Australian Government
Department of Agriculture and Water Resources

cebra
Centre of Excellence for Biosecurity Risk Analysis

Ministry for Primary Industries
Manatū Ahu Matua

CEBRA Report Cover Page			
Title, ID, & Output #	*Incorporating real-time economic components in Australia's FMD modelling capability and evaluating post-outbreak management to support return to trade. Project 1608D*		
Project Type	*Data and information – Benefit cost*		
Project Sponsor	*Tim Chapman, First Assistant Secretary, Biosecurity Animal Division*	**DAWR Project Leader/s**	*Dr Graeme Garner*
CEBRA Project Leader	*Prof. Tom Kompas, University of Melbourne*	**NZ MPI Project Leader/s**	*N.A.*
Project Objectives	*The aim of this project was to evaluate economy-wide impact of post-outbreak FMD management, including surveillance approaches and management of vaccinated animals. The specific objectives were:* *1. Build capacity in Australia's FMD modelling platform (AADIS) to test the effectiveness of different diagnostic procedures and sampling approaches to meet OIE surveillance requirements for regaining FMD-free status.* *2. Study implications and quantify costs of post-outbreak management of FMD where vaccination has been used in the control program. Three different approaches will be compared:* *a) Vaccinate-and-retain* *b) Vaccinate-and-remove (slaughter to waste)* *c) Vaccinate-and-remove (slaughter and salvage)*		
Outputs	*A detailed report on the work and the findings to be provided* *Papers for publication in the scientific literature* *Presentations to key stakeholders*		
CEBRA Workplan Budget	**Year 2016-17**		
	$150,900		
Project Changes	*Nil*		
Research Outcomes			
Recommendations			
Related Documents			

Report Complete	

Research Team

Graeme Garner Australian Government, Department of Agriculture and Water Resources

Clare Death	Australian Government, Department of Agriculture and Water Resources
Iain East	Australian Government, Department of Agriculture and Water Resources
Richard Bradhurst	CEBRA, University of Melbourne
Aaron Dodd	University of Melbourne
Tom Kompas	CEBRA, University of Melbourne

Report of CEBRA Project 1608D

Incorporating economic components in Australia's FMD modelling capability and evaluating post-outbreak management to support return to trade

Graeme Garner, Richard Bradhurst, Clare Death, Aaron Dodd, Iain East and Tom Kompas

Summary

Foot-and-mouth disease (FMD) has been identified as the single greatest disease threat to Australia's livestock industries. Vaccination is increasingly being recognised as an important tool to assist in containing and eradicating FMD outbreaks. The two options for vaccinated animals at the end of an outbreak are to remove them from the population in order to expedite regaining FMD-free status ('vaccinate-and-remove'), or to keep the animals in the population and allow them to live out their normal commercial lives ('vaccinate-and-retain'). More than 90% of the economic costs of an FMD outbreak in Australia would arise from revenue losses caused by immediate and prolonged export bans by Australia's FMD sensitive markets. Following an outbreak of FMD, surveillance will be required to demonstrate that infection has been eradicated from the population in order to meet international requirements to regain FMD-free status and to satisfy trading partners so as to regain access to international markets. Although there is growing interest in vaccinate-and-retain policy for the control of FMD to avoid the need for large scale culling of at-risk animals, keeping vaccinated animals in the population will make achieving recognition of free status more difficult under current international rules.

From a policy perspective it would be very useful if disease managers had access to decision support tools that could be used to evaluate policies and approaches to regain FMD-free status and facilitate early return to trade. This project expanded the functionality of the Australian Animal Disease model (AADIS) currently being used by animal health authorities in Australia to support FMD planning and preparedness, to include capacity to evaluate different approaches to post-outbreak surveillance in previously infected areas and a module for post-outbreak management of vaccinated animals.

To demonstrate how the improved functionality can be used, case studies of hypothetical outbreaks in Qld, WA and Vic. are reported. These studies involved comparing different approaches to disease control and post-outbreak management. In the first study, vaccination used with stamping out provided no improvement over stamping out on its own in the Qld case study scenario, provided a small but significant improvement in the WA case study and was highly effective in reducing the size and duration of the outbreak in the Vic. case study. This finding highlights that when it comes to considering the use of vaccination, a 'one size fits all' approach is not appropriate.

In the second demonstration study we showed how a reduced sampling intensity surveillance approach used with a control program not involving vaccination, could significantly reduce the number of samples collected and the cost of the post-outbreak surveillance program without increasing the risk of missing residual infected herds when compared to a baseline surveillance

based on the European Union FMD Directive. However, when emergency vaccination is used, there was a high likelihood that some vaccinated herds will be exposed to infection and under a vaccinate-and-retain policy, post-outbreak surveillance programs, even when census sampling is used, cannot be guaranteed to find all of these herds. 'There is a risk that some animals in vaccinated herds that were exposed to FMD virus could have been infected and some of these could be carriers. Recovered animals that are not carriers do not pose a risk of transmitting FMD. Carriers are considered a potential but unquantified risk for spread of FMD. After a comprehensive surveillance program the risk of carriers remaining in the population is low but not zero.'

The third demonstration study compared (a) vaccinate-and-retain; (b) vaccinate-and-remove (slaughter to waste) and (c) vaccinate-and-remove (slaughter and salvage) policies for managing vaccinated animals. The vaccinate-and-remove strategies were associated with higher post-outbreak management costs but lower loss of trade costs. In terms of overall cost, there would be significant savings compared to the vaccinate-and-retain policy. From a cost point of view there was no advantage of removal with salvage compared to removal to waste under the study assumptions. Any savings made through salvage are offset by trade losses associated with longer time required to remove all vaccinated animals, and regain markets.

This project has developed and demonstrated modelling functionality to support policy development around important issues to facilitate regaining FMD free status and regaining market access after an FMD outbreak. However, the limited nature of the studies and uncertainty around some parameters means that more work is required before it is possible to provide clear advice and guidelines to disease managers. It is anticipated that the work done in this project will continue under a MLA-CSIRO FMD project funded under the Rural R&D for Profit Program.

1. Introduction

Foot-and-mouth disease (FMD) is recognised as the single greatest disease threat to Australia's livestock industries (Matthews 2011, Buetre et al. 2013). Early detection of an incursion, effective control of an outbreak and rapid return to trade are essential to minimise the economic impact of an outbreak. Australia's policy for an FMD response is to contain, control and eradicate the disease in order to re-establish the FMD-free status of Australia as quickly as possible, while minimising 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' (Animal Health Australia 2014).

Following an outbreak of FMD, surveillance will be required to demonstrate that infection has been eradicated from the population and enable any remaining movement restrictions to be lifted within the country. Proof of freedom will also be needed to satisfy trading partners and regain access to international markets. To regain its FMD-free status after an outbreak, Australia will need to meet international animal health guidelines which include minimum time periods since the last case of disease, and appropriate surveillance aimed at identifying disease and FMD infection or transmission (OIE 2016). The AUSVETPLAN FMD strategy sets out principles for designing a post-outbreak surveillance program (Animal Health Australia 2014).

> *'To provide confidence that FMDV is no longer circulating a comprehensive surveillance program will be required. This will need to be carefully designed and followed to ensure that it produces sufficient data that are reliable and acceptable to the OIE and international trading partners, while avoiding a program that is excessively costly and logistically complicated. The surveillance program will build on surveillance, tracing and diagnostic testing done during the control phase. The post-outbreak surveillance program should include clinical and serological surveillance, and targeted and random components.'*

Although vaccination is increasingly being recognised as an important tool to assist in containing and eradicating FMD outbreaks, it will make achieving recognition of free status more difficult—keeping vaccinated animals in the population will delay the period until FMD-free status is regained under the World Organisation for Animal Health (OIE) guidelines and add additional complications to the post-outbreak surveillance program. If vaccination is used in the control program subsequent actions will depend on how the vaccinated population is managed.

There is no agreed approach to post-outbreak management of vaccinated animals in AUSVETPLAN with the options being to:

- allow vaccinated animals to remain in the population to live out their normal commercial lives (*vaccinate-and-retain*);
- remove all vaccinated animals from the population (*vaccinate-and-remove*).

