods.
[e]Number of vaccination doses and vaccination teams unlimited.

Table 5. Descriptive statistics of the predicted number of infected premises and outbreak duration for the stamping out strategy and each of the five vaccination control strategies, by country

Strategy	Number of IPs Median (5, 95%)	Change Relative to SO[a]	Duration (days) Median (5, 95%)	Change Relative to SO[a]
Australia:				
SO	123 (89, 199)	Baseline	108 (84, 163)	Baseline
VS1	98 (77, 137)	19.2%	98 (72, 121)	9.3%
VS2	101 (80, 142)	17.1%	98 (78, 122)	9.3%
VS3	101 (85, 139)	15.9%	99 (76, 131)	8.3%
VS4	110 (82, 159)	8.2%	103 (86, 141)	4.6%
VS5	90 (74, 134)	26.5%	93 (76, 113)	20.5%
Canada:				
SO	538 (198, 769)	Baseline	186 (104, 320)	Baseline
VS1	450 (150, 752)	16.4%	167 (92, 275)	10.2%
VS2	452 (148, 725)	16.0%	167 (95, 269)	10.2%
VS3	389 (171, 736)	27.7%	160 (87, 255)	14.0%
VS4	474 (192, 770)	11.9%	179 (98, 290)	3.8%
VS5	393 (165, 604)	27.0%	138 (85, 247)	25.8%
New Zealand:				
SO	197 (65, 303)	Baseline	110 (66, 174)	Baseline
VS1	73 (43, 113)	62.8%	56 (46, 81)	49.1%
VS2	92 (48, 151)	53.2%	62 (49, 93)	43.6%
VS3	95 (54, 162)	51.7%	67 (49, 88)	39.1%
VS4	97 (48, 166)	50.6%	66 (49, 109)	40.0%
VS5	71 (46, 123)	63.9%	58 (46, 113)	47.3%
UK:				
SO	145 (85, 250)	Baseline	111 (81, 150)	Baseline
VS1	80 (63, 135)	44.8%	81 (63, 117)	27.0%
VS2	100 (79, 153)	31.0%	82 (68, 118)	26.1%
VS3	110 (81, 162)	24.1%	91 (74, 125)	18.0%
VS4	112 (82, 178)	22.8%	94 (71, 133)	15.3%
VS5	75 (62, 111)	48.3%	76 (62, 106)	31.5%
USA:				
SO	137 (102, 207)	Baseline	74 (62, 95)	Baseline
VS1	139 (96, 196)	1.5%	71 (58, 91)	4.1%
VS2	141 (102, 211)	2.9%	70 (60, 85)	5.4%
VS3	139 (94, 187)	1.5%	70 (59, 86)	5.4%
VS4	139 (97, 201)	1.5%	74 (61, 96)	0.0%
VS5	110 (88, 146)	19.7%	64 (51, 84)	13.5%

[a]A positive percentage indicates deterioration in outbreak measure relative to baseline (SO).

varied in the different vaccination strategies and outbreak duration, with the country as a fixed effect. Similar to the approach described above, a backwards stepwise elimination approach was used to identify explanatory variables significantly associated with outbreak duration. Model fit was assessed using the R^2 value and the overall F statistic. All statistical analyses were conducted in R version 3.3 [28].

Results

Descriptive statistics of the predicted number of IPs, predicted outbreak duration (in days) and the predicted number of farms and animals vaccinated by strategy and country are shown in Tables 5 and 6, respectively. The proportional reduction in the median outbreak measure, relative to the median for that

Table 6. Results of the predicted number of farms vaccinated and animals vaccinated for the vaccination control strategies used in a simulated outbreak of foot and mouth disease in five countries

Strategy	Premises vaccinated	Animals vaccinated (×1000)
	Median (5, 95%)	Median (5, 95%)
Australia:		
SO	0	0
VS1	508 (372, 788)	161 (121, 259)
VS2	394 (259, 614)	111 (73, 175)
VS3	297 (202, 471)	97 (66, 168)
VS4	212 (116, 359)	59 (31, 112)
VS5	497 (374, 816)	165 (125, 269)
Canada:[a]		
SO	0	0
VS1	362 (253, 510)	261 (235, 294)
VS2	396 (252, 566)	266 (250, 325)
VS3	446 (250, 722)	255 (238, 301)
VS4	529 (383, 629)	261 (219, 284)
VS5	1548 (710, 2187)	1064 (476, 1411)
New Zealand:		
SO	0	0
VS1	1296 (747, 1930)	122 (68, 203)
VS2	1292 (792, 2062)	129 (61, 245)
VS3	1040 (598, 1740)	107 (49, 176)
VS4	1049 (663, 1538)	96 (56, 176)
VS5	1302 (880, 2115)	123 (68, 258)
UK:		
SO	0	0
VS1	1025 (731, 1843)	425 (301, 742)
VS2	826 (471, 1641)	329 (172, 672)
VS3	501 (254, 861)	189 (91, 342)
VS4	448 (258, 814)	165 (88, 328)
VS5	1011 (728, 1673)	430 (301, 718)
USA:		
SO	0	0
VS1	723 (522, 994)	81 (52, 233)
VS2	725 (562, 1021)	79 (40, 207)
VS3	681 (474, 901)	74 (43, 215)
VS4	23 (0, 132)	2 (0, 17)
VS5	673 (543, 885)	73 (44, 200)

[a]Vaccine doses were artificially constrained at 250 000 for VS1-4 for each of the Canadian models.

country's SO strategy are provided in Table 5. Figure 2 is a three dimensional line plot showing the relationship between the scaled median number of IPs, scaled median outbreak duration and the scaled median number of animals vaccinated for each of the vaccination strategies from each country.

In all countries vaccination significantly reduced the predicted number of IPs ($Z = 2.045$ 12.745, $P = 0.041$ to <0.01) and outbreak duration ($Z = 4.201$ to 13.614, $P < 0.01$) compared with SO alone. The reduction in the mean predicted number of IPs for the most effective vaccination strategy in each country, relative to the mean predicted IPs for SO alone varied between 20 and 64%. Similar figures for outbreak duration ranged between 13 and 49% (Table 5).

All models predicted larger numbers of IPs when vaccination started at 17 days post detection (VS2), compared with vaccination starting at 10 days (VS1), Table 5. The reduction in the mean predicted number of IPs for vaccination start at 10 days (VS1) in each country relative to the mean predicted IPs for delayed vaccination (VS2) varied between 0.4 and 14% (Table 5). The timing of vaccination was retained in the final negative binomial regression model for the predicted total number of IPs (Table 7). In this model, starting vaccination at day 17 increased the predicted total number of IPs by a factor of 1.11 (95% CI 1.07 1.14) compared with starting vaccination at day 10 (Table 7). Differences in outbreak duration for day 10 and day 17 vaccination start were less consistent and of lower magnitude (Table 5). Day of vaccination start was not retained in the final multiple linear regression model for outbreak duration (Table 8).

When vaccination was restricted to cattle farms (VS3), the predicted median number of IPs and outbreak duration were similar to the correspondingly timed all farm vaccination strategy (17 day vaccination start, VS2; Table 5). Species vaccinated was not retained in either of the two regression models (Tables 7 and 8). Limiting vaccination to high risk areas within each country (VS4) had a consistent negative impact on the total number of IPs or outbreak duration compared with the comparably timed strategy (17 day vaccination start, VS2) applied to all areas (Table 5). The predicted median number of IPs and outbreak duration for VS4 were higher for four of the five countries. Area vaccinated was retained in each of the two regression models (Tables 7 and 8). Vaccinating high risk areas only increased the total number of IPs by a factor of 1.06 (95% CI 1.03 1.10) and outbreak duration by 7.6 days (95% CI 5 10 days), compared with vaccination of susceptible species in all areas.

For most countries, the best performing vaccination strategy was VS5 in which there were no constraints on vaccine deployment (Fig. 2). Unconstrained resources for vaccination was significantly associated with a reduction in total IPs in the negative binomial regression model (Table 7). In the final negative binomial model, unrestricted vaccination resource decreased the total number of IPs by a factor of 0.90 (95% CI 0.87 0.94) compared to a standard vaccination resource strategy. Similar findings were identified for outbreak duration, with resource availability retained in the final multivariable linear regression model (Table 8). The range in reduction in the mean predicted number of IPs and outbreak duration for unrestricted vaccination in each country relative to the comparably timed resource restricted strategy (VS1, 10 day vaccination) was −5 to +21% and −3 to +16%, respectively (Table 5).

The majority of countries predicted the smallest numbers of farms and animals vaccinated for the risk targeted strategies (VS3 cattle farms only, VS4 high risk areas only). For Australia, New Zealand and UK, VS3 achieved a reduction in the predicted median number of farms and animals vaccinated of between +20 to +54% and +13 to +55%, respectively. The USA reported a marginal increase in the number of farms and animals vaccinated of +1% and +2%, respectively (Table 6). We note that Canada has
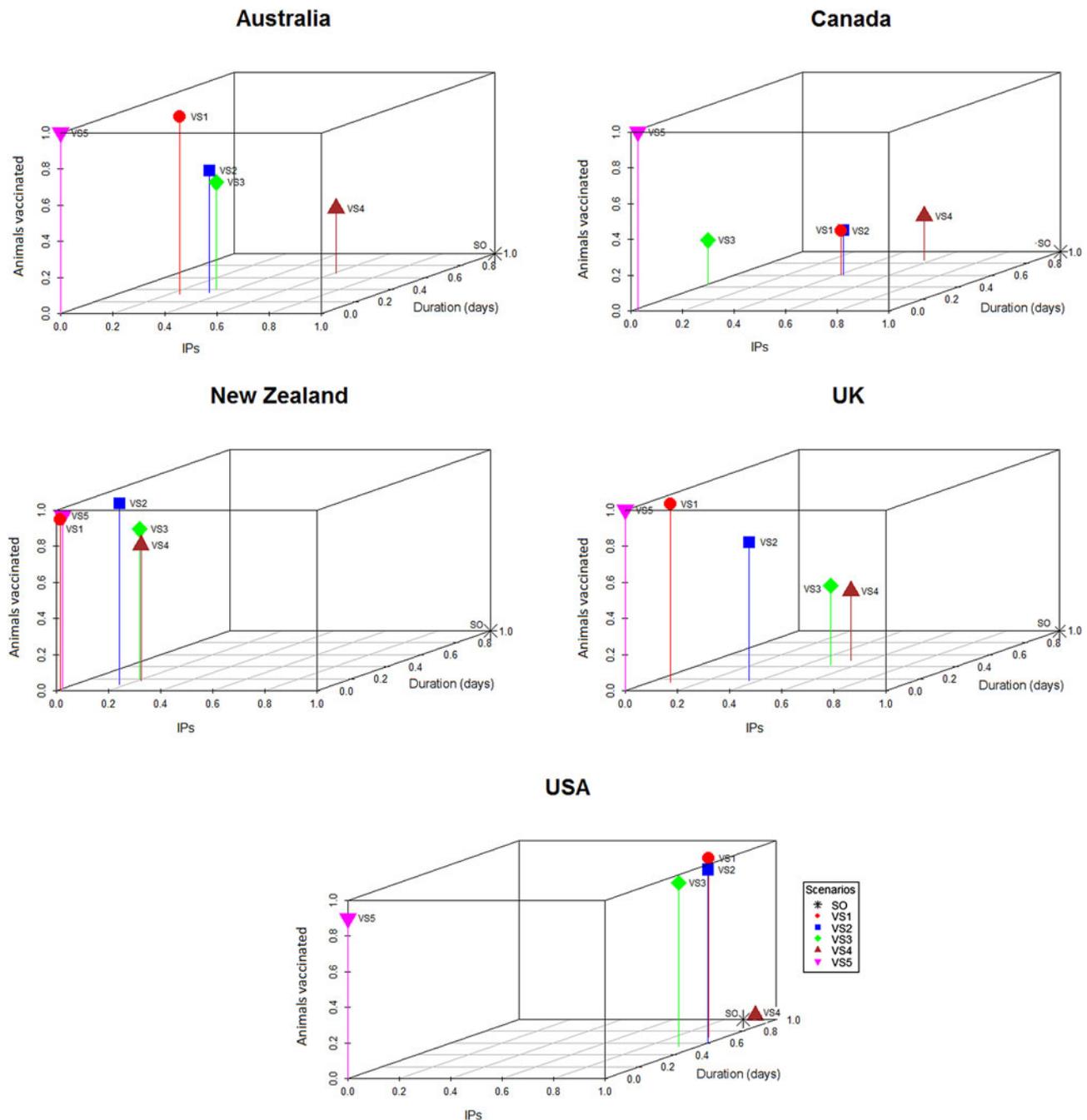
Fig. 2. Three dimensional scatter plots showing the median number of IPs and median outbreak durations generated by the stamping out and vaccination strat egies (Table 4) against the median number of doses used for the respective strategy within each country. The medians were scaled to lie between 0 and 1 within each country, so that the worst control strategy has a score of 1 and the best a score of 0 within each country.

been excluded from these comparisons because the number of vaccine doses was constrained at 250 000 cattle doses for VS1 4.