Under option 2, vaccinated animals could be subject to (a) slaughter to waste i.e. remove and dispose of vaccinated animals; or (b) slaughter and salvage i.e. attempt to sell either raw or processed product from vaccinated animals. For (b) there may be some residual value of products that could offset some of the costs.

For a country like Australia with large export-focussed livestock industries, it is important to have clear guidelines on management and surveillance required to regain FMD-free status and facilitate early return to trade in the event of an FMD outbreak. These should be based on sound epidemiological principles. Determining the best approach to regaining FMD-free status will depend

on the nature of the outbreak, type of control program (particularly whether vaccination has been used or not) and an economic evaluation of the different options. The focus of this project was on building capability to quantify and compare the performance and impact of different approaches to managing vaccinated animals and doing post-outbreak surveillance. This capability can then be used to provide sound economic evidence to support policies on post-outbreak management to facilitate return to trade.

The objectives of this study were:

1. Build capacity in Australia's FMD modelling platform (AADIS) to test the effectiveness of different diagnostic procedures and sampling approaches to meet OIE surveillance requirements for regaining FMD-free status.

2. Study implications and quantify costs of post-outbreak management of FMD where vaccination has been used in the control program. Three different approaches will be compared:
   a) Vaccinate-and-live
   b) Vaccinate-and-remove (slaughter to waste)
   c) Vaccinate-and-remove (slaughter and salvage)

Early in the course of the project a workshop with jurisdictional and industry stakeholders was held. The workshop brought together policy-makers, disease-managers, researchers and industry representative to discuss the requirements for enhancing Australia's national FMD modelling platform – AADIS (Australian Animal Disease model) used to support FMD preparedness and planning (Bradhurst et al. 2015) – to enable simulation modelling of FMD post-outbreak management in Australia. In addition to discussing the key requirements to address post-outbreak surveillance issues both where vaccination has and has not been used in the response, the workshop also considered a small set of study scenarios to be used as case studies to test the AADIS modifications. This workshop provided important focus and direction to the project. The report of the workshop is attached (Appendix 1).

To address the objectives, the project has added a post-outbreak management and surveillance module to the AADIS model. The approaches used for these activities are described in section 3. The software changes and updates to the AADIS model are described in Appendix 6. To demonstrate how the improved model can be used to compare different management approaches, in section 4 we provide some examples using case studies. These involve three outbreak scenarios, use different approaches to control (with and without vaccination), compare different surveillance regimes to demonstrate freedom from FMD and compare different approaches to managing the vaccinated population.

2. Background

2.1 Regaining FMD-free status after an outbreak

In the event of an FMD outbreak, to regain its FMD-free status, Australia would have to put a case, in the form of a dossier, to OIE that provides 'sufficient' evidence to provide confidence that we have actually eradicated FMD (OIE 2016, USDA 2015). This dossier would include extensive descriptions of the livestock populations and management systems in Australia, animal health services (both field and laboratory), and detailed information on how the outbreak was managed (relevant legislation, events, chronology control strategies, measures implemented, etc). A key element underpinning the Australian case will be surveillance data to support:

a) Our assertions that FMD was restricted to the known infected areas. This would be largely based on surveillance done during the outbreak through suspect clinical investigations and tracing of movements
b) That if FMD was still in the country we would know about it. This would be based on enhanced reporting and investigation of any suspect cases after the outbreak, enhanced clinical inspection of susceptible animals (e.g. at abattoirs, saleyards, etc.) and some post-outbreak targeted testing of high risk groups and/or locations.
c) Absence of circulating virus in previously infected areas. This is likely to involved structured surveys designed to provide appropriate statistical confidence that FMD has been eradicated

For this project it is c) that we will be concentrating on. Here we use the term post-outbreak surveillance to represent structured surveillance activity that is done to substantiate freedom from infection.

The OIE code provides general information on surveillance in its FMD Chapter (Article 8.8.40) including serological surveillance. However, it does not specify a particular design or surveillance sampling strategy, but leaves it to the affected country to justify their approach. There is little information available on appropriate surveillance measures though some publications (e.g. Caporale et al. 2012) discuss the principles involved. The European Union (EU) Directive on FMD control (European Union 2003) provides details on how FMD is to be managed in member states including requirements for lifting of restrictions. The requirements are summarised in Appendix 2. In brief, the Directive specifies:

- Sampling should not begin until at least a month after the last outbreak of FMD or last use of vaccine
- Preliminary cleansing and disinfection on infected holdings to have been completed
- A survey involving clinical inspection and serological testing has been done with negative results (details of survey design in different areas is in Annex III)
- If vaccination has been used a survey should be carried out that will include clinical inspection and laboratory testing of all vaccinated animals

The EU FMD directive specifies levels of surveillance that will apply in Protection Zones (PZ) and Surveillance Zones (SZ) which have radii of 3km and 10km respectively around infected holdings. The EU requirements, including their implementation, were further considered at an EPIZONE, EUFMD (FAO) workshop held in Belgium in January 2007 (Anon. 2007). Key recommendations from this workshop are summarised in Appendix 3.

In the absence of a pre-defined post-outbreak FMD surveillance strategy in Australia, and indeed for other counties, for this study, we have adopted the European approach (European Union 2003; Anon 2007) as the baseline for developing a surveillance evaluation module in AADIS (see also Section 3.1).

2.2 Freedom from infection

Freedom from FMD implies the absence of the FMD virus in a specified population. Depending on when they are assessed animals infected with FMD may be:

- Acutely infected
- Recovered
- Persistently infected ('carrier')

Carriers are animals from which live virus can be recovered more than 28 days post-infection (Salt 1993, Kitching and Mackay 1998). Up to 50% of FMD-recovered sheep and cattle may become carriers irrespective of their vaccination status (Moonen and Schrijver 2000, Parida 2009). Pigs do not become carriers. Carriers are considered a potential but unquantified risk for spread of FMD (Moonen and Svrijver 2000). Recovered animals that are not carriers do not pose a risk of transmitting FMD, although their presence in a population after a control program could be an indication of undiscovered infection.

Due to limitations in sampling and diagnostic test performance, available methods cannot provide absolute certainty of the absence of infection (Schuppers et al. 2012). Demonstrating freedom from infection is a probabilistic concept that involves a level of confidence that disease is not present at a specified (minimum) level. Assessing the disease-free status of a country may be achieved through random survey, non-survey-based surveillance or both, using classical statistical or Bayesian methods (Caporale et al. 2012). Survey-based approaches have generally been preferred because they are considered more objective and defensible and a quantitative estimate of confidence of a disease being absent from a population can be readily calculated (Caporale et al. 2012).

The purpose of post-outbreak surveillance is to detect acute or persistent infection, especially sub-clinical infections and recovered animals that may have been missed during the control program and by other (e.g. clinical) surveillance. For the purpose of this report, herds containing recovered or persistently infected animals at the end of the outbreak are referred to as 'residual herds'.

2.3 The challenge of vaccination

There is growing interest in vaccinate-and-retain policy for the control of FMD, with emergency vaccination being used to avoid the need for large scale culling of at-risk animals (Paton et al. 2006). If vaccination has been used during the control program, vaccinated animals will test positive using standard serological tests (OIE 2012, OIE 2016). Vaccinated animals that have been exposed to infection, particularly soon after vaccination, may become infected then recover or go on to become carriers. Vaccinated animals that are subsequently infected can be identified using FMD non-structural protein (NSP) tests (OIE 2016). It is important to identify NSP-positive animals in a vaccinated population, even if they are not carriers, as they may cause problems for market access in the future.

The options for vaccinated animals at the end of an outbreak are:

- Keep the animals in the population and allow them to live out their normal commercial lives ('vaccinate-and-retain')
- Remove them from the population in order to expedite regaining FMD-free status ('vaccinate-and-remove')

Under the second option there is a further decision to be made as to whether to simply slaughter and dispose of the vaccinated animals or to attempt to salvage some value from the slaughtered vaccinates.
Post-outbreak surveillance to support regaining FMD-free status will be much more difficult under a vaccinate-and-retain strategy (Caporale et al, 2012). Since vaccinated ruminants exposed to infection may become sub-clinically and persistently infected it is necessary to find and remove all vaccinated infected animals in order to regain FMD –free status without vaccination (Paton et al. 2006, Paton et al. 2014).

2.4 Serological tests

Animals infected with FMD virus produce antibodies to both virus structural proteins and non-structural proteins. Vaccinated animals produce antibodies mainly or entirely to the structural proteins (SP). Thus, SP serological tests can be used to screen unvaccinated populations for evidence of FMD virus exposure or infection. These tests are serotype-specific and are highly sensitive, providing that the virus or antigen used in the test is closely matched to the strain circulating in the field. Commercial kits are available. SP antibodies generally appear around five days after infection

The detection of antibody to FMD viral non-structural proteins (NSPs) can be used to identify past or present infection with any of the FMD serotypes, regardless of whether the animal has also been vaccinated or not. NSP testing is the preferred diagnostic method to distinguish virus infected carrier animals from non-infected vaccinated animals (Clavijo et al. 2004). A number of commercial kits are available. NSP tests can be used to confirm suspected cases of FMD and to detect viral activity or to substantiate freedom from infection on a population basis (OIE 2012). However, there is experimental evidence that some cattle, vaccinated and subsequently challenged with live virus and confirmed persistently infected, may not be detected in some NSP tests, causing false-negative results (Brocchi *et al*., 2006). In addition, vaccinated animals that have been subsequently infected with FMD tend to develop lower NSP antibody levels than those in non-vaccinated animals (Parthiban et al. 2015). NSP antibodies appear around 7 seven days after infection.

Lack of vaccine purity may affect diagnostic specificity.

Performance of laboratory tests is measured in terms of sensitivity (Se) and specificity (Sp):

- Se is the proportion of true infected samples that will test positive using the test. (1-Se) is the probability that the test gives a false negative result
- Sp is the proportion of non-infected samples that will test negative using the test. I1-Sp) is the probability that a test gives a false positive result.

As no diagnostic test is perfect (i.e. Se =100%, Sp=100%) both false positive and false negative test results can be expected when undertaking surveillance. The rate of false positive and false negative results are however, entirely predictable based on test performance. FMD test performance will vary with different tests, between species and between vaccinated and non-vaccinated animals (Paton et al. 2006, Backer et al. 2012).

Performance of FMD serological tests has been reported in a number of publications (Brocchi et al 2006 , Paton et al. 2006). Specificity of a commercial SP test (PrioCheck, Life Technologies) has been reported as greater than or equal to 99% in all species (http://tools.thermoifisher.com/content/sfs/brochures/animalhealth_flyer_priocheck_fmdv_typespecific.pdf). Sensitivity varies with virus type and was found to be around 80-99%, higher with Type O compared to Types A or Asia1. This is consistent with reports from the literature. CSIRO-AAHL (Watson pers.comm. May 2017) citing the literature reported high specificity generally >99%, and the following 95% confidence intervals for sensitivity to Type O virus of 0.89-1, 0.69-1 and 0.67-0.82 for sheep, cattle and pigs respectively.

NSP tests, in general have high specificity (97-99%) in both vaccinated and non-vaccinated cattle and high sensitivity in unvaccinated cattle. A commercial test (IDEXX ELISA, IDEXX) has been reported to have a Se of 97.14% and a SP >99% in all species (see Table 1). The high specificity of commercial NSP tests in all species has been confirmed in a New Zealand study (Kittelberger et al. 2008. Sensitivity has been found to be lower in infected vaccinated cattle. In their modelling study, Backer et al. (2012) assumed NSP test for non-vaccinated cattle to have Se of 98% and Sp 97%. For vaccinated cattle they assumed Se 70% and Sp 99%.

Table 1 Reported specificity of a commercial NSP ELISA test by species (https://www.idexx.com/pdf/en_us/livestock-poultry/fmd-multispecies-ab-test-sell-sheet.pdf)

Species	**Specificity**
Cattle	99.4
sheep	99.4
Goats	99.1
Pigs	99.7

Although NSP tests can be used to identify vaccinated animals that have been infected, the use is not without problems. Serosurveillance of a large number of animals will give rise to many false positive test reactors, since the tests have imperfect Sp and true positive test results cannot be distinguished readily from false positive ones. In addition, NSP testing cannot differentiate between a recovered and a carrier animal. Due to the major trade implications associated with falsely declaring freedom from infection, all positive results would be followed up with a regime of further testing.

2.5 Evaluating surveillance

A key question is how do we evaluate surveillance approaches? What is our measure of success? For an export-focussed country like Australia failure to find residual infected herds is very serious as it could jeopardise claims regarding our FMD-free status, should seropositive animals subsequently be found. In addition, however, authorities do not want to undertake an unnecessarily detailed and complex surveillance program that may take considerable time and expense to complete and generate large numbers of false positive results that have to be followed up. During a surveillance program it is the number of positive herds (i.e. true positives and false positives) that are found that will generate a workload to clarify their actual status. Under the OIE Code (OIE 2016), finding evidence of infection in the target population automatically invalidates any claim for freedom.

For this project we can compare different approaches to post-outbreak surveillance in terms of:

- Effectiveness in finding residual herds
- Number of false positive reactors generated

- Time taken
- Resources and cost (field teams, laboratory tests, reagents)

3. Methods

3.1 Incorporating post-outbreak surveillance into the AADIS model

A post-outbreak surveillance system needs to consider both a sampling strategy[1] and a testing regime.

1. Sampling strategy:
   - How many herds do we sample?
   - How many samples do we take per herd?
   - What herds do we sample?
   - Where do we sample?

2. Testing regime:
   - What tests or combination of tests do we use?
   - What are the test characteristics that will influence surveillance performance (e.g. Se / Sp)?
   - How do we interpret the results?
   - How do we manage reactors?

In developing a surveillance evaluation module in AADIS, we have adopted the European surveillance model as a starting point (see Appendices 1 and 2). Subsequently we can consider different approaches and compare them to this baseline. In looking at surveillance approaches, there are two situations to be considered:

1. Control program without vaccination
2. Vaccination has been used in the control program and vaccinated animals are not removed from the population (NB If vaccinated animals are removed from the population there is no need to undertake additional surveillance in this group)

Post-outbreak surveillance will be much more difficult when vaccinated populations are involved (Caporale et al, 2012). For vaccinated populations, the EU Directive requires:

a) A survey for detecting FMD virus in the vaccination zone based on clinical, epidemiological and serological investigations (Article 56) which includes:
   - A survey of the non-vaccinated animals
   - Serosurveillance of all vaccinated herds using NSP tests
b) A survey to regain freedom from infection after emergency vaccination (Article 61)

3.1.1 Defining the target populations for surveillance

Based on the EU surveillance model, surveillance needs to be considered at two levels i.e. within the PZ and within the SZ. These zones can be considered equivalent to Australia's Restricted Areas (RAs) and Control Areas (CAs).

1. We can define RAs for the purpose of post-outbreak surveillance at the end of a simulated outbreak using a 3 km buffer around all IPs

1 May use different strategies for different species

2. We can define CAs for the purpose of post-outbreak surveillance at the end of a simulated outbreak using an annulus with inner ring 3km and outer ring 10 km around all IPs
3. Surveillance will be based on 'clusters' where a cluster represents a discrete infected area Anon 2007). For our purposes, a cluster is defined as a group of two or more overlapping/intersecting CAs. Each cluster will be considered a separate entity for sampling purposes and will have its own 3 km and 10 km sampling zones (see Figure 1)