Discussion

This study builds on findings from earlier research using FMD outbreak scenarios in the UK [5] to assess the effect of vaccination on large outbreaks of FMD using five simulation models. Previously, various vaccination strategies were tested within the framework of a multi model comparison study, with findings pro viding confidence in both the internal validity and consistency of

predictions generated by different modelling platforms [3 5]. Other researchers have demonstrated the importance of different startup conditions, particularly location specific factors such as animal density, contact networks and farm level reproductive number to achieve success using vaccination as a means for con trolling an outbreak of FMD [12]. On the strict assumption that each of the simulation models in this study provide valid estimates of the likely outcomes arising from an incursion of FMD into the respective countries in which they are deployed, the findings from this study will assist decision makers by highlighting consistent patterns in the relative effect of vaccination approaches that

Table 7. Estimated regression coefficients and their standard errors from a negative binomial regression model of variables associated with the predicted number of infected places from four FMD simulation models

Explanatory variable	Coefficient (s.e.)	z	P	IRR (95% CI)
Intercept	4.61 (0.019)	253.974	<0.01	
Vaccination start:				
Day 10	Reference			1.00
Day 17	0.101 (0.016)	6.112	<0.01	1.11 (1.07 1.14)[a]
Vaccination area:				
All	Reference			1.00
High risk	0.062 (0.016)	3.760	<0.01	1.06 (1.03 1.10)
Vaccination resource:				
Limited	Reference			1.00
Unlimited	0.101 (0.019)	5.300	<0.01	0.90 (0.87 0.94)
Country:				
Australia	Reference			1.00
Canada	1.411 (0.019)	75.096	<0.01	4.10 (3.95 4.25)
New Zealand	0.188 (0.019)	9.759	<0.01	0.83 (0.80 0.86)
UK	0.062 (0.019)	3.228	<0.01	0.94 (0.90 0.98)
USA	0.251 (0.019)	13.184	<0.01	1.29 (1.24 1.33)

[a]Interpretation: compared with a vaccination start at 10 days after the date of first detection and after controlling for the effect of other variables included in the model, vaccination start at 17 days after the date of first detection was associated with a 1.11 (95% CI 1.07–1.14) times increase in the predicted number of infected places.

outperform SO alone. The findings provide direction regarding key decisions faced by response managers, including the timing of vaccination, application of risk targeted strategies and vaccine resource requirements.

This study assessed control strategies for large outbreaks representing a 90th or 95th percentile incursion into an area with relatively high livestock densities. Hence, they represent relatively severe outbreak scenarios, only relevant to the consideration of risk associated with large FMD outbreaks. A number of other studies have failed to show a benefit of vaccination over stamping out alone for FMD control [6, 29, 30]. A notable feature of these studies was that the outbreaks that were simulated were relatively small and/or involved low density livestock populations. Similarly, other researchers [6, 12, 31] have demonstrated variability in the effectiveness of vaccination strategies associated with the geographic region in which the outbreak occurred and the characteristics of the index farm. Also, Roche *et al.* [14] found that using current estimates of human resource capacity

Table 8. Estimated regression coefficients and their standard errors from a multiple linear regression models of variables associated with predicted outbreak duration (in days) from four FMD simulation models

Explanatory variable	Coefficient (SE)	t	P	95% CI
Intercept	99.55 (1.31)	76.15	<0.01	
Vaccination area:				
All	Reference			
High risk	7.59 (1.42)	5.35	<0.01	5 to 10[a]
Vaccination resource:				
Limited	Reference			
Unlimited	8.25 (1.42)	5.82	<0.01	11 to 5
Country:				
Australia	Reference			
Canada	69.55 (1.74)	40.05	<0.01	66 to 73
New Zealand	34.85 (1.74)	20.07	<0.01	38 to 31
UK	11.95 (1.74)	6.88	<0.01	15 to 8
USA	28.41 (1.74)	16.36	<0.01	32 to 25

[a]Interpretation: compared with a vaccination of all areas and after controlling for the effect of other variables included in the model, vaccination of high risk areas only was associated with a 8 (95% CI 5–10) day increase in outbreak duration.

for surveillance and infected premises operations in Australia, FMD outbreaks were effectively controlled using a SO strategy. However, under more constrained resource allocations, ring vaccination was likely to achieve eradication faster than SO alone or pre emptive culling.

Consistent with other studies [5, 12, 31, 32], early vaccination was associated with a significant reduction in the total number of IPs, although the relative reduction was small for most countries except the UK and New Zealand. The relative reduction in outbreak duration followed a similar pattern, although this was less marked across all countries. This was not unexpected given the short time period differential (a 10 day vaccination start *vs.* 17 day vaccination start) chosen for this study. Nevertheless, our results support previous studies and outbreak findings [10, 11] that highlight the gains to be achieved from an early decision to vaccinate. Further studies to help understand the early predictors of large scale outbreaks would assist decision makers when considering additional disease management strategies such as vaccination [33, 34].

We tested two risk based vaccination strategies, the first compared vaccination of all farms *vs.* carrying out vaccination only on those farms with cattle (with all FMD susceptible species vaccinated on those farms). Vaccinating cattle farms (alongside SO) out performed SO alone in all countries. The reductions in the predicted number of IPs and outbreak durations achieved were generally of a lower magnitude compared to vaccinating all farms. However, cattle farm only vaccination was not retained in either of the multivariable models and our inference is that vaccinating animals on farms with cattle was not inferior to vaccinating all farm types. Other studies [5, 12, 35] have identified the effectiveness of cattle only compared with all species vaccination, although these studies are not directly comparable with the study described in this paper. The second risk based vaccination strategy limited vaccination to high risk areas. High risk areas were specified by each country, being pre determined by the veterinary authorities based on expert knowledge and regional attributes such as the density and species of livestock present. Although limiting vaccination to high risk areas out performed SO alone, the impact was significantly lower compared with vaccination strategies that included all areas.

In this study, high risk zones were chosen based on local knowledge of regional attributes including farm types and animal density. Other researchers have determined that although livestock density is an important characteristic affecting FMD spread, simply identifying areas of high livestock density does not capture the required complexity to inform decision making around control strategies. Porphyre *et al.* [12] found that the intrinsic characteristics of the virus strain is likely to have an important influence on local spread and thereby the farm level reproduction number and shape of the transmission kernel function. Hence, identifying high risk zones for targeted vaccination requires knowledge of how the characteristics of the incursion virus strain interact with the underlying population of animals at risk and contact networks to produce a defined transmission kernel [36, 37]. Risk based vaccination strategies are clearly an important area for future study.

If risk based vaccination programmes, such as cattle only or high risk area vaccination, can be shown to be equally effective as all species or all area vaccination, there could be substantial benefits as less vaccine is required, less resource is required to carry out the vaccination strategy, fewer animals are vaccinated and post outbreak surveillance effort is reduced. The ability of cattle only vaccination to reduce the number of animals vaccinated will, however, depend on the production systems and livestock demographics of the outbreak area.

The capacity to implement vaccination was variable between countries. Not surprisingly, we found that the strategy in which vaccination teams and vaccine supply were unlimited out performed all other strategies in the majority of country settings (Fig. 2, Tables 7 and 8). In reality, resources are always finite and the effectiveness of any control strategy will depend greatly on the availability of adequate resources required to implement it. The benefits of carrying out rapid and effective vaccination are demonstrated here, consistent with other FMD vaccination modelling studies [31, 38]. Equally important is maintaining high SO efficacy, to minimise the interference of vaccination resource requirements with other response activities, including surveillance, tracing, depopulation and disposal [38]. When comparing resource requirements for the risk based vaccination strategies (cattle farms only, high risk area vaccination), considerable savings in the number of farms and animals vaccinated were achieved (Table 6), which is an important finding in the context of a sometimes comparable performance in bringing the outbreak under control. Assessing the influence of vaccination personnel resources on vaccination efficacy across a variety of incursion scenarios and determining the optimal personnel resource availability, are important focus areas for outbreak preparedness [14].

A decision to deploy vaccination poses significant challenges during the early stages of an outbreak given the considerable uncertainty and often competing objectives. Techniques such as adaptive management, which apply structured decision making processes to include uncertainty when solving dynamic problems [39] create a rational basis for evaluating different disease intervention strategies. Assisting decision making by clearly defining the objectives of a disease control programme is also fundamental to success [9]. Hence, the objectives along with the metrics used to measure these objectives, need to be clearly understood and decided from the outset. In the context of an FMD outbreak, the decision to vaccinate early is complex given the uncertainty of success and the challenge of defining appropriate objectives. The decision is multidimensional, incorporating the direct benefits associated with bringing the epidemic under control, but must also consider the economic, social, cultural and political implications, across a spectrum of stakeholder groups. The macro economic benefits of reduced outbreak sizes and earlier eradication also need to be understood in the context of important policy decisions regarding how vaccinated animals will be managed at the end of the outbreak.

Currently, under the OIE guidelines, requirements to regain free status after emergency vaccination differ. Under a 'vaccinate to retain' policy a country can only regain FMD freedom 6 months after the last case and after surveillance on all vaccinated animals has been completed and confirmed no evidence of circulating FMD virus. This strategy also adds considerable logistical complexity to the post outbreak phase, including the management of vaccinated animals and surveillance for substantiating freedom from virus circulation. On the other hand, 'vaccinate to remove' is considered lower risk, so countries can regain disease freedom 3 months after culling all vaccinated animals [40]. The macro economic benefits of vaccination may increase significantly if proposals to align the time requirement for regaining FMD freedom after vaccination, are achieved. Although this study focused on two key measures (objectives) of outbreak success, it is important to recognise the trade offs incurred by the choice of either a

vaccinate to retain or vaccinate to remove policy. Estimating the number of livestock that would be vaccinated (which equates to the extra animals required to be culled under a 'vaccinate to remove' policy), in the context of the competing objectives around minimising outbreak duration or the total number of IPs is illustrated in Figure 2.

As animal health authorities give serious consideration to vaccination as a tool to support FMD control and eradication in non endemic countries, interest in testing vaccination strategies in a modelling environment has grown. With this study, we compared strategies in multiple country settings to provide insights around key decisions, including the timing of vaccination, risk targeted approaches and resource requirements. It is reassuring that despite differences in production systems, livestock demographics and control measures between countries and the use of different modelling platforms, there was consistency in the relative effectiveness of the vaccination strategies tested here. An indication of vaccination strategies that outperform SO alone and are robust to different startup conditions, are extremely useful to support response policy development.

It is important, however, to appreciate that model outputs are not standalone. When informing disease management, findings must be evaluated along with relevant veterinary and livestock sector expertise. It is also important to appreciate that while vaccination may have benefits in terms of achieving disease control objectives, keeping vaccinated animals in the population will delay the period until FMD free status is regained under OIE guidelines [40] and adds logistical complexity to the post outbreak management phase. Thus, vaccination carries with it additional operational demands and uncertainty around the period to return to international trade.