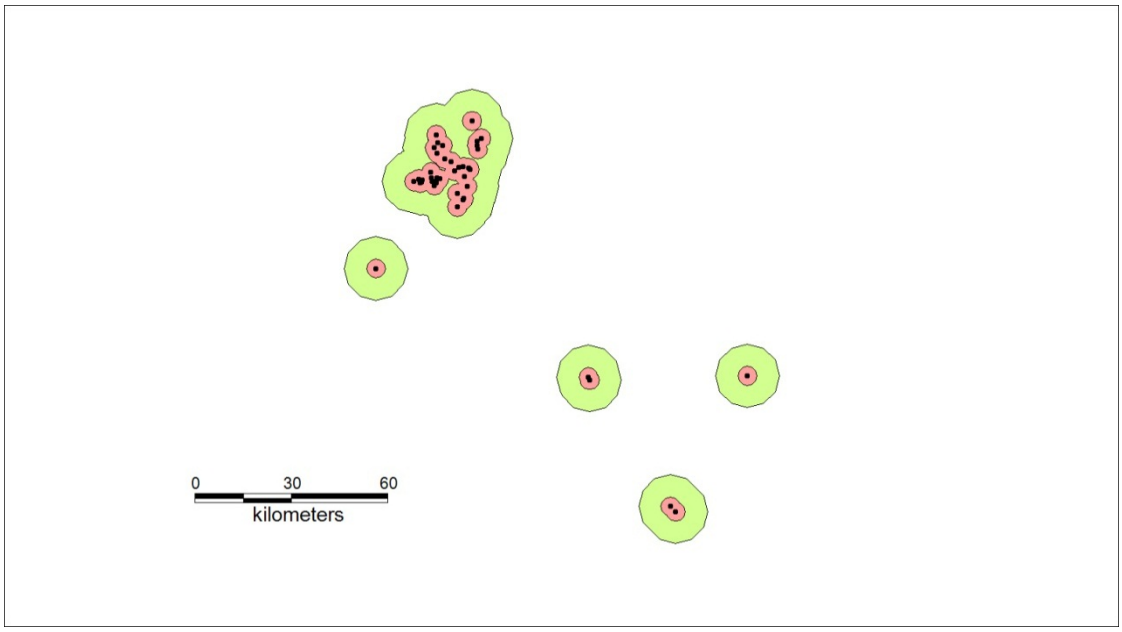


Figure 1: Clusters (n=5) associated with a hypothetical FMD outbreak. CAs shown in green, RAs in Red, IPs as black dots

It is not possible to 'prove' that infection is not present in a population. Rather, freedom from infection is a probabilistic concept that involves a level of confidence that disease is not present at a specified (minimum) level. This minimum level is commonly referred to as the 'design' prevalence.

To determine the minimum sample size necessary to detect the presence of infection, the following information is required (Cannon 2001):

1. Population size
2. Design prevalence
3. Confidence
4. Sensitivity of the test

There are a range of tools available that can be used to calculate sample sizes when testing for disease freedom (e.g. Canon and Roe 1982, Cameron 1999, Sergeant 2017). For simplicity, in this study we will use the following approximation from Cannon and Roe (1982) to estimate sample size for different herd sizes:

$$n = (1-(1-\alpha)^{1/d})(N-d/2)+1 \quad (1)$$

where:

n=sample size
d=no. positives in the population

N=herd size
α= desired confidence level

NB if n>N then n=N

3.1.2 Post-outbreak surveillance in RAs

Based on the EU approach, for cattle and pigs, surveillance will be based on clinical inspection of animals in all holdings (herds). No specific sample collection and testing is required. However, while this may be adequate for detecting evidence of active infection, it will provide little assurance that recovered cattle herds, potentially containing carrier animals, have not been missed during the control program. Accordingly we will include the option of sampling cattle according to a user specified sampling regime (default: as for sheep i.e. all holdings, 95:5 sampling regime).
All sheep holdings to be sampled consistent with a 95:5 sampling regime i.e. to be 95% confident that a within-herd or flock prevalence of at least 5% would be detected. This would require up to 59 animals to be sampled per flock[2].

3.1.3 Post-outbreak surveillance in CAs

The EU approach considers clinical surveillance only of cattle and pig herds (all animals) to be adequate. However, for the reasons specified above, we will include the option of sampling cattle according to a user specified sampling regime (default: as for sheep i.e. multistage sampling – 95:2 herd prevalence and 95:5 within herd prevalence).
For sheep, multistage sampling can be used.

a) Randomly select sufficient holdings to be 95% confident of detecting infection assuming a 2% flock prevalence. This would involve sampling a maximum 149 holdings in the CA. Equation (1) can be used to determine the exact number of the holdings that need to be sampled depending on the total number of eligible holdings in the CA.
b) Holdings to be sampled consistent with a 95:5 sampling regime. Maximum number of samples required per holding is 59[2]**.**

3.1.4 Post-outbreak surveillance in Vaccination Zone (VZ)

Additional surveillance will be required when vaccination is used. If a suppressive ring vaccination strategy is used, then the VZ could be the same as the RA, although this may vary depending on the sizes of the RA and VZ respectively. Under the EU model, the population to be sampled will consist of all vaccinated premises, excluding those that became IPs. Surveillance in the VZ will include:

1. Clinical inspection of all susceptible animals in all herds
2. Testing for infection with FMDV using NSP antibody test or by another approved method. This will involve sampling all vaccinated animals of susceptible species and their non-vaccinated offspring in all herds in the vaccination zone – i.e. census sampling (European Union 2003). However, the EUFMD workshop (Anon 2007) recommended alternative sampling regimes for cattle and pigs (sampling all pigs in large pig enterprises is considered impractical and unnecessary). Two approaches could be considered, depending on what species are vaccinated.

2 Equation (1) can be used to determine exact number of animals to be sampled per holding

a) <u>All animals vaccinated</u>
   - Cattle: sample all herds, all animals. <u>Alternative:</u> all herds/(95:5 animals) – max. of 59 animals per holding[2]
   - Sheep/goats: sample all herds/all animals
   - Pigs: sample all herds/95:5 animals (sampling all pigs considered impractical) – max. of 59 animals per holding[2]

b) <u>Cattle only vaccinated</u>
   - Cattle: sample all herds/ (95:5 animals) – max. of 59 animals per holding[2]
   - Sheep/goats: clinical surveillance all herds plus sample all herds/(95:5 animals) – max. of 59 animals per holding[2]
   - Pigs: clinical surveillance all herds/all animals

3.1.5 Undertaking the sampling

Once the sampling regime has been specified, herds are selected randomly from the population(s) at risk. As with other disease control processes in AADIS, post-outbreak surveillance is subject to resource constraints. Potential limitations are:

a) How fast samples can be collected in the field – function of number of sampling teams and how long it takes to sample each herd
b) How quickly the samples can be tested – function of laboratory throughput and time to do a run of samples

Parameter settings used for this project are shown in Table 2

Table 2: Diagnostic test parameter settings

Test	Species	Sensitivity	Specificity	Sensitivity	Specificity	cost ($)	Throughput
		vacc	vacc	Non_vacc	Non_vacc		(tests/day)
qPCR	bov	0.95	0.99	0.95	0.99	47	1000
qPCR	ovi	0.95	0.99	0.95	0.99	47	1000
qPCR	sui	0.95	0.99	0.95	0.99	47	1000
C-ELISA	bov	0.99	0.99	0.99	0.99	35	10000
C-ELISA	ovi	0.99	0.99	0.99	0.99	35	10000
C-ELISA	sui	0.99	0.82	0.99	0.82	35	10000
3ABC-LISA	bov	0.8	0.99	0.93	0.99	35	10000
3ABC-ELISA	ovi	0.8	0.99	0.9	0.99	35	10000
3ABC-ELISA	sui	0.7	0.99	0.73	0.99	35	10000

3.1.6 Follow-up testing to confirm status of reactors

When testing large numbers of samples, even using a test with relatively high specificity, it is inevitable that false positive reactors can be expected. All positive results must be followed up since

there can be no uncertainty about the presence of infection. When herds with reactors are found, approaches include:

a) assess whether the number of observed positive results is statistically more consistent with false positive than a true positive herd
b) detailed follow-up involving laboratory and/or field investigation in every herd where positive results are seen to determine whether virus circulation is occurring.

If specificity of the serological test system were reliably known then (a) would be adequate to assign a herd status. However, currently this approach is not considered compatible with EU directive 2003/85/EC (Anon. 2007). In the first round of model development we will not consider (a).

It is unusual to base surveillance on a single test result. In practice, it can be assumed that any sample that tests positive in an initial (screening) test would be subject to a second confirmatory test (OIE 2016, Brocchi et al. 2006, Paton et al. 2006). So we need to factor in a 'testing process' rather than a single test result. The user has the option of specifying the combination of tests to be used. For unvaccinated populations this could involve two different SP tests or an SP and a NSP test. For vaccinated populations a combination of NSP tests may be used. However, testing in series using a screening and confirmatory test, while increasing specificity will reduce overall sensitivity of the testing procedure which has to be taken into account.

The details of how the numbers of positive and negative herds found during post-outbreak surveillance are estimated in a simulated FMD post-outbreak surveillance program in AADIS are given in appendix 4.