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A Simulation Study of the Use of Vaccination to Control Foot-and-Mouth Disease Outbreaks Across Australia

Tim R. Capon[1], Michael G. Garner[2], Sorada Tapsuwan[1]*, Sharon Roche[3], Andrew C. Breed[3,4], Shuang Liu[1], Corissa Miller[3], Richard Bradhurst[5] and Sam Hamilton[3]

[1] CSIRO Land & Water, Acton, ACT, Australia, [2] CSIRO Health & Biosecurity, Acton, ACT, Australia, [3] Epidemiology and One Health Section, Department of Agriculture, Water and the Environment, Canberra, ACT, Australia, [4] School of Veterinary Science, University of Queensland, Brisbane, QLD, Australia, [5] Centre of Excellence for Biosecurity Risk Analysis, The University of Melbourne, Melbourne, VIC, Australia

This study examines the potential for foot-and-mouth disease (FMD) control strategies that incorporate vaccination to manage FMD spread for a range of incursion scenarios across Australia. Stakeholder consultation was used to formulate control strategies and incursion scenarios to ensure relevance to the diverse range of Australian livestock production regions and management systems. The Australian Animal Disease Spread model (AADIS) was used to compare nine control strategies for 13 incursion scenarios, including seven control strategies incorporating vaccination. The control strategies with vaccination differed in terms of their approaches for targeting areas and species. These strategies are compared with two benchmark strategies based on stamping out only. Outbreak size and duration were compared in terms of the total number of infected premises, the duration of the control stage of an FMD outbreak, and the number of vaccinated animals. The three key findings from this analysis are as follows: (1) smaller outbreaks can be effectively managed by stamping out without vaccination, (2) the size and duration of larger outbreaks can be significantly reduced when vaccination is used, and (3) different vaccination strategies produced similar reductions in the size and duration of an outbreak, but the number of animals vaccinated varied. Under current international standards for regaining FMD-free status, vaccinated animals need to be removed from the population at the end of the outbreak to minimize trade impacts. We have shown that selective, targeted vaccination strategies could achieve effective FMD control while significantly reducing the number of animals vaccinated.

Keywords: Australian animal disease spread model, AADIS, vaccination, stamping out, epidemiology, outbreak, livestock

INTRODUCTION

Foot-and-mouth disease (FMD) is recognized as the single greatest disease threat to Australia's livestock industries (1, 2). Early detection of an incursion, effective control of an outbreak, and rapid return to trade are essential to minimize the economic impact of an outbreak. Australia's policy for an FMD response is to contain, control, and eradicate the disease and re-establish the FMD-free

status of Australia as quickly as possible, while minimizing social and financial disruption. The Australian Veterinary Emergency Plan (AUSVETPLAN) states that the "re-establishment of trade for affected industries would be one of the highest priorities of disease response efforts" (3).

Australia's preferred approach to control an outbreak of FMD is to use stamping out, supported by a combination of measures that include a national livestock standstill, quarantine, regional movement controls, tracing, and surveillance (3). Additional measures that may be taken if authorities consider that they would be beneficial in containing and managing the outbreak include vaccination, pre-emptive culling, zoning/compartmentalization, and risk-based movement controls. Australia invests considerable resources in preparedness and planning for emergency animal diseases, including maintaining a government- and industry-funded vaccine bank for FMD (3). Despite changes to Australian contingency plans to recognize that vaccination could be an important component of an FMD control program as soon as an outbreak is detected, it is unclear how, when, or even if vaccination should be used, and if it is used, how vaccinated animals should be managed.

Modeling studies in Australia (4–6) and overseas (7–9) have shown that vaccination is effective in reducing the duration and size of outbreak situations where disease is widespread, where there is a high rate of spread, or resources for stamping out are limited. Reports suggest that early vaccination may have allowed earlier eradication that took place in FMD outbreaks in Korea (10) and Japan (11, 12). Thus, vaccination is increasingly recognized as a useful tool in containing and eradicating FMD outbreaks. However, while vaccination can contribute to earlier eradication of disease, it will have additional costs—keeping vaccinated animals in the population will delay the period until FMD-free status is regained under the World Organization for Animal Health standards (13)—and add additional complexity to the post-outbreak surveillance for demonstrating the re-establishment of FMD-free status. These issues are of particular concern for countries with significant exports of livestock and livestock products as the use of vaccination and the presence of FMD vaccinated animals in the population could be expected to cause significant market access difficulties.

Australia has no recent experience with controlling an outbreak of FMD. Decision support tools including disease models offer valuable insights into the effectiveness of different control measures (14). In particular, the decision to vaccinate is best made early in an outbreak as vaccination is likely to perform better when implemented earlier (5). However, a decision to vaccinate early in the outbreak may result in using vaccination in situations where it may offer little to no additional benefit with implications for post-outbreak surveillance, management of vaccinated animals, and regaining FMD-free status and access to markets. Conversely, not using vaccination may lead to larger and longer outbreaks, increased control costs and greater ongoing impacts on industry and local communities.

While a number of modeling studies have already assessed FMD spread and control in Australia [e.g., (4–6)], these have tended to focus on a limited range of introduction scenarios along the eastern seaboard, representing scenarios considered to

be most likely or worst-case situations for FMD introduction and spread. FMD introduction, spread, and control in other areas of Australia are poorly understood. Disease managers would benefit from a clearer understanding of how, and under what conditions, vaccination could provide benefits in terms of managing an FMD outbreak in Australia.

The objective of this study is to thoroughly investigate the possible incursion scenarios and control options available to manage an FMD outbreak, with a focus on vaccination as a disease control option. The first stage of this study elicited stakeholders' views regarding the use of vaccination as part of a control strategy, incursion scenarios, and factors affecting emergency animal disease management decisions. The second stage of the study focused on how vaccination might be applied and the effect of vaccination on the size and duration of an outbreak. Drawing on the results of the stakeholder consultations, simulations were designed to better understand the consequences of alternative approaches to incorporating vaccination into control strategies for FMD.

METHODS

Stakeholder Consultation

Inputs from Australian state and territory jurisdictional stakeholders were collected through workshops and surveys. These were conducted during April to August 2017. This research received ethics approval from the CSIRO Human Ethics research committee. Stakeholders were selected from a panel of government and industry stakeholders affiliated with Animal Health Australia (AHA). AHA is a not-for-profit public company with membership made up of Commonwealth, state and territory governments, livestock industries, service providers, and associate members. AHA manages a range of national programs on behalf of its members that improve animal and associated human health, biosecurity, market access, livestock welfare, productivity, and food safety and quality (15). Selected stakeholders were sent an email invitation by AHA to participate in the consultation process (workshops or surveys depending on their availability). Two face-to-face workshops were held, each consisting of ~30 participants. Surveys were sent to representatives of the Australian jurisdictional governments to request information about two or three incursion scenarios of interest based on the most likely or important scenarios for FMD introduction for their jurisdiction. Details are provided in the **Supplementary Materials**.

Simulation Study Design

Simulations were conducted using the Australian Animal Disease Spread model (AADIS) (16)[1]. AADIS is a stochastic spatial simulation model that simulates livestock disease spread and control at the national scale. AADIS uses the herd as its epidemiological unit of interest. A "herd" in AADIS is defined as a group of comingling animals of the same species under the

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[1]AADIS is available under license for research purposes from the Australian Government Department of Agriculture, Water and the Environment (DAWE). Please contact Andrew.Breed@awe.gov.au at the Epidemiology and One Health Section, DAWE, for more information.

same production system. There are 11 different herd types in the AADIS FMD model (**Table 1**), and this allows for common attributes such as movement patterns and biosecurity practices to be applied based on herd type.

AADIS has a hybrid architecture that combines equation- and agent-based modeling techniques. The spread of disease within a herd is represented by an SEIR compartmental equation-based model (EBM) implemented as a system of ordinary differential equations (ODEs). The parameterization of the ODE system reflects the herd's production system and the subject FMD virus strain. At the time of infection, the herd's ODE system is solved numerically to yield predictions of the proportion of the

population that are infected, infectious, and have clinical signs of disease over time. The solution remains in place until an external event such as vaccination or culling acts upon the herd, triggering the resolving of the ODE system. The spread of disease between herds is modeled with a stochastic and spatially explicit agent-based approach. The model incorporates the attributes and spatial locations of individual farms, saleyards, weather stations, local government areas, and direct and indirect movement patterns. AADIS simulates disease spread in daily time steps, and FMD transmission between herds is modeled through five discrete pathways: 1—farm to farm animal movements, 2—local spread (infection of farms and herds within close geographical proximity by unspecified means), 3—indirect contact (*via* fomites or animal products), 4—animal movements *via* saleyards or markets, and 5—wind-borne spread. The proportions of infected and infectious animals in the population predicted by a herd's EBM inform the likelihood that between-herd spread will occur.

The AADIS unit of interest for the control of disease is the "farm" — defined as an establishment that has one or more herds. AADIS simulates disease control according to the availability of resources, such as personnel and vaccine, and models the suite of control measures prescribed in AUSVETPLAN (3). These control measures include movement controls of animals and fomites (national livestock standstill, regional movement restrictions, and quarantine of farms), stamping out of different farm types (culling and disposal of animals and decontamination of farms), surveillance (farmer reporting and active surveillance within declared areas), tracing (direct and indirect contacts), pre-emptive culling (dangerous contacts, ring culling, and slaughter on suspicion), and vaccination (suppressive, protective, or mass

**TABLE 1 |** Farm and animal populations used in the AADIS FMD model.

Farm type	Number of farms	Number of animals mean (min–max)
Extensive beef	1,331	1,909 (1,200–46,575)
Intensive beef	51,383	280 (30–7,436)
Feedlot	508	1,825 (100–39,963)
Mixed beef/sheep	21,556	242 (30–5,700)
Dairy	8,675	298 (40–2,742)
Small pigs	1,873	244 (40–4,850)
Large pigs	333	4,922 (1,000–17,896)
Sheep	22,150	1,649 (20–44,000)
Smallholder	103,641	5 (1–14)
Total	**202,775**	

This represents a synthetic farm population dataset obtained from Agricultural Census data (17) and industry data and reports. The bold values are statistically significant values.

TABLE 2 | Starting conditions for simulation study FMD incursion scenarios: seed herds and snapshots.

Incursion scenario	ID	Scenario description	Seed herd			Snapshot
			Scenario starting date	Farm type	# animals	# infected herds when FMD is first detected[a]
New South Wales	NSW1	Hobby farm in the Sydney basin	May 10	Smallholder	8	6
	NSW2	Intensive sheep in the Riverina	November 10	Sheep farm	1,210	2
	NSW3	Commercial piggery, airborne spread to dairies	July 1	Commercial piggery	4,643	9
Queensland	QLD1	Backyard pigs in South Eastern Queensland	January 10	Smallholder	9	4
	QLD2	Interstate transport of infected cattle	June 10	Intensive beef	109	13
	QLD3	Piggery in central Queensland near extensive beef region	May 1	Small pig farm	363	2
South Australia	SA1	Interstate transport of infected sheep	November 1	Mixed sheep/beef	3,271	3
Tasmania	TAS1	Sheep in southern highlands	August 10	Sheep farm	1,418	2
Victoria	VIC1	Hobby farms at Bacchus Marsh	May 1	Smallholder	12	3
	VIC2	Dairy farm in South Western Victoria	September 10	Dairy herd	516	44
	VIC3	Intensive beef in South East Victoria	October 1	Intensive beef	89	16
Western Australia	WA1	Smallholder in South West WA	May 10	Smallholder	7	10
	WA2	Commercial piggery in northern agricultural region	May 10	Commercial piggery	10,836	10

[a]Simulated number of infected herds in the population when the first IP is confirmed at the end of the silent spread phase.

FIGURE 1 | Locations of seed herds for each incursion scenario.
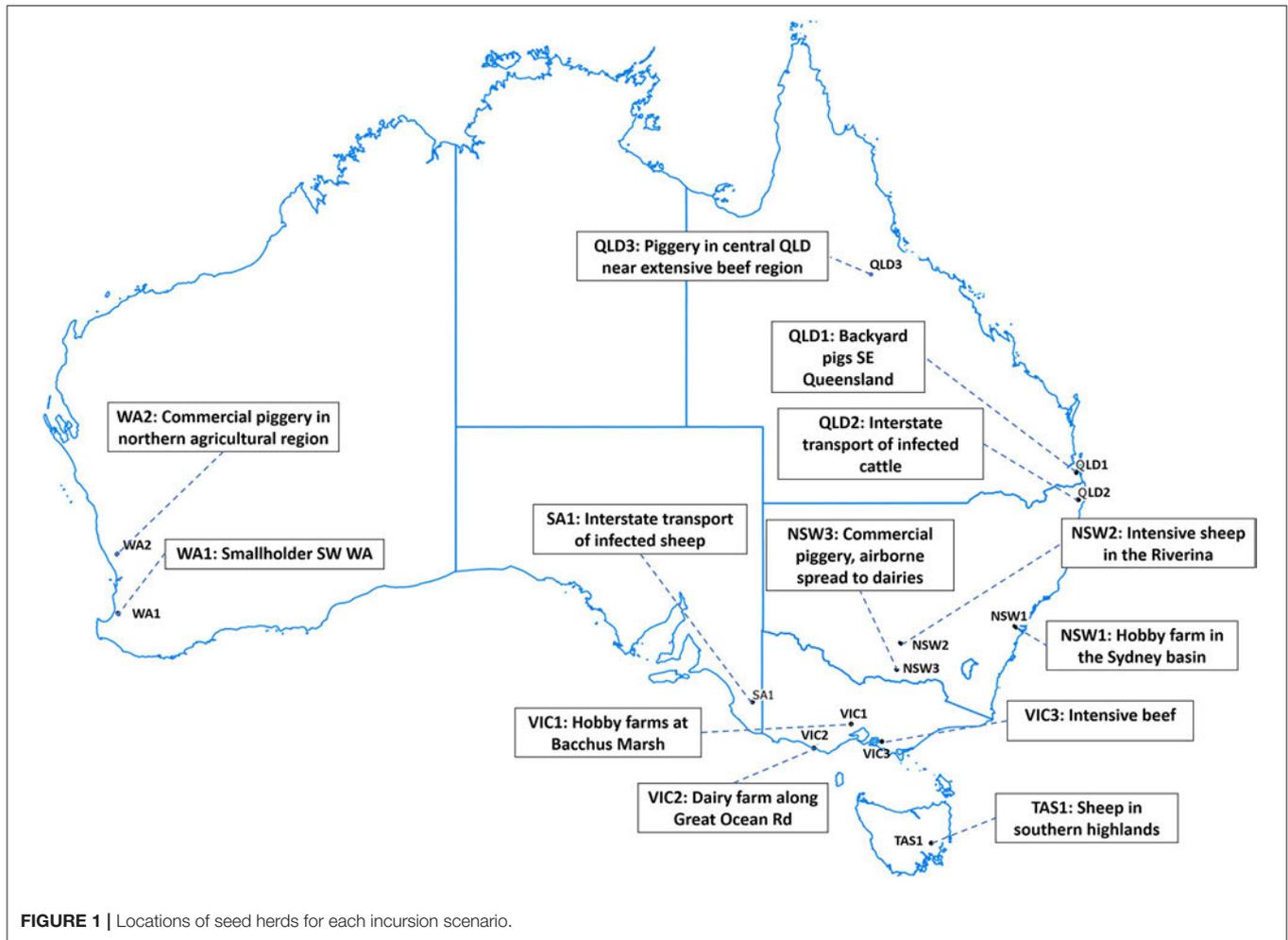
vaccination). All control measures are defined and resourced per jurisdiction. Further details on AADIS can be found in Bradhurst et al. (16, 18).

To characterize the incursion scenarios and control strategies for this study, AADIS was parameterized using a combination of values estimated for previous studies (5) and values estimated through stakeholder consultation (as described in Section Stakeholder Consultation above). Details of the AADIS parameterization are provided in the **Supplementary Materials**.

Incursion Scenarios

To examine the effectiveness of alternative approaches to incorporating vaccination into a control strategy across a range of starting conditions, we simulated control strategies for 13 incursion scenarios. Findings from the workshops and surveys were used to develop the characteristics of the incursion scenarios of interest to stakeholders. This included the method of FMD introduction, when FMD was introduced, type of source farm, time until first detection, and the reasons for selection of the scenarios. This approach ensured that the modeled outbreaks were relevant to the state and territory governments.

To convert inputs from stakeholder consultation into scenarios for the simulation study, we selected simulation runs based on stakeholders' scenario descriptions. A small set of up to 50 simulation runs was conducted for each incursion scenario at a time of year consistent with the scenario descriptions (as shown in **Table 2**). The simulation run that most resembled the description was used to identify the first infected farm, or "seed herd," for each incursion scenario. The selection was based on species, farm type, and geography of the starting location. Time until detection was fixed across incursion scenarios to focus comparisons on differences due to geographical conditions. A time of 21 days of silent spread before detection and disease control begins was chosen based on recent studies in Australia (6, 19, 20). The disease situation at detection (i.e., at the end of the silent spread phase of these representative runs) was saved as a "snapshot." **Figure 1** shows the locations of the seed herds for each of the 13 incursion scenarios.

The use of snapshots to capture the details of the incursion scenarios in AADIS ensured that alternative control strategies could be compared from an identical starting point when the disease was first detected, and control commenced.

TABLE 3 | Description of each control strategy in terms of approach to stamping out and targeting of vaccination.

Control strategy	Stamping out	Pre-emptive culling of DCPs[%]	Vaccination	Targeting of vaccination		
				Animals/Operations	Ring or Annulus	Area
1	Yes	No	No	–	–	–
2	Yes	Yes	No	–	–	–
3	Yes	No	Yes	All species*	5-km ring	All
4	Yes	No	Yes	All species	5-km ring	High-risk area[#]
5	Yes	No	Yes	All species except pigs and smallholders	5-km ring	All
6	Yes	No	Yes	Vaccination of specialist cattle producers^	5-km ring	All
7	Yes	No	Yes	Vaccination of specialist cattle producers^	5-km annulus, 5-km from IPs (out–in)	High-risk area[#]
8	Yes	No	Yes	Feedlots and large dairy farms >500 head	5-km annulus, 5-km from IPs (out–in)	All
9	Yes	Yes	Yes	All species	5-km ring	All

*Beef cattle on extensive properties were not targeted for vaccination in any control strategy because large extensive cattle properties are found only in northern Australia. They involve large areas with very low stocking densities and they are considered a low risk for FMD establishing/spreading. ^Including feedlots, dairy and intensive beef farms, but excluding extensive beef and mixed beef–sheep farms to avoid including large numbers of sheep on mixed farms in the vaccination program. [#]High-risk areas were defined as local government areas with high cattle herd densities and high cattle densities (>25 cattle per sq km). [%]DCPs are "Dangerous Contact Premises".

TABLE 4 | Descriptive statistics for the Control Strategy 1 benchmark control strategy for all incursion scenarios.

Variable	Scenario	Mean	SD	Min	Max	p25	p50	p75	p95
Total number of IPs	NSW1	10	3	6	38	8	9	11	15
	NSW2	2	0	2	4	2	2	3	3
	NSW3	12	4	9	62	10	11	12	17
	QLD1	5	1	4	16	4	5	5	8
	QLD2	36	8	19	73	31	36	41	49
	QLD3	2	6	1	123	1	2	2	3
	SA1	5	1	3	17	5	5	6	7
	TAS1	2	1	2	5	2	2	3	4
	VIC1	2	0	2	3	2	2	2	2
	VIC2	872	690	218	5,593	528	734	1,046	1,511
	VIC3	128	225	30	3,291	72	91	116	226
	WA1	23	9	11	82	18	21	26	42
	WA2	15	3	10	63	13	14	15	18
Last day of control	NSW1	47	5	41	80	43	46	48	57
	NSW2	41	3	40	71	40	40	40	46
	NSW3	51	6	45	93	48	49	51	63
	QLD1	48	3	43	74	46	48	49	53
	QLD2	62	12	48	137	54	57	65	87
	QLD3	36	21	28	356	29	32	40	49
	SA1	48	6	44	86	45	45	49	63
	TAS1	47	3	42	75	45	46	48	51
	VIC1	39	0	39	40	39	39	39	39
	VIC2	223	82	112	718	175	207	249	348
	VIC3	124	61	59	609	92	109	136	201
	WA1	64	21	44	195	55	58	64	107
	WA2	51	4	45	83	48	50	52	60

Design of Control Strategies

For this study, nine control strategies were selected to provide a comparison of seven alternative approaches using vaccination with two benchmark control strategies with stamping out but no vaccination. Stamping out is the default approach for controlling an outbreak of FMD and aims to ensure infected premises are quarantined and that susceptible animals are destroyed to limit virus spread (3). For each incursion scenario, 500 simulation runs were conducted of each control strategy. Preliminary work has shown that this is adequate in providing a high degree of convergence (<5%) for key outbreak metrics (number of IPs, duration, and costs). Convergence provides an indication across a set of simulation runs to how close the sample mean of key "per-run indicators" is to the theoretical population mean (21).

Table 3 describes the main points of difference between the control strategies.

All control strategies included stamping out. Control Strategies 2 and 9 included the pre-emptive culling of DCPs. Control Strategies 3 to 9 included some form of vaccination in addition to stamping out. For all vaccination strategies, vaccination was triggered on day 14 of the control phase only if there were five or more infected premises (IPs), as it was considered unlikely that vaccination would be applied if there were only a small number of IPs. The approaches to vaccination differed in terms of the animal species and farm types targeted, whether a suppressive vaccination approach was used (5-km radius ring around an IP with vaccination from inside out) or a protective vaccination approach within an annulus (5 km wide starting 5 km away from an IP, i.e., in an area between 5 and 10 km from the IP, with vaccination occurring from the outside in) was used, and whether all areas were targeted or only herds in pre-identified high-risk, livestock-dense areas were targeted for vaccination. High-risk areas were defined as local government areas with high cattle herd density (>0.175 herds per sq km) and high cattle density (>25 cattle per sq km). Estimates of resource teams available to undertake control activities were provided by jurisdictional animal health staff and considered the availability of resources from both the public and private sectors. Details of the model settings and parameters are included in the **Supplementary Materials**.

Sensitivity Analysis

In addition to the baseline control strategies, sensitivity analyses were conducted to test how sensitive the results are to two key assumptions used in the study:

(a) Timing of vaccination—vaccination was assumed to start 14 days into the control program based on the expected time for vaccine to be available for deployment. To test the sensitivity

TABLE 5 | Descriptive statistics for Control Strategy 3 for all incursion scenarios.