AADIS reports the number of herds with one or more positive animals following a two test regime (screening test with any positives subject to a confirmatory test) and we can assume that all herds positive using this approach will require follow-up. This would be consistent with Australia's conservative approach to managing FMD risk.

3.1.7 Costs of surveillance

Costs will be incurred through:

- Coordination
- Collection of samples
- Laboratory tests
- Following-up positive results [NB currently not included in AADIS cost reporting]

Coordination of surveillance activities is achieved through the continued operation of Local and State Disease Control Centres (LDCC and SDCHQ) beyond the control phase. The cost of operating a disease control centre was estimated at $120,000 per centre per day. This cost is broken down as follows: $88,000/day salaries, $22,000/day fixed overhead (rent etc.), $6,000/day operating expenses (meals etc.) and $4,500/day accommodation. Staffing levels were 100 people, per centre, for 14hrs/day at Victorian public service pay rates including penalties (which translates to $600-1200 per person per day). These figures are derived from actual costs and staffing levels during [non-biosecurity] emergencies in Victoria (Steven Riley, pers. comm., 2017), and are concordant with the costs incurred in NSW during the 2007-8 Equine Influenza outbreak (Kevin Cooper, pers. comm., 2012).

Clinical inspection and sample collection was costed based on the estimated time taken to muster and inspect an 'average' herd of each type. We assumed that a surveillance team of two people (one professional, plus one assistant) would inspect on average 500 head per day at a daily salary cost of $1500. In addition, a fixed cost of $100 for travel and $150 for disposables (per herd) was incurred. The cost of a surveillance visit (excluding laboratory tests) for each herd type is shown in Table 3. Finally, the cost of laboratory testing was calculated by multiplying the number of samples collected from each herd (dependent on the sampling strategy) by the cost of the test used ($35x2; Table 2).

Table 3: Cost of a surveillance visit (excluding laboratory costs) for each herd type.

Herd type	**Surveillance visit cost ($)**
beef extensive	1750
beef intensive	1300
feedlot	1750
mixed beef	1300
mixed sheep	1750
dairy	1000
pigs small	850
pigs large	1150
sheep	1750
smallholders	625

3.1.8 Reporting of results

AADIS reports the following results in relation to post-outbreak surveillance:

- Number of herds clinically examined
- Total herds tested
- Total samples collected
- Time taken to complete testing
- Number of residual herds detected (true positives)
- Number of false positive herds
- Number of true negative herds
- Number of residual herds not detected (false negatives)
- Costs of surveillance

3.2 Incorporating post-outbreak management of vaccinated animals into AADIS

3.2.1 Role of vaccination

Modelling studies in Australia (Garner et al., 2014; Roche et al., 2013; Abdalla et al., 2005) and overseas (Roche et al., 2014; Keeling et al., 2003; Tomassen et al., 2002; Backer et al. 2012; Sanson et al 2017) have shown that vaccination can be effective in reducing the duration and/or size of

outbreaks particularly in 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 been beneficial in eradicating the disease earlier than was the case with recent FMD outbreaks in Korea (Sakamoto, 2012) and Japan (Akashi, 2012). However, while vaccination can positively 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 FMD-free status is regained under OIE guidelines (Geale et al. 2013; OIE 2016) add additional complexity to the post-outbreak surveillance programs as discussed in Section 3.1.

If vaccination is used during a control program then the period before FMD-free status can be regained varies depending on how the vaccinated animals are managed. A country can regain its FMD-free status three months after the disposal of the last animal killed or the slaughter of all vaccinated animals, whichever occurred last, where a stamping out policy, emergency vaccination and surveillance according to articles in the OIE Code (OIE 2016). However, if vaccinated animals were to be retained in the population, the OIE Code specifies that countries must wait at least six months after the detection of the last case or the last vaccination (whichever is latest) before obtaining official freedom from FMD. This is conditional on undertaking surveillance including a serological survey based on the detection of antibodies to non-structural proteins of FMDV to demonstrate no evidence of infection in the remaining vaccinated population (OIE 2016).

3.2.2 Managing vaccinated animals

Because the requirements for recovery of FMD free status following different control strategies with and without vaccination are clearly described in the OIE International Animal Health Code, the preferred approach to managing vaccinated animals after an outbreak can be evaluated in economic terms. That is, do the costs and benefits associated with a vaccinate-and-live strategy outweigh the costs and benefits incurred through a vaccinate-and-remove strategy. Table 4 summarises the major costs associated with the respective management approaches. For this exercise we focussed on the measurable costs and while we recognise the importance of intangibles (such as welfare benefits, social acceptability etc.), they are not captured in this analysis.

Table 4: Summary of potential costs and benefits for different approaches to managing vaccinated animals

Approach	Benefits	Costs
Vaccinate-to-retain	• No costs of removing animals: (slaughter, disposal, compensation) • No loss of genetics • Continuity of production • Producer goodwill • Vaccinated animals have a value	• Longer time to achieve FMD-free status • Delayed return to markets • Additional surveillance costs • Separate slaughter and product processing chains to safeguard exports to FMD-free markets • Additional product processing costs • Record keeping and information management • Finding new markets

Vaccinate-to-remove (waste)	• Shorter time to achieve FMD-free status • Earlier return to markets	• Compensation for mandatory acquisition and slaughter of stock • Vaccinated animals have no value • Animal processing and disposal costs • Production loss • Loss of genetics • Producer resentment
Vaccinate-to-remove (salvage)	• Shorter time to achieve FMD-free status • Earlier return to markets • Vaccinated animals have some value (less than non-vaccinated animals; NB some classes of slaughtered animals will have negligible value)	• Compensation for mandatory acquisition and slaughter of stock • Production loss • Loss of genetics • Producer resentment • Animal processing costs • Additional product processing costs • Finding new markets

AADIS has been modified to enable a user to select from three vaccination options:

- Vaccination disabled (no vaccination)
- Vaccinate-and-remove (to waste)
- Vaccinate-and-remove (with salvage)
- Vaccinate and retain

The option chosen by the user influences the combination of management actions applied within AADIS to manage vaccinated animals after an outbreak. Table 5 summarises these actions. *Vaccination disabled (no vaccination)* is the default option, and is included here for comparison.

The *vaccinate-and-retain* strategy assumes that vaccinated animals will be allowed to live out their normal commercial lives. As such, the destruction, disposal and decontamination of vaccinated animals is not undertaken and, consequently, compensation is not required. However, as discussed above, the OIE code requires a six month waiting period (OIE 2016) in this situation. In addition, comprehensive surveillance of the vaccinated population will be required (see Section 3.1.4).

Under a *vaccinate-and-remove (to waste)* strategy we assume that all vaccinated animals will be destroyed and disposed to waste as part of the post-outbreak management program. Because these herds were not infected, decontamination is not required. However, as the animals will have been compulsorily destroyed, full compensation is assumed to be payable (though, this is not currently covered by Australia's Emergency Animal Disease Response Agreement - EADRA). Following the OIE code (OIE 2016), a waiting period of three months applies.

In contrast, the *vaccinate-and-remove (with salvage)* strategy requires only the destruction of vaccinated animals, with any disposal costs being met by the processor undertaking the salvage. Because we implicitly assume that the vaccinated animals will have a value arising from the sale of their salvageable products, compensation would only be payable for the difference between the market prices of vaccinated and unvaccinated animals (again, this is not currently allowed for in EADRA). The costs and benefits of the various salvage options are outlined in next section.

Table 5: Summary of the management actions applied under the different vaccination strategies.

Strategy	Vaccination	Destruction	Disposal	Decontamination	Compensation	Trade
Vaccination disabled	No	Yes	Yes	Yes	Full	Three months
Vaccinate-and-retain	Yes	-	-	-	None	Six months
Vaccinate-and-remove (waste)	Yes	Yes	Yes	-	Full	Three months
Vaccinate-and-remove (salvage)	Yes	Yes	-	-	Partial	Three months

Appendix 6 details the software changes made to the AADIS model to support post-outbreak management.

3.2.3 Costs associated with vaccination

As indicated above, the selection of a preferred approach to managing vaccinated animals after an outbreak can be considered in economic terms. Given the aim of our analysis was to evaluate the relative (rather than absolute) difference in performance of the alternative strategies; we have focussed on direct costs and benefits in the first instance.