| Variable	Scenario	Mean	SD	Min	Max	p25	p50	p75	p95
Total number of IPs	NSW1	10	2	6	22	8	9	11	14
	NSW2	2	0	2	4	2	2	2	3
	NSW3	12	3	9	52	10	11	12	16
	QLD1	5	1	4	19	4	5	5	7
	QLD2	36	7	19	61	31	35	40	49
	QLD3	2	6	1	127	1	2	2	3
	SA1	5	2	3	30	5	5	6	7
	TAS1	2	1	2	10	2	2	3	4
	VIC1	2	0	2	3	2	2	2	2
	VIC2	221	52	127	807	191	214	243	292
	VIC3	64	16	35	176	54	61	71	94
	WA1	21	5	11	45	17	20	24	31
	WA2	15	3	11	53	13	14	15	19
Last day of control	NSW1	48	7	40	96	43	46	49	62
	NSW2	40	2	40	55	40	40	40	43
	NSW3	56	9	45	96	49	53	61	70
	QLD1	49	4	43	78	46	49	50	55
	QLD2	63	6	46	91	61	63	65	72
	QLD3	35	15	28	321	29	33	39	47
	SA1	48	7	44	87	45	45	49	65
	TAS1	47	4	42	90	46	47	48	51
	VIC1	39	1	39	50	39	39	39	39
	VIC2	99	17	73	225	90	96	106	125
	VIC3	72	11	56	144	65	68	77	95
	WA1	62	9	47	110	56	62	66	77
	WA2	54	8	45	93	48	52	60	68
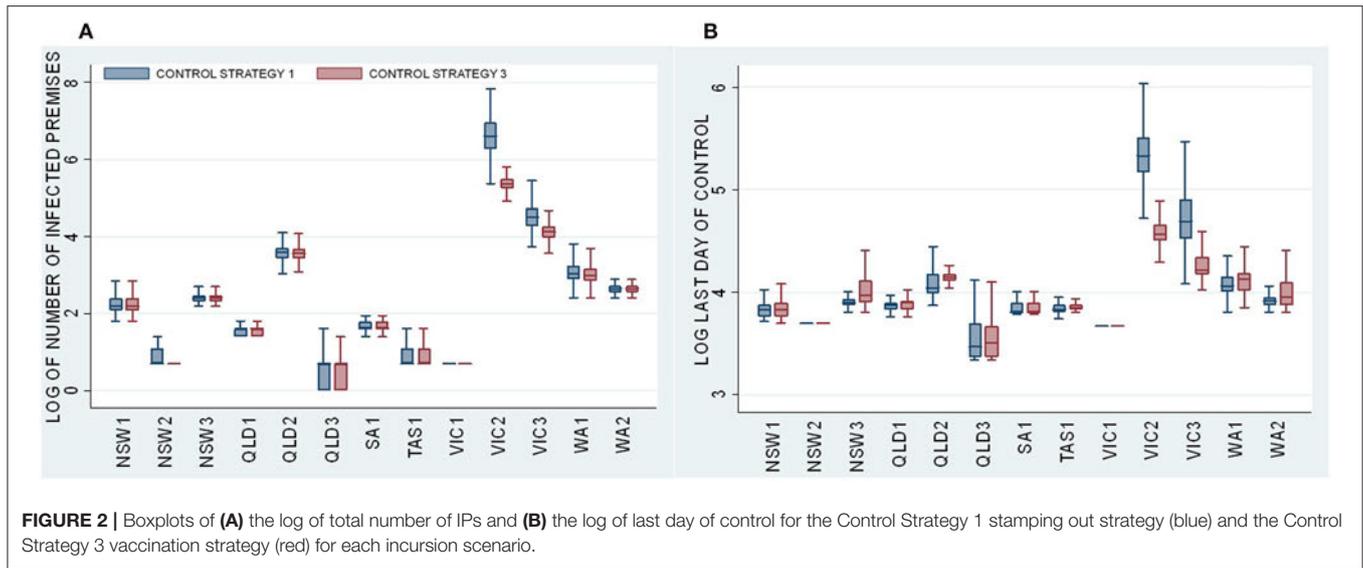
FIGURE 2 | Boxplots of **(A)** the log of total number of IPs and **(B)** the log of last day of control for the Control Strategy 1 stamping out strategy (blue) and the Control Strategy 3 vaccination strategy (red) for each incursion scenario.

TABLE 6 | Dunn tests on number of IPs.

Number of IPs		Comparisons between Control Strategies 2 to 9 and Control Strategy 1 (stamping out only)							
Incursion scenario	Dunn test statistics	1 vs. 2	1 vs. 3	1 vs. 4	1 vs. 5	1 vs. 6	1 vs. 7	1 vs. 8	1 vs. 9
NSW1	Statistics	**3.9634****	0.2847	−0.5694	−0.0694	−0.3014	0.0407	−0.8018	**5.4542****
NSW1	*p*-value	**0.0013**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	**0.0000**
NSW2	Statistics	−0.2444	1.4432	0.3430	0.7574	0.4186	1.4809	0.8098	0.4711
NSW2	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
NSW3	Statistics	−0.4152	−0.8427	−0.1364	−0.2337	0.7346	−0.1541	−0.7765	−0.6992
NSW3	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
QLD1	Statistics	−0.5503	0.0942	0.3700	−0.3724	−0.4173	−0.6084	−0.3909	0.5117
QLD1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
QLD2	Statistics	−2.2111	1.0125	0.7260	2.7675	2.1013	0.1648	0.2215	**3.1511****
QLD2	*p*-value	0.4865	1.0000	1.0000	0.1017	0.6410	1.0000	1.0000	**0.0293**
QLD3	Statistics	−0.6188	−1.0859	−1.4378	1.8802	1.8277	0.4982	−0.0048	−0.6831
QLD3	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
SA1	Statistics	1.2517	0.3504	−0.3402	**2.9022***	−0.7021	0.7780	0.4911	1.0832
SA1	*p*-value	1.0000	1.0000	1.0000	**0.0667**	1.0000	1.0000	1.0000	1.0000
TAS1	Statistics	0.7128	1.4346	−0.0736	0.4477	0.1497	2.0318	0.3194	1.3158
TAS1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	0.7592	1.0000	1.0000
VIC1	Statistics	−1.0145	−1.6814	0.3363	0.0000	−0.6754	−1.6906	−0.3425	0.6725
VIC1	*p*-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
VIC2	Statistics	0.6126	**30.6157****	**29.6603****	**30.1835****	**28.5593****	**20.9707****	**17.0234****	**31.5525****
VIC2	*p*-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
VIC3	Statistics	1.1924	**18.7642****	**17.5880****	**17.5623****	**16.7609****	**9.3049****	**7.2829****	**19.7776****
VIC3	*p*-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
WA1	Statistics	**4.6269****	**3.2538****	1.3965	**3.1902****	1.7224	1.6745	0.3430	**6.8012****
WA1	*p*-value	**0.0001**	**0.0205**	1.0000	**0.0256**	1.0000	1.0000	1.0000	**0.0000**
WA2	Statistics	**3.8885****	1.3583	0.3939	−0.1568	0.5833	1.6344	**2.7819***	**3.4730****
WA2	*p*-value	**0.0018**	1.0000	1.0000	1.0000	1.0000	1.0000	**0.0973**	**0.0093**

*, **, *** mean significant at $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. The bold values are statistically significant values.

of the results to timing of vaccination, vaccination programs starting on day 10 and day 21 were also simulated.

(b) Vaccination ring radius—based on stakeholder inputs, we assumed a 5-km ring vaccination radius. To test how sensitive

the results are to the size of the vaccination ring, we also simulated a 3-km ring radius.

For the sensitivity analyses, the nine control strategies were run for each of the 13 incursion scenarios, with changed parameter values for these assumptions. Previous studies have conducted sensitivity analyses of other AADIS parameters, including time to detection and duration of the national standstill (16), and parameters relevant to FMD transmission, such as the probability of spread, infectivity, and susceptibility (22).

Statistical Analysis

The Kruskal–Wallis test was used to test whether there were differences in the mean number of IPs and the last day of control for each incursion scenario and control strategy combination. This test is a non-parametric analog to the ANOVA and was chosen as the appropriate test due to the data being non-normally distributed. The null hypothesis is that there are no significant differences in the median number of IPs and the last day of control for each of the control strategies, for each of the starting locations. The null hypothesis was rejected at the 95% confidence level. To examine specifically which control strategies and which incursion scenarios result in significant differences in the number

of IPs and last day of control, we performed a Dunn test (23). The Dunn test is the appropriate non-parametric pairwise multiple comparison procedure when a Kruskal–Wallis test is rejected (24). We applied a Bonferroni adjustment to account for the number of pairwise comparisons conducted.

RESULTS

We compared alternative disease control strategies that incorporate vaccination with benchmark control strategies with stamping out only, across the range of incursion scenarios. We first present the results for the benchmark strategies, then the assessment of the effectiveness of vaccination based on a comprehensive ring vaccination approach (Control Strategy 3) for all incursion scenarios, before providing a more detailed analysis of the alternative types of vaccination strategy. Finally, we report the results of the sensitivity analyses.

Incursion Scenarios Derived From Stakeholder Consultation

Table 2 describes the starting conditions of each incursion scenario, including production type and number of animals

TABLE 7 | Dunn tests on last day of control.

Last Day of Control		Comparisons between Control Strategies 2 to 9 and Control Strategy 1 (stamping out only)							
Incursion scenario	Dunn test statistics	1 vs. 2	1 vs. 3	1 vs. 4	1 vs. 5	1 vs. 6	1 vs. 7	1 vs. 8	1 vs. 9
NSW1	Statistics	**−8.9822*****	−0.6765	−0.1648	−0.6704	−1.3076	0.4781	−1.0602	**−10.8082*****
NSW1	p-value	**0.0000**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	**0.0000**
NSW2	Statistics	0.3989	2.1061	0.0786	0.9690	0.3778	1.2704	1.0085	−0.3777
NSW2	p-value	1.0000	0.6335	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
NSW3	Statistics	−0.2852	**−9.1792*****	−1.0577	**−7.8178*****	**−3.2603****	−0.7075	−0.6496	**−8.9966*****
NSW3	p-value	1.0000	**0.0000**	1.0000	**0.0000**	**0.0200**	1.0000	1.0000	**0.0000**
QLD1	Statistics	−2.5167	−2.6580	−0.7841	−2.1815	−2.7051	−2.0661	−1.8084	**−2.9727***
QLD1	p-value	0.2132	0.1415	1.0000	0.5246	0.1229	0.6987	1.0000	**0.0531**
QLD2	Statistics	**−3.3983****	**−8.5038*****	**−6.4720*****	**−8.3998*****	**−7.4976*****	**−5.9211*****	−1.0667	**−10.1058*****
QLD2	p-value	**0.0122**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	1.0000	**0.0000**
QLD3	Statistics	−0.6267	−1.6059	−1.7620	0.7397	0.8837	0.0145	−1.2479	−0.8343
QLD3	p-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
SA1	Statistics	1.1272	−0.6250	−1.4629	1.4540	−1.0461	0.8012	0.6988	0.8665
SA1	p-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
TAS1	Statistics	0.4497	−0.5745	−0.3701	−0.4942	−0.5315	0.4408	−0.1987	0.3866
TAS1	p-value	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
VIC1	Statistics	−1.9164	−1.9033	0.0000	−0.3165	−0.9533	−1.9104	−0.3243	−1.2788
VIC1	p-value	0.9957	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
VIC2	Statistics	0.4837	**30.5759*****	**28.9434*****	**30.6717*****	**26.7298*****	**22.9713*****	**16.4683*****	**29.3161*****
VIC2	p-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
VIC3	Statistics	0.9270	**25.4775*****	**25.7184*****	**24.7720*****	**23.4256*****	**12.2731*****	**7.9626*****	**22.7966*****
VIC3	p-value	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
WA1	Statistics	1.3173	**−4.5509*****	2.4955	**−5.6252*****	−1.8958	2.7270	1.8492	**−5.3097*****
WA1	p-value	1.0000	**0.0001**	0.2264	**0.0000**	1.0000	0.1150	1.0000	**0.0000**
WA2	Statistics	1.0975	**−5.4508*****	−0.1338	**−5.9318*****	**−6.8597*****	0.6469	0.6700	**−5.4624*****
WA2	p-value	1.0000	**0.0000**	1.0000	**0.0000**	**0.0000**	1.0000	1.0000	**0.0000**

*, **, *** mean significant at p < 0.1, p < 0.05, and p < 0.01, respectively. The bold values are statistically significant values.

in each seed herd and the number of infected herds in the population for each snapshot, that is, when the outbreak is first detected, and the control program begins.

Benchmark Strategies for All Incursion Scenarios

For comparison with alternative approaches using vaccination, simulations were conducted with a benchmark strategy of stamping out only (Control Strategy 1) and stamping out with pre-emptive culling of DCPs (Control Strategy 2). **Tables 4**, **5** present descriptive statistics for all incursion scenarios for the benchmark, Control Strategy 1, for the total number of IPs and the last day of control (i.e., duration of the control program).

The last day of control measures the number of days of disease control as the number of days of culling plus two incubation periods (28 days). For many of the incursion scenarios, the outbreaks were small and controlled relatively quickly. The Victorian scenarios VIC2 and VIC3 were the largest, followed by WA1, a scenario in Western Australia. In particular, the VIC2 outbreak could become very large and potentially last more than 12 months.

The pre-emptive culling of DCPs is an additional control measure that could be considered to help contain and manage the outbreak. In this study, Control Strategy 2 allows comparison with Control Strategy 9, which combines vaccination with the pre-emptive culling of DCPs.

Comparing the strategies of stamping out only (Control Strategy 1) and stamping out with pre-emptive culling of DCPs (Control Strategy 2) using Dunn tests, we found that there were statistically significant differences in the total number of IPs for incursion scenarios NSW1, WA1, and WA2 and in the last day of control for NSW1 and QLD2. The differences between the medians, however, are small and do not appear important for disease control. Notably, no statistically significant differences were found between Control Strategy 1 and Control Strategy 2 for the two incursion scenarios with the largest outbreaks, i.e., VIC2 and VIC3.

The Effect of Vaccination on Outbreak Size and Duration

Descriptive statistics and Dunn test statistics were used to compare the effect of the vaccination strategy across all 13

FIGURE 3 | Boxplots of **(A)** VIC2 total number of IPs, **(B)** VIC2 last day of control, **(C)** VIC3 total number of IPs, and **(D)** VIC3 last day of control for each control strategy, Control Strategy 1 to Control Strategy 9.

FIGURE 4 | Boxplots of the total number of vaccinated animals for Scenario VIC2 for the control strategies with vaccination (Control Strategy 3 to 9).

FIGURE 5 | Boxplots of the total number of vaccinated animals for Scenario VIC3 for the control strategies with vaccination (Control Strategy 3 to 9).

incursion scenarios by comparing a stamping out only (Control Strategy 1) with a comprehensive vaccination strategy (Control Strategy 3), which involves vaccinating all species in a 5-km radius of each infected premises. **Figure 2** presents boxplots of the distributions of (a) the total number of IPs and (b) the last day of control across all 500 iterations for Control Strategies 1 and 3. For each incursion scenario, NSW1 to WA3, **Figure 2** shows boxplots for Control Strategy 1 on the left and Control Strategy 3 on the right.

Figure 2 presents the log of the size and duration of all the outbreaks. Most of the incursion scenarios shown in **Figure 2** lead to small outbreaks that are controlled relatively quickly by Control Strategy 1. Vaccination (Control Strategy 3) offers no benefits in terms of reducing the size of the outbreak (number of IPs) or duration. Note that there is very little difference in the size and duration of the smaller outbreaks (NSW1–NSW3, QLD1–QLD3, SA1, TAS1, VIC1, WA1, and WA2) between Control Strategy 1—stamping out only (blue) and Control Strategy 3—vaccination strategy (red). A Dunn test statistic confirms that there are no significant differences in the median value of the total number of IPs and last day of control between Control Strategy 1 and Control Strategy 3 for all incursion scenarios shown in **Figure 2**.

However, in the case of Victorian scenarios (VIC2 and VIC3), the outbreaks are larger. In these cases, vaccination is effective in reducing the size and duration of the outbreaks. There is a marked contrast between the median of 734 for the total number of IPs for the VIC2-Control Strategy 1 (stamping out only) and the median of 214 for the VIC2-Control Strategy 3 (stamping out with vaccination). The same pattern holds for VIC3, with a median of 91 IPs for VIC3-Control Strategy 1 compared with 61 for VIC3-Control Strategy 3. Although only Control Strategy 3 is presented in **Figure 2**, Dunn tests comparing every vaccination strategy (Control Strategy 3 to Control Strategy 9) with Control Strategy 1 showed similar effects (see **Tables 6**, **7**).

Alternative Vaccination Strategies and the Size and Duration of Large Outbreaks

Here, we focused on comparing the seven alternative vaccination approaches (Control Strategy 3 to Control Strategy 9) with the benchmark stamping out approaches (Control Strategy 1 and Control Strategy 2) for the two incursion scenarios in Victoria, VIC2 and VIC3, which were associated with larger outbreak sizes and for which vaccination was shown to be very effective in reducing size and duration of the outbreaks. VIC2 begins in a dairy herd in southwest Victoria, and VIC3 begins in an intensive beef property in southeast Victoria (see **Table 2** and **Figure 1**). **Figure 3** compares the effect of the different vaccination strategies on outbreak size and duration.

All vaccination strategies were effective in reducing outbreak size and duration. However, Control Strategy 7 and Control Strategy 8 (the annulus strategies) were less effective than the ring vaccination strategies. Additionally, there was little difference in outbreak size and duration for Control Strategies 3, 4, 5, and 6. There were significant differences, however, in the numbers of animals vaccinated under the different strategies. The total number of vaccinated animals is shown for each vaccination strategy for scenario VIC2 in **Figure 4** and for scenario VIC3 in **Figure 5**. **Tables 8**, **9** present the results of the Dunn test of statistical differences comparing these strategies.

Control Strategy 6 consistently performed well in this study. This strategy applies vaccination to specialist cattle producers within a 5-km radius around each IP, including feedlots and dairy and intensive beef farms, but excluding mixed beef–sheep farms to avoid including large numbers of sheep on mixed farms in the vaccination program. Note that for Control Strategy 8, very few farms met the stringent criteria to be vaccinated. For example, under scenario VIC2, the median number of premises being vaccinated per run was only 1 (range 0–8).

Figure 6 presents the proportions of the simulation runs for each incursion scenario where the vaccination trigger of five or more infected premises on day 14 of the control phase was met (out of 500 simulations runs for Control Strategy 3).

TABLE 8 | Dunn test of total animals vaccinated for Scenario VIC2.

Control strategies	Dunn test statistics	Control strategies					
		3	4	5	6	7	8
4	Statistics	**12.8766**					
	p-value	**0.0000***					
5	Statistics	−0.08046	**−1.30E + 01**				
	p-value	1.0000	**0.0000***				
6	Statistics	**38.0533**	**25.1767**	**38.1338**			
	p-value	**0.0000***	**0.0000***	**0.0000***			
7	Statistics	**20.6108**	**7.7342**	**20.6912**	**−1.74E + 01**		
	p-value	**0.0000***	**0.0000***	**0.0000***	**0.0000***		
8	Statistics	**29.3102**	**16.4336**	**29.3907**	**−8.7431**	**8.6995**	
	p-value	**0.0000***	**0.0000***	**0.0000***	**0.0000***	**0.0000***	
9	Statistics	1.6069	**−1.13E + 01**	1.6873	**−3.64E + 01**	**−1.90E + 01**	**−2.77E + 01**
	p-value	1.0000	**0.0000***	0.9612	**0.0000***	**0.0000***	**0.0000***

*, **, *** mean significant at p < 0.1, p < 0.05, and p < 0.01, respectively. The bold values are statistically significant values.

TABLE 9 | Dunn test of total animals vaccinated for Scenario VIC3.

Control strategies	Dunn test statistics	Control strategies					
		3	4	5	6	7	8
4	Statistics	**10.8898**					
	p-value	**0.0000***					
5	Statistics	−1.0787	**−1.20E + 01**				
	p-value	1.0000	**0.0000***				
6	Statistics	**10.1952**	−0.6946	**11.2739**			
	p-value	**0.0000***	1.0000	**0.0000***			
7	Statistics	**−2.12E + 01**	**−3.21E + 01**	**−2.01E + 01**	**−3.14E + 01**		
	p-value	**0.0000***	**0.0000***	**0.0000***	**0.0000***		
8	Statistics	**−4.3208**	**−1.52E + 01**	**−3.2421**	**−1.45E + 01**	**16.8406**	
	p-value	**0.0002***	**0.0000***	**0.0125****	**0.0000***	**0.0000***	
9	Statistics	1.5089	**−9.3809**	2.5876	**−8.6863**	**22.6704**	**5.8298**
	p-value	1.0000	**0.0000***	0.1015	**0.0000***	**0.0000***	**0.0000***

*, **, *** mean significant at p < 0.1, p < 0.05, and p < 0.01, respectively. The bold values are statistically significant values.

It is worth noting that for Control Strategy 3, vaccination was triggered in 7 of the 13 scenarios (NSW1, NSW3, QLD3, VIC2, VIC3, WA1, and WA2). On the other hand, there were four scenarios where vaccination was never triggered (NSW2, QLD3, TAS1, and VIC1). Vaccination was never triggered in these scenarios because there were fewer than five IPs on Day 14 of the control phase.
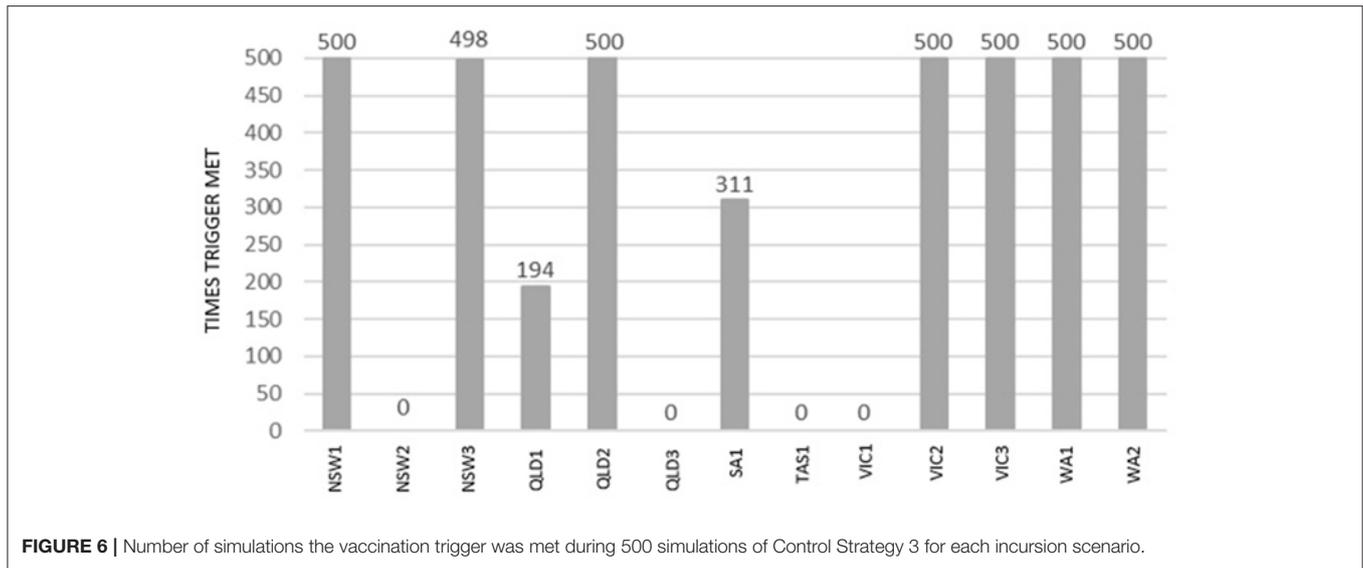
Results of Sensitivity Analyses

Sensitivity analysis around the assumptions of the timing of vaccination (day 10 vs. day 21 vs. baseline day 14) and vaccination ring radius (3 km vs. baseline 5 km) suggests that results are robust to changes in the assumptions around vaccination. **Table 10** presents the Dunn test results for the assumptions of the timing of vaccination (day 10 vs. day 21) and vaccination ring radius (3 km vs. baseline 5 km).

DISCUSSION AND CONCLUSION

This paper shows the results of a simulation study informed by stakeholder consultation that investigated options for incorporating vaccination into control strategies for FMD outbreaks across Australia, including areas considered to be at lower risk for introduction and spread of FMD.

For previously FMD-free countries, FMD control has tended to be based on stamping out and indeed this is Australia's preferred approach as described in AUSVETPLAN (3). However, the use of vaccination in control of an FMD outbreak is increasingly recognized as an important option (9, 25, 26). This is driven by resourcing issues and ethical, environmental, and welfare concerns over the large-scale culling of animals (5, 25, 27–30). While vaccination may contribute to earlier eradication of the disease, it will be associated with additional costs—keeping vaccinated animals in the population will delay the period until

FIGURE 6 | Number of simulations the vaccination trigger was met during 500 simulations of Control Strategy 3 for each incursion scenario.

TABLE 10 | Dunn tests for sensitivity analyses—comparisons of Control Strategy 1 with Control Strategy 3 for baseline simulation assumptions and changed vaccination assumptions for sensitivity analysis.