The direct costs incorporated into AADIS were those incurred through:
- Vaccination
- Destruction
- Disposal
- Compensation
- Trade losses

Costs associated with production losses, loss of genetics and losses associated with a delayed return to full market share (see Table 4) were ultimately not included in our analysis. This was due to the lack of consensus about how these losses would accrue; in particular, how long it would take to return to full market share (Matthews 2011, Buetre et al. 2013). Consequently, our results should be viewed as conservative estimates of the true costs of an FMD outbreak.

Vaccination costs were estimated to be $5/head of cattle/pigs and $4.40/head of sheep. This cost is broken down as follows: $3/head in labour costs (team of two; above), $1.20/head of cattle/pigs and $0.60/head of sheep for the vaccine dose and $0.80 for cold storage and handling (Kevin de Witte, pers. comm., 2011; Abdalla et al., 2005). The cost of vaccination did not vary between strategies.

The cost of destruction was estimated to be $6/head of cattle and $4/head of sheep/pigs. This was estimated by disaggregating the cost of slaughter and disposal reported in Abdalla et al. (2005). To do this we first estimated the cost of disposal (below) and then subtracted that from the herd level estimates (accounting for inflation). The remaining amount represented the cost of slaughter, which we divided by the number of head to get a per head estimate. These amounts are roughly equal to the cost of inspection/vaccination once consumables are taken into account, so are likely to be

reasonable estimates. Whilst the cost of destruction will, in practice, vary slightly between the different strategies, for simplicity we have assumed that they are the same (Table 6).
Table 6: Cost estimates by species for each of the major management actions.

Species	**Vaccination ($)**	**Destruction ($)**	**Disposal ($)**	**Compensation ($)**
Cattle	5	6	67.50	742.5
- *Feedlot*	5	6	67.50	872
- *Dairy*	5	6	67.50	895
Sheep	4.40	4	2.25	69
Pigs	5	4	9	222.5
Smallholders	5	4	2.25	150

Disposal costs were estimated to be $67.50/head of cattle, $9/head of pigs and $2.25/head of sheep. This cost was determined based on an average disposal cost of $90/tonne and average live weights (adults and juveniles) of 750, 100 and 25 kg respectively. Per tonne costs for rendering, deep burial and incineration were drawn from McClaskey et al. (2004) and were inflated and exchanged into 2017 Australian dollars. This estimate is within the range of reported costs of deep burial in Australia (BDA Group, 2009), although, it is likely that in some locations prices may be much higher.

Following the intent of the Emergency Animal Disease Response Agreement (EADRA), compensation payable to owners of vaccinated animals destroyed during the post-outbreak management phase was assumed to be the average market value of those animals (adults and juveniles). Estimates of the amount payable for each of the species (Table 6) remained un-changed in AADIS from the estimates used in previous stages of development (e.g. Bradhurst et al. 2015, Bradhurst et al., 2016).

Under a vaccinate-and-remove (with salvage) strategy only partial compensation will be required because the strategy is dependent on the animal having a value greater than zero. In this case, the compensation will be the difference between the market value of vaccinated and unvaccinated animals. However, the value of a vaccinated animal depends on the processing method(s) used to salvage animal products. Possible options include:
- Slaughter for export to non-sensitive markets;
- Slaughter for domestic consumption;
- Slaughter and process (can, salt or cook) for export or domestic consumption; and
- Slaughter via a knackery for pet food.

Of these options, slaughter for domestic consumption was considered to be the most feasible (hence, likely) option for processing the anticipated volume of animals requiring salvage under this scenario. Primarily, this is due to the relatively limited capacity of both the knackery and canning processors, and the difficult technical barriers to trade (such as volume caps and shelf-life limits) in the FMD-endemic meat market (MLA, 2016), limiting the rate at which animals could be slaughtered and salvaged (see trade losses, below). Consequently, we assumed that vaccinated animals would be salvaged on to the domestic consumption and pet food market, at a discount of 50% (Garner et al., 1997; Abdalla et al., 2005). Compensation was, therefore, half the market value of an unvaccinated animal in the vaccinate-and-remove (with salvage) strategy.

Trade losses during the post-outbreak management period were estimated to be $32.5M/day. During an outbreak, Butere et al. (2013) estimated that the oversupply of animal products on the domestic market due to the loss of export markets would result in a decline in the gross value of production of approximately $32.5M per day. Because the waiting period in the OIE code does not

start until the last vaccinated animal is destroyed (under the vaccinate-and-remove strategies; OIE, 2016), for each additional day that the commencement of that waiting period is delayed, a loss of $32.5 M is assumed to be incurred.

Table 7: Estimated removal rate of vaccinated animals (animals per day)

Species	**To waste**	**With salvage***
Cattle	1000	800
Sheep	5000	4000
Pigs	2000	1600

The trade losses arising from an outbreak are, therefore, dependent on the time taken to remove vaccinates from the population. Based on our understanding of the industry, and figures published by individual processors (e.g. JBS Australia Pty Ltd http://www.jbssa.com.au/ourfacilities/ProcessingFacilities/default.aspx), we assume here that a large abattoir could be contracted to remove 1000 head of cattle or 5000 head of sheep per day (Table 7). Similarly, based
on the monthly kill statistics, provided by Australian Pork Limited, we assume that 2000 head of pigs could be slaughtered per day. For the vaccinate-to-remove (salvage) scenario we assume that the rate of removal is 20% lower to account for increased processing, possible delays in the sale of vaccinated animals and/or the use of smaller scale processors such as knackeries or canneries (Table 7).

4. CASE STUDIES

Three outbreak scenarios were identified with the assistance of workshop participants (see workshop report – Appendix 1). Workshop participants were divided into three groups to discuss a potential case study, which could be used to test the modifications to the AADIS model. These case study scenarios were used in studies to test the new functionality added to the AADIS model.

We assume that all outbreaks are associated with FMD virus type O. Control programs with and without vaccination were simulated. Two post-outbreak surveillance strategies were tested in situations where vaccination had or had not been used in the control program. For the vaccination scenarios, each of the three post-outbreak management outbreak options (i.e. vaccinate-and-retain, vaccinate-and-remove to waste or salvage) were modelled to enable costs to be compared.

The purpose of these case studies was to demonstrate how the modified AADIS model can be used to evaluate different approaches to disease control including different post-outbreak management options. These case studies are for demonstration purposes only. The restricted nature of these demonstration scenarios means that only limited inferences can be made from these results as to the relative performance of the different strategies and approaches.

4.1 Scenario descriptions

4.1.1 Darling Downs, Queensland

The outbreak begins on large piggery in the Lockyer Valley region of southern Queensland in February [seed herd #108909, containing 1378 pigs]. The source of the outbreak is backpackers

carrying contaminated fomites arriving on a piggery near Toowoomba in Queensland for temporary employment. FMD is confirmed three weeks after introduction. During this period infected animals are sent to the nearby saleyard in Toowoomba.

Control is based on:

- stamping out of IPs only
- movement restrictions (3 day national livestock standstill, initial CA would be whole state reducing to 20 km radius around IPs after 14 days, initial RA would be whole of local government areas containing IPs, reducing to 5 km radius around IPs after 14 days
- surveillance and tracing
- vaccination: 3km suppressive ring vaccination of cattle only (excluding feedlots) assuming national sharing of vaccine stocks. Feedlots were excluded from vaccination based on the studies and subsequent policies developed by the Queensland Department of Agriculture and Fisheries (FMD Vaccination Strategy for Queensland Version 0.6, 28 September 2015. A report submitted to Animal Health Committee 2015)

4.1.2 Gippsland, Victoria

FMD is introduced through illegal feeding of swill containing infectious material sourced from overseas, in a small Gippsland piggery, in September. The outbreak begins on a small pig farm just west of Leongatha in Victoria [seed herd #108386, 25-sow piggery containing 247 pigs]. FMD is not recognised and reported to the authorities until 14 days after introduction.

Control is based on:

- stamping out of IPs only
- movement restrictions
    - 3 day national livestock standstill,
    - initial CA would be whole state reducing to 10 km radius around IPs after 14 days,
    - initial RA would be 10 km radius around IPs, reducing to 3 km radius around IPs after 14 days
- surveillance and tracing
- vaccination:
    - 3km suppressive ring vaccination of cattle plus sheep (on mixed cattle-sheep properties only)
    - vaccination limited to identified high risk regions
    - assume national sharing of vaccine stocks.