Variable	Incursion scenario	Dunn test statistics	Baseline simulations	Sensitivity analysis simulations with changed assumptions		
			(B)	(1)	(2)	(3)
			Day 14/5 km	Day 14/3 km	Day 10/5 km	Day 21/5 km
			Control Strategy 1 vs. 3	Control Strategy 1 vs. 3	Control Strategy 1 vs. 3	Control Strategy 1 vs. 3
Number of IPs	VIC2	Statistics	31.5108	20.6578	24.5240	23.0540
	VIC2	p-value	0.0000***	0.0000***	0.0000***	0.0000***
Last day of control	VIC2	Statistics	31.1772	18.4195	23.8080	27.0068
	VIC2	p-value	0.0000***	0.0000***	0.0000***	0.0000***
Number of IPs	VIC3	Statistics	25.0053	22.3874	20.7088	18.4084
	VIC3	p-value	0.0000***	0.0000***	0.0000***	0.0000***
Last day of control	VIC3	Statistics	18.3969	16.5565	17.4394	12.4666
	VIC3	p-value	0.0000***	0.0000***	0.0000***	0.0000***

(B) Baseline assumption: vaccination from Day 14 and 5-km vaccination ring radius.
(1) Alternative: vaccination from Day 14 and 3-km vaccination ring radius.
(2) Alternative: vaccination from Day 10 and 5-km vaccination ring radius.
(3) Alternative: vaccination from Day 21 and 5-km vaccination ring radius.
*, **, *** mean significant at $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.

FMD-free status is regained under current World Organization for Animal Health standards (13, 31) and add additional complexity to post-outbreak surveillance programs (32).

This analysis has shown that many outbreaks of FMD in Australia, based on incursion scenarios identified by stakeholders, were comparatively small. Management through stamping out without vaccination may be the most appropriate response for these smaller outbreaks, as vaccination did not reduce the size or duration and the cost of vaccination may increase control costs substantially. The largest simulated outbreaks were observed for two Victorian incursion scenarios (VIC2 and VIC3). This is consistent with previous work that identified southeastern Australia as the area most vulnerable to an FMD outbreak because of its geographic and climatic

conditions, including its relatively high human population and its higher stocking rates (20). In Victoria, the temperature, climate, and higher rainfall mean that there is more intensive farming than in most other parts of Australia.

For the large simulated outbreaks in Victoria, vaccination was shown to reduce both the size (total number of IPs) and length of an outbreak. This finding is also consistent with previous modeling studies in Australia (4, 5, 28) and overseas (9, 25, 26, 33–36), which found that vaccination can be an effective strategy in suppressing the spread of infection particularly if livestock density is high, disease is widespread, there is a high rate of spread, or resources for stamping out are limited.

Suppressive ring vaccination, that is, vaccinating in a ring immediately around IPs, was found to be more effective than

vaccination in an annulus, further out from the IPs. A previous study using multiple models and a United Kingdom outbreak scenario also concluded that suppressive ring vaccination was a more effective use of vaccine resources (5). A similar impact on outbreak size and duration was found regardless of the approach to ring vaccination (Control Strategies 3–6). However, there were significant differences in the numbers of animals vaccinated under the different strategies. Vaccinating cattle only was particularly effective. In their multi-model study, Roche et al. (9) reported that a cattle-only vaccination strategy was as effective as vaccinating all susceptible species for three of the four models used in their study.

Issues with management of vaccinated animals following an FMD outbreak and trade restrictions have limited the use of vaccination as a first-line control strategy, especially for countries with large export industries. FMD-free status can be recovered 3 months after the last reported case under stamping-out or pre-emptive culling strategies, and this increases to 6 months when vaccination is used unless all vaccinated animals are removed from the population, in which case free status can be regained 3 months after removing the vaccinated animals (13). To minimize duration of the closure of export markets, under current international standards, vaccinated animals would need to be removed from the population (31). However, culling vaccinated animals obviously has additional animal welfare, economic, and social impacts. In this situation, it would be desirable to minimize the number of animals vaccinated while still achieving effective control. This study and others [e.g., (9)] confirm that selective, targeted vaccination can be an effective strategy to reduce the number of animals vaccinated. We found that targeting vaccination to high-risk areas (strategy Control Strategy 4) or to cattle only (Control Strategy 6) achieved effective control of the large Victorian outbreak scenarios, while significantly reducing the number of animals vaccinated compared to more expansive vaccination strategies.

Given the finding that vaccination when used with stamping can be very effective in reducing the size and duration of large outbreaks compared to stamping out on its own, a key issue is deciding when it should be used. That is, how can decision makers identify situations when an outbreak is likely to be large. A decision to vaccinate early in the outbreak may result in situations where it was not actually required and have consequent implications for post-outbreak surveillance, management of vaccinated animals, and regaining FMD-free status and access to export markets (31, 32). Conversely, not using vaccination in some situations may lead to much larger and longer outbreaks, increased control costs, and greater impacts on industry and local communities (6). During an outbreak, decisions on control are often made under significant uncertainty and in conditions that are continually evolving. Resources are often limited and will influence the effectiveness of disease control efforts. The decision to vaccinate and choice of strategy will ultimately depend on the nature of the epidemic, available resources to implement it, and objectives of the control program [(37); also see AUSVETPLAN, (3)]. Work by Hutber et al. (38), Halasa et al. (39), and Sarandopoulos (40) indicates that information available early in an outbreak can be used to make inferences

about the potential severity of an FMD outbreak. In a detailed study involving simulated FMD outbreaks in Australian and New Zealand, Garner et al. (6) showed that relatively simple metrics that would be available to disease managers early in an outbreak such as the cumulative number of IPs were consistently found to be strongly associated with the final size and the duration of the outbreak.

There are two key implications from these findings. First, combining stakeholder consultation to formulate scenarios and strategies for epidemiological modeling revealed that many incursion scenarios of concern to stakeholders in Australia are likely to lead to small outbreaks. These outbreaks could be managed effectively with stamping out alone and is consistent with findings in other low livestock density situations (33). This highlights the importance of incorporating the views and expertise of stakeholders in scenario formulation and not just focusing on large, worst-case scenarios when comparing control strategies. Stakeholder consultation helped identify the concerns and priorities of disease managers across the Australian jurisdictions and ensured that the simulations were driven by decision-makers' needs rather than just the possibilities of the modeling platform.

Second, notwithstanding the effectiveness of vaccination to reduce the size and duration of large outbreaks, under current international standards (13), there remains a strong disincentive to use vaccination under the belief that a vaccination policy will always result in the longest return to markets for exports of susceptible livestock and their products. To minimize trade impacts, vaccinated animals need to be removed from the population at the end of the outbreak. Given this situation, we have shown that targeted vaccination strategies are effective in achieving control while reducing the numbers of animals vaccinated. Differential time periods are being challenged (41) and new diagnostic approaches that improve surveillance might be able to provide acceptable levels of confidence in the infection status of vaccinated populations in the future.

Future research could further investigate and validate the effectiveness of vaccination as a control strategy for FMD. We suggest analysis to determine whether vaccination can reduce the probability of extremely large and long outbreaks. In this study, the focus was on the median size and duration of an outbreak. Examining the effect of alternative control strategies on the probability of large and long outbreaks will provide decision makers with a better understanding of the potential role of vaccination. An additional area for further work also includes spatially and temporally mapping the risk of FMD spread to help identify regions where vaccination is more likely to play a useful role. More comprehensive modeling studies could be used to assess which areas may be more vulnerable or susceptible to large outbreaks. Further work to refine early decision indicators of severe outbreaks to support decision-making is important. Lastly, we recommend further research to investigate the trade-offs between the cost of using vaccination as a control strategy and the effectiveness of the outcome. The costs should include consideration of direct costs of the control strategies and indirect costs, such as revenue loss from animal movement restrictions, loss from trade embargoes, and the cost of business recovery

and continuity after eradication. The effectiveness of the outcome should be considered not only in terms of infected premises and control duration but also in terms of numbers of animals vaccinated and culled. This could consider the ethical, welfare, and social benefits of reducing culling using vaccination.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by CSIRO Human Ethics research committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

TC: project lead and main author of manuscript writing. MG: epidemiological modeling and write up of methods and results. ST: statistical analysis and write up of methods and results. SR and SL: stakeholder consultation design and implementation. CM, ACB, and SH: provided input toward conceptual model and analysis of results. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry:	Adequacy of Australia's biosecurity measures and response preparedness
Question No:	IQ22-000011
Hearing Date:	10 August 2022
Division/Agency:	Biosecurity Animal Division (BAD)
Topic:	FMD vaccine storage - status and cost associated
Hansard Page:	15-16
Question Date:	10 August 2022
Question Type:	Spoken

Senator Canavan asked:

CHAIR: I have one quick question on clarity of Senator Roberts's line of questioning. I'm just not clear: would the storage of FMD vaccines in Australia itself change our FMD-free status? I mean just the storage of them per se, not the use of them.
Dr Parker: I would have to take that on notice.
CHAIR: Thank you. Have we costed storing a variety of vaccines here in Australia?
Senator COLBECK: Based on the question that I asked a moment ago about the UK now being FMD-free based on eradicating it, I would be interested in an answer to that question, too, because they are not on the list as having FMD. They do have the bank, so I think that almost answers the question, but—
CHAIR: I thought it would too, but the officials have taken it on notice. Do you have anything to add, Mr Metcalfe?
Mr Metcalfe: We will take that on notice.
CHAIR: Finally, could you take on notice whether you have costed it and, if so, how much it would cost to store that?
Mr Metcalfe: We will do our best to respond.

Answer:

Australia's foot-and-mouth disease (FMD) status will not be impacted if vaccines are stored in Australia.

The Department of Agriculture, Fisheries and Forestry has not costed storage of FMD vaccines in Australia. The current vaccine bank is stored off shore, and is managed by Animal Health Australia under a national program co-funded by states/territories, industry and the Commonwealth.

It is important to note that vaccination would not be deployed immediately or in every outbreak scenario. An epidemiological assessment of the situation will be undertaken to determine if vaccination would be part of the response strategy and how it would be used.

Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry: Adequacy of Australia's biosecurity measures and response preparedness

Question No: IQ22-000012

Hearing Date: 10 August 2022

Division/Agency: National Animal Disease Preparedness Coordinator

Topic: Former Minister - actions and advice

Hansard Page: 16

Question Date: 10 August 2022

Question Type: Spoken

Senator Ciccone asked:

Senator CICCONE: What actions did the former minister take once becoming aware of the FMD outbreak in Indonesia?

Mr Metcalfe: This was through the caretaker period. Of course, the minister was aware of the significant funding that was in the budget and was primarily associated with the response to a lumpy skin disease outbreak in Indonesia, but the minister certainly remained well briefed through that entire period and, as I indicated, provided a briefing to the opposition spokesperson.

Senator CICCONE: I go back to my question. What actions did the minister take?

Mr Metcalfe: We will need to double-check exactly what may have occurred. There was a lot of activity, as you would expect, right through this period, so I might take that on notice.

Senator CICCONE: On that caretaker period that you mentioned: could you explain for my benefit and maybe for others in the committee what a minister can do during the caretaker provisions?

Mr Metcalfe: The government remains the government and is in full possession of its powers; however, there is the convention, of course, that no significant appointments, contracts or other policy matters are progressed without consultation—that does not require agreement—with the opposition.

Senator CICCONE: So could the minister have taken action to either raise awareness or address the risks of FMD?

Mr Metcalfe: I've indicated we'll take that on notice. There certainly were visits by officials. There was media awareness. There were other activities underway. But I will need to go back and check, and we will provide you with a full answer.

Senator CICCONE: Since the initial briefing back in May, did your department provide any advice to the minister about the actions that should be taken to prevent the FMD outbreak reaching Australia?

Mr Metcalfe: I will take that on notice.

Senator CICCONE: Did your department have discussions with other departments about the possibility of closing the border with Indonesia?

Mr Metcalfe: No.

Senator CICCONE: So no requests had come from a ministerial office asking about the closure of the border?

Mr Metcalfe: Not that I'm aware, but, for the sake of completeness, we'll go back and check our records.