4.1.3 Bunbury, WA

FMD is introduced via the port of Fremantle. Contaminated imported stockfeed is sent to, and infects, sheep on a mixed sheep farm in south west Western Australia. The outbreak begins on a sheep farm near the town of Harvey [seed herd #93268 (sheep flock, n=288, of mixed sheep-beef property)]. The outbreak starts in May and is not detected for 30 days.

Control is based on:

- stamping out of IPs only
- movement restrictions
    - 3 day national livestock standstill,
    - initial CA would be whole state reducing to 25km radius around IPs after 14 days, reducing to 10 km after 28 days

    - initial RA would be the whole of local government areas containing IPs, reducing to 10 km radius around IPs after 14 days and reducing to 3 km radius around IPs after 28 days
- surveillance and tracing
- vaccination:
    - 3km suppressive ring vaccination of cattle plus sheep (on mixed cattle-sheep properties only)
    - assuming national sharing of vaccine stocks

Figure 2 shows the location of the initial incursion for each scenario. Further details including key parameter settings and resources for each case study are given in Appendix 5. Unless otherwise specified the simulations used AADIS baseline parameter settings.

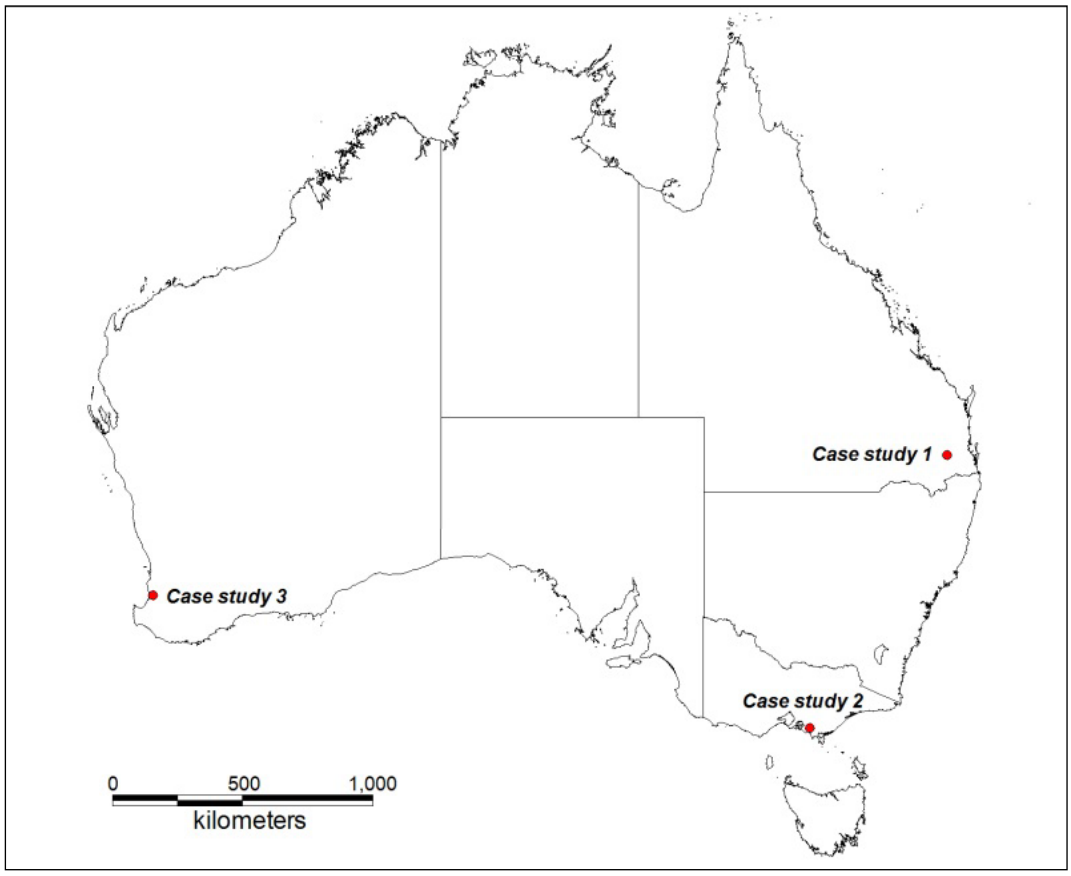


Figure 2: Seed herd locations for the three case study scenarios.

4.2 Modelling approach

For each outbreak scenario, the model was initially run without any control measures to the end of the 'silent spread' phase i.e. the period up until first detection (n=1000 iterations) and an iteration consistent with the median number of infections at this point in time selected This run served as the basis (i.e. the starting situation) for subsequently comparing control strategies. The advantage of this

approach is that control programs all start from the same infection situation. Figures 3-5 show the location of infected herds at the end of the silent spread phase for each case study scenario