Answer:

1. **What actions did the former minister take once becoming aware of the FMD outbreak in Indonesia?**

   The former minister:

   - was advised of the foot-and-mouth disease (FMD) outbreak in Indonesia on 6 May 2022 and requested daily fact updates from the department from 9 May until 20 May 2022

   - requested a briefing from the Australian Chief Veterinary Officer and Deputy Secretary of the department's Biosecurity and Compliance Group on 9 May 2022 (the former Shadow Minister, Julie Collins, was briefed on the same day).

2. **So could the minister have taken action to either raise awareness or address the risks of FMD?**

   The outbreak of FMD in Indonesia occurred during the Caretaker Period. During the caretaker period, the business of government continues and ordinary matters of administration still need to be addressed. However, successive governments have followed a series of practices - the 'caretaker conventions' - which aim to ensure that their actions do not bind an incoming government and limit its freedom of action.

3. **Since the initial briefing back in May, did your department provide any advice to the minister about the actions that should be taken to prevent the FMD outbreak reaching Australia**

   On 6 May 2022, the department advised that financial assistance would be offered to the Indonesian Government to respond to this outbreak.

   From 9 to 20 May the department provided advice on departmental actions taken, including:

   - advising chief veterinary officers in New Zealand, Timor-Leste and Papua New Guinea, state and territory chief veterinary officers, National Biosecurity Committee members and industry stakeholders of the outbreak

   - removing Indonesia from the department's FMD-free country list, reviewing import permits for animal products from Indonesia that may carry FMD and suspending those of concern

   - an Operational Change Advice to operational staff at borders and those managing vessels, including livestock carriers to alerts staff of the increased risk of travellers, mail and conveyances (including personnel) from Indonesia and providing advice on measures to limit the possible introduction of the virus into Australia

     : officers were advised that all goods from Indonesia should now be assessed as coming from an FMD affected country

   - providing advice to the Australian Border Force, the Australian Airports Association and the Board of Airline Representatives regarding the FMD risk in Indonesia and heightened border response in the traveller pathway

   - providing advice to the live export industry on the need for increased vigilance around disinfection requirements for vessels, stockpersons and accredited veterinarians

- publication of a departmental media statement and the Australian Chief Veterinary Officer engaging in media interviews

- targeted communication material for international travellers

- exploring options for vaccine supply to Indonesia

- engaging with the Australian Centre for Disease Preparedness on technical assistance that could be provided to Indonesia to strengthen their capacity to manage the FMD outbreak

- FMD testing of meat products seized from travellers and mail from Indonesia

- the Australian Chief Veterinary Officer and Deputy CVO to travel to Indonesia on 29 May 2022 to meet with senior government officials to discuss the outbreak.

Refer to IQ22-000015 for a chronology of departmental actions.

4. **So no requests had come from a ministerial office asking about the closure of the border?**

No.

Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry:	Adequacy of Australia's biosecurity measures and response preparedness
Question No:	IQ22-000014
Hearing Date:	10 August 2022
Division/Agency:	National Animal Disease Preparedness Coordinator
Topic:	Chronology of actions after the former minister advised of FMD outbreak
Hansard Page:	17
Question Date:	10 August 2022
Question Type:	Spoken

Senator Ciccone asked:

Senator CICCONE: Alright. As soon as the former minister was advised about the outbreak, did he increase any passenger screening at our airports?
Mr Metcalfe: There were a number of measures taken across the period from when lumpy skin disease was detected and whatever. We could go back and provide you with some form of a chronology as to what occurred.
Senator CICCONE: Yes. And also, could you provide whether we increased our mail and cargo screening?
Mr Metcalfe: We'll take that on notice.

Answer:

The Department of Agriculture, Fisheries and Forestry implemented a range of heightened border measures, including screening of travellers and mail, in response to the increased risk of foot-and-mouth disease (FMD) due to the active outbreak in Indonesia.

Refer to IQ22-000015 for a full list of events and departmental actions associated with the FMD outbreak in Indonesia.

International mail and cargo screening

- All non-letter class mail from Indonesia is routinely screened by detector dog or x-ray, and subject to a biosecurity inspection. Since 10 June 2022, 100% of non-letter class mail from Indonesia has been inspected for biosecurity risk material including FMD risk.

- The department continued its normal biosecurity intervention for cargo as goods with FMD risk are required to meet certain import conditions.

The following departmental actions were taken between 9 May and 21 May 2022 (during caretaker period):

9 May 2022

- The department issued internal advice to its operational areas about the FMD outbreak and outlined interim advice on how to manage FMD risk goods from Indonesia while the import conditions for FMD goods from Indonesia were being updated on the department's Biosecurity Import Conditions database (BICON).

- The department commenced enhanced real-time risk assessment of travellers arriving into Australia from Indonesia.

11 May 2022

- [Import Industry Advice Notice](#) published targeting stakeholders associated with shipping or importing goods from Indonesia, advising of the outbreak of FMD in Indonesia and the revised import conditions for FMD risk material from Indonesia.

- The department removed Indonesia from Australia's FMD-free country list.

13 May 2022

- The department implemented 100% assessment and intervention of passengers from direct flights from Indonesia.

- The department provided an FMD briefing to the Australian Border Force (ABF) executive management and directors based at international airports.

- The department provided an FMD briefing to airport operators and airlines.

17 May 2022

- The department issued an FMD advice to airports, airlines and the ABF.

- The department provided an information sheet to Australia Post on the FMD outbreak in Indonesia and advising all non-letter class mail from Indonesia is screened by the department and may undergo heightened intervention.

18 May 2022

- An Operational Staff Notice was published advising staff in traveller and mail operations of the requirements for collection and testing of FMD susceptible products seized at the border between 18 and 31 May 2022.

Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry:	Adequacy of Australia's biosecurity measures and response preparedness
Question No:	IQ22-000016
Hearing Date:	10 August 2022
Division/Agency:	Australian Chief Veterinary Office
Topic:	Vaccine arrival date
Hansard Page:	18
Question Date:	10 August 2022
Question Type:	Spoken

Senator McDonald asked:

Senator McDONALD: Thank you. I want to turn to the vaccines again. I understand that the public sector vaccines from Elanco Argentina were sent yesterday and will arrive on 16 August, and that they have been labelled 'not for sale'. So the private sector is hoping to see vaccinations in early September. Does that sound about right to you?

Dr Parker: The date I have is actually 22 August, but I'm happy to take the actual arrival date on notice and notify the Senate when that occurs. There are a range of challenges within the Indonesian system about access for some of the larger private-sector players in the marketplace. I know that they have released, I think, in the order of 60,000 vaccines which have been used previously. Really, that's a matter for the Indonesians going forward. But, from speaking with industry earlier this week, I am aware that LSD vaccines have arrived in Jakarta and that there are now increasing numbers. The Indonesians have appointed five different companies to be able to import the vaccine into the country, so I think it would be fair to say there's quite a bit of momentum in this space.

Senator McDONALD: That's terrific.

Answer:

As of 18 August, vaccines are expected to arrive in Jakarta from 21 August 2022. This timing is subject to all relevant final import clearances being obtained by the importer in Indonesia.

Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry: Adequacy of Australia's biosecurity measures and response preparedness

Question No: IQ22-000017

Hearing Date: 10 August 2022

Division/Agency: Legal and Governance Division

Topic: Awareness campaign

Hansard Page: 19

Question Date: 10 August 2022

Question Type: Spoken

Senator McDonald asked:

Senator McDONALD: Alright, given the shortness of time today, what I am hearing on the ground is some of the front line of detection and treatment for lumpy skin or foot-and-mouth detection will be at a very grassroots level. I have been trying to identify if there has been any work done on providing some very visual aids like posters to go into station lap rooms so that young stockmen and women who are riding around would be able to recognise the disease. But at the moment I can only find big companies doing it for themselves. I am very keen to understand how local farmers would be able to do it. That is a very specific example. I don't need to get into that now but, on the front line, if a farmer detects something that they think looks like lumpy skin or foot-and-mouth at this point, do they clearly understand what their go-to is in Australia? They are telling me 'no', so I think that is my answer. I don't want to hold us up, though, because I know the chair will have to move on.
...
Mr Metcalfe: On the earlier point you raised about the awareness down at the stockhand level and whatever, I can advise that we have of course, as you know, a whole series of on-plant vets in meat establishments. They have recently been trained to recognise any possible symptoms. But down at the property level, I met recently with the head of the Red Meat Advisory Council and he was detailing a whole range of activities that are underway at the business level, at the property level, in relation to that awareness for people who may be in first-hand contact with animals. But we will take your question as being on notice and we will try and provide you with a more detailed response.
 Senator McDONALD: Thank you. I really appreciate that, because obviously we talk about things at a higher level but at a lower level that may not necessarily be getting through, which is my point.
Mr Metcalfe: Yes. I don't need to tell you—you would be aware of it—there has been a massive information campaign underway in all sorts of social media and other ways of trying to get through to people, from my department, from MLA, from individual companies. The Gundaroo vet surgeon where I take my dogs has a major campaign underway. It goes on and on, but it is a very good point you mention. We want to make sure that there's no possible single point of failure, so we'll come back as to what the whole system is doing to try and ensure that people are well aware of the symptoms and the way to report them et cetera.

Answer:

Raising awareness of livestock diseases is a joint responsibility between the Commonwealth's lead agency the Department of Agriculture, Fisheries and Forestry, Animal Health Australia (AHA), and state and territory governments.

The department, AHA and state and territory governments work together via the National Biosecurity Communication and Engagement Network (NBCEN). This network helps to ensure biosecurity messaging is nationally consistent and aligned.

AHA also support the National Farmers Federation (NFF) and Red Meat Advisory Council (RMAC) Industry Taskforce Communications Working Group to roll out specific communication campaigns related to signs and symptoms of disease, and have also been rolling out fortnightly webinars of which the first webinar had more than 2,400 tune in.

Information campaigns at the national, state/territory and industry level have reinvigorated the spotted anything unsual mantra which focuses on the tagline of *'Look, check, ask a vet'*. Awareness materials have included fridge magnets and posters, and more recently digital channels including social media and direct email. The printed materials have been available to producers through various events including field days and relevant expos/conferences. All department, AHA, state/territory and industry communications regarding livestock diseases point to the Emergency Animal Disease Watch hotline (1800 675 888).

On-farm biosecurity is also a major focus of biosecurity communications at the Commonwealth and state/territory level. The website www.farmbiosecurity.com.au is a joint initiative between AHA and Plant Health Australia (PHA), containing free resources and comprehensive advice, including a facility for producers to order a farm biosecurity gate sign.

The website supports producers to build a biosecurity toolkit specific to their farming enterprise – helping them to identify biosecurity risks and put control measures in place. The pest and disease national reporting hotlines feature prominently on this website.

The department, AHA and state and territory departments also produce disease specific awareness materials. In recent years these have included materials related to foot-and-mouth disease, lumpy skin disease, Japanese encephalitis, and African Swine Fever.

These materials are available on the deparment, AHA and PHA websites:

- https://www.agriculture.gov.au/
- https://animalhealthaustralia.com.au/
- https://www.planthealthaustralia.com.au/

Rural and Regional Affairs and Transport References
Answers to questions on notice
Agriculture, Fisheries and Forestry Portfolio

Inquiry: Adequacy of Australia's biosecurity measures and response preparedness

Question No: IQ22-000031

Hearing Date: 10 August 2022

Division/Agency: Biosecurity Animal Division

Topic: Passengers Carrying Food

Question Date: 12 August 2022

Question Type: Spoken

Senator Canavan asked:

1. Does the Department have any evidence, data or research into the effectiveness of banning all incoming passengers from Indonesia carrying food into Australia?
2. New Zealand has introduced a ban on passengers carrying food from Indonesia. Why hasn't this been done in Australia?

Answer:

1. The Department of Agriculture, Fisheries and Forestry does not currently have evidence, data or research on the effectiveness of banning all incoming passengers from Indonesia carrying food into Australia.

2. The department is currently reviewing the import of meat and meat products for personal use from all foot-and-mouth disease (FMD) affected countries.

   New Zealand and Australia operate under separate pieces of biosecurity legislation. The department understands that New Zealand has banned the import of meat and meat products (not all food) with passengers from Indonesia.