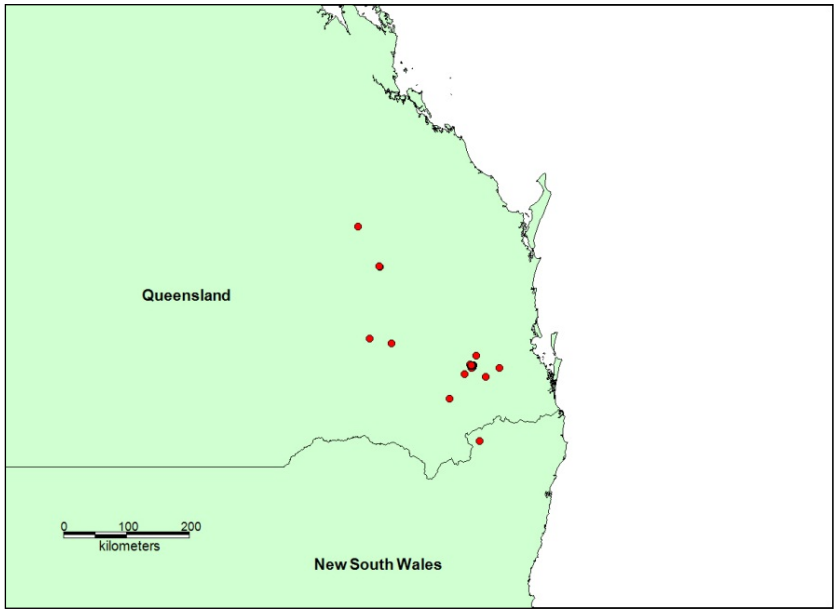


Figure 3: Case study 1. Infected herds (n=28) at end of silent spread phase

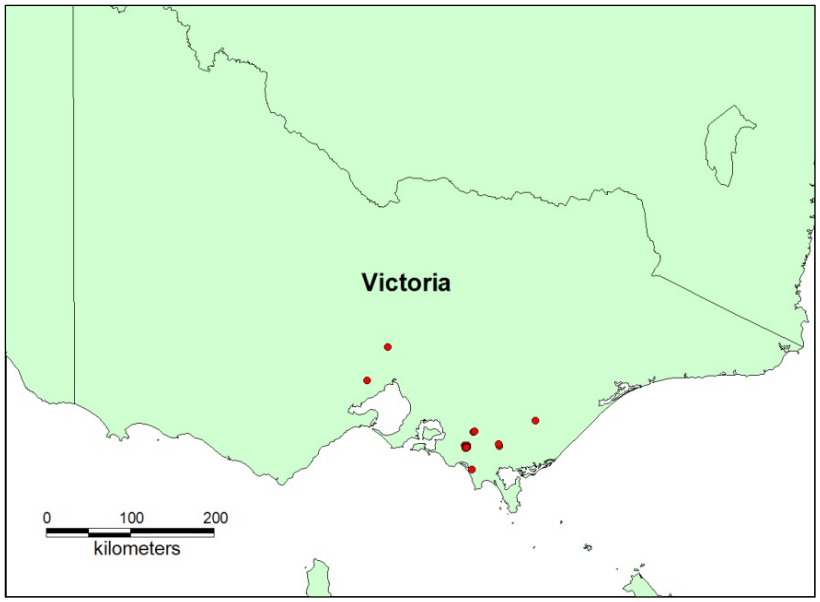


Figure 4: Case study 2. Infected herds (n=18) at end of silent spread phase

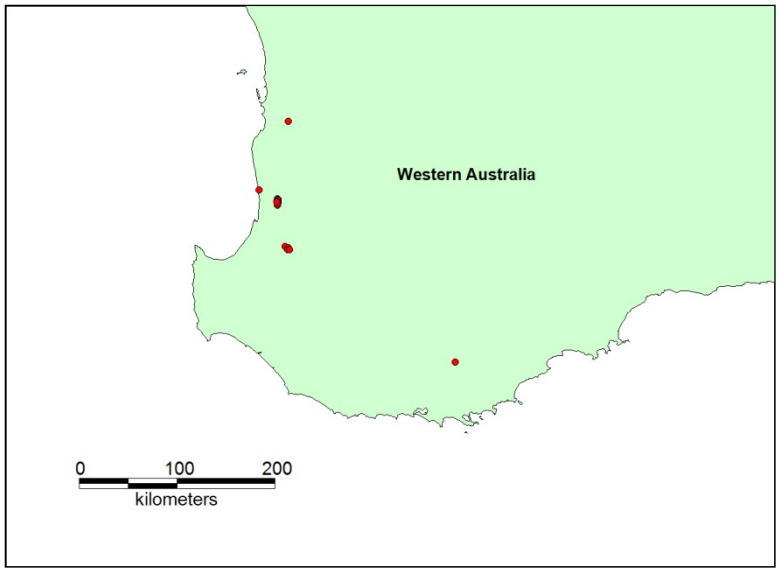


Figure 5: Case study 3. Infected herds (n=20) at end of silent spread phase

Subsequent sets of model simulations were then run starting from the day of first detection, using the pre-agreed control settings described above. Control programs with and without vaccination were simulated. Depending on the nature of the study, the model was run until the end of outbreak or until the end of the post-outbreak surveillance program. The demonstration studies are described in Section 4.3.

With AADIS, a comprehensive range of outbreak metrics are available for analysis including:

a) Outbreak characteristics

- Total IPs
- Total VPs
- Number of jurisdictions infected
- Control program duration (days from first detection until lifting of last CA/RA i.e. no more control actions pending
- Post-outbreak surveillance duration (days from commencing post-outbreak surveillance i.e. 30 days after last case; until all laboratory test results are know
- Post-outbreak vaccination management duration (when vaccinate-to-remove approach is used: the number of days to remove all vaccinated animals)
- Days out of market

b) Post-outbreak surveillance statistics

- Number herds clinically inspected
- Number of non-vaccinated herds tested
- Number of vaccinated herds tested
- Number of non-vaccinated samples collected
- Number of vaccinated samples tested
- Number of positive herds found (both true positive and false positive)
- Number of negative herds found (both true negative and false negative)

c) Cost statistics

- Control centre costs
- Surveillance costs
- Cull costs
- Disposal costs
- Disinfection costs
- Compensation payments
- Vaccination costs
- Total control costs
- Post-outbreak surveillance costs
- Post-outbreak laboratory testing costs
- Post-outbreak cull costs (for vaccinate-to-remove)
- Post-outbreak disposal costs (for vaccinate-to-remove)
- Total post-outbreak management costs
- Trade losses
- Total outbreak costs

4.3 Demonstration studies

The following set of simulation studies was run. Their purpose was to demonstrate how AASIS can be used to address questions around use of vaccination, particularly to assess approaches to managing vaccinated animals, and to test post-outbreak surveillance strategies to support proof of freedom. For each study the model was run under the control program was complete or for 365 days, whichever came first. One thousand iterations were run for each simulation.

4.3.1 Evaluating control programs

For each outbreak scenario we compared control programs with and without vaccination. The performance of disease control was assessed in terms of:

- Total IPs
- Total animals culled
- Size of the infected area
- Number of jurisdictions infected
- Number of herds (and animals vaccinated)
- Duration of the control program
- Control costs

4.3.2 Evaluating post-outbreak surveillance

In this set of simulations we show how AADIS can be used to assess the performance of the post-outbreak surveillance system. Using the Victorian outbreak scenario, we compare two hypothetical post-outbreak surveillance approaches, after control programs without and with vaccination.

a) Baseline: uses default settings (adapted from EU Directive).
b) Reduced: assumes a reduced sampling intensity compared with the baseline.

The sampling regimes for the baseline and reduced surveillance approaches are shown in Table 8.

Table 8:Post-outbreak sampling regimes under baseline and reduced sampling intensity approaches

	Baseline	**Reduced sampling intensity**
RA		
cattle	All herds, clinical + 95:5 sampling	All herds, clinical + 95:10 sampling
sheep	All flocks, clinical + 95:5 sampling	All flocks, clinical + 95:10 sampling
pigs	clinical inspection only	clinical inspection only
CA		
cattle	95:2 herds, clinical + 95:5 sampling	95:5 herds, clinical + 95:10 sampling
sheep	95:2 flocks, clinical + 95:5 sampling	95:5 flocks, clinical + 95:10 sampling
pigs	clinical inspection only	clinical inspection only

As discussed in Section 3.1.6, we assume that the testing process to identify positive herds will involve an initial (screening) test followed by a second (confirmatory) test. The characteristics and performance of diagnostic tests used for this study are listed in Table 9.

Table 9: Diagnostic test performance settings

Test	**species**	**Vaccinated**		**Non vaccinated**		**Cost ($)**	**Throughput (tests per day)**
		Se	**Sp**	**Se**	**Sp**		
SP ELISA	cattle	-	-	0.99	0.99	35	10000
	sheep	-	-	0.99	0.99	35	10000
	pigs	-	-	0.99	0.82	35	10000
NSP ELISA	cattle	0.8	0.99	0.93	0.99	35	10000
	sheep	0.8	0.99	0.9	0.99	35	10000
	pigs	0.7	0.99	0.73	0.99	35	10000

The two approaches will be compared in terms of:

- Workload (herds tested and total samples collected)
- Time taken to complete the surveillance
- Effectiveness (proportion of residual herds missed i.e. number of false negative herds)
- Positives results requiring follow-up (includes false and true positives)
- Cost of the surveillance

4.3.3 Evaluating management of vaccinated animals

For each outbreak scenario, we used a control program involving emergency ring vaccination and compared the three strategies for managing the vaccinated population:

a) Vaccinate-and-retain
b) Vaccinate-and-remove (waste)
c) Vaccinate-and-remove (salvage)

The performance of post-outbreak management was assessed in terms of The time and costs associated with managing vaccinated animals, time out of markets and overall cost of an outbreak

- Control costs
- Post-outbreak management costs (including surveillance and where appropriate removal of vaccinated animals)
- Days out of market
- Trade losses
- Total outbreak costs

4.4 Statistical methods

Descriptive statics are provided. Datasets were transferred into Excel (Microsoft Corp. USA) and graphs were drawn using the DPlot add-in package (Hydesoft Computing, Vicksburg, MS, USA). Results are presented as standard box and whisker plots. The box represents the 25 – 75 percentiles range. The horizontal band within the box represents the median. The whiskers represent the 0 – 25 percentile (lower) and the 75 – 100 percentile (upper).

Where comparisons between different approaches were made, data were analysed analysed using STATA version 14 (StataCorp, College Station, TX, USA).

Initially all data was examined for normality using: (i) visual appraisal of histograms of the data, (ii) determination of the skew and kurtosis of each data set and its deviation from the values expected in a normal distribution and (iii) an automated search of a subset of the ladder of powers for a transform that converted the data to normality. All of the data sets were non-normal. No standard transformations transformed the data into a normal distribution. All data sets were log transformed to minimise the over-distribution (left skew) observed.

Data sets for different approaches were compared using both the one-way ANOVA and the Kruskal-Wallis tests. The one-way ANOVA has been reported as robust to deviations from normality when the data sets are large and was used because it is a more rigorous test (Feir-Walsh & Toothaker, 1974; Schmider et al., 2010). In addition, pairwise comparisons of datasets could be done automatically when more than two groups were being compared. To examine the impact of the data being non-normal, all results were checked using the Kruskal-Wallis test. The one-way ANOVA and the Kruskal-Wallis test produced comparable results for each comparison examined.

5. Results

5.1 Evaluating control programs

Control programs with and without vaccination were compared.

5.1.1 Case study 1 (Qld)

Descriptive statistics for the no vaccination and vaccination strategies are summarised in Figure 6 and Table 10.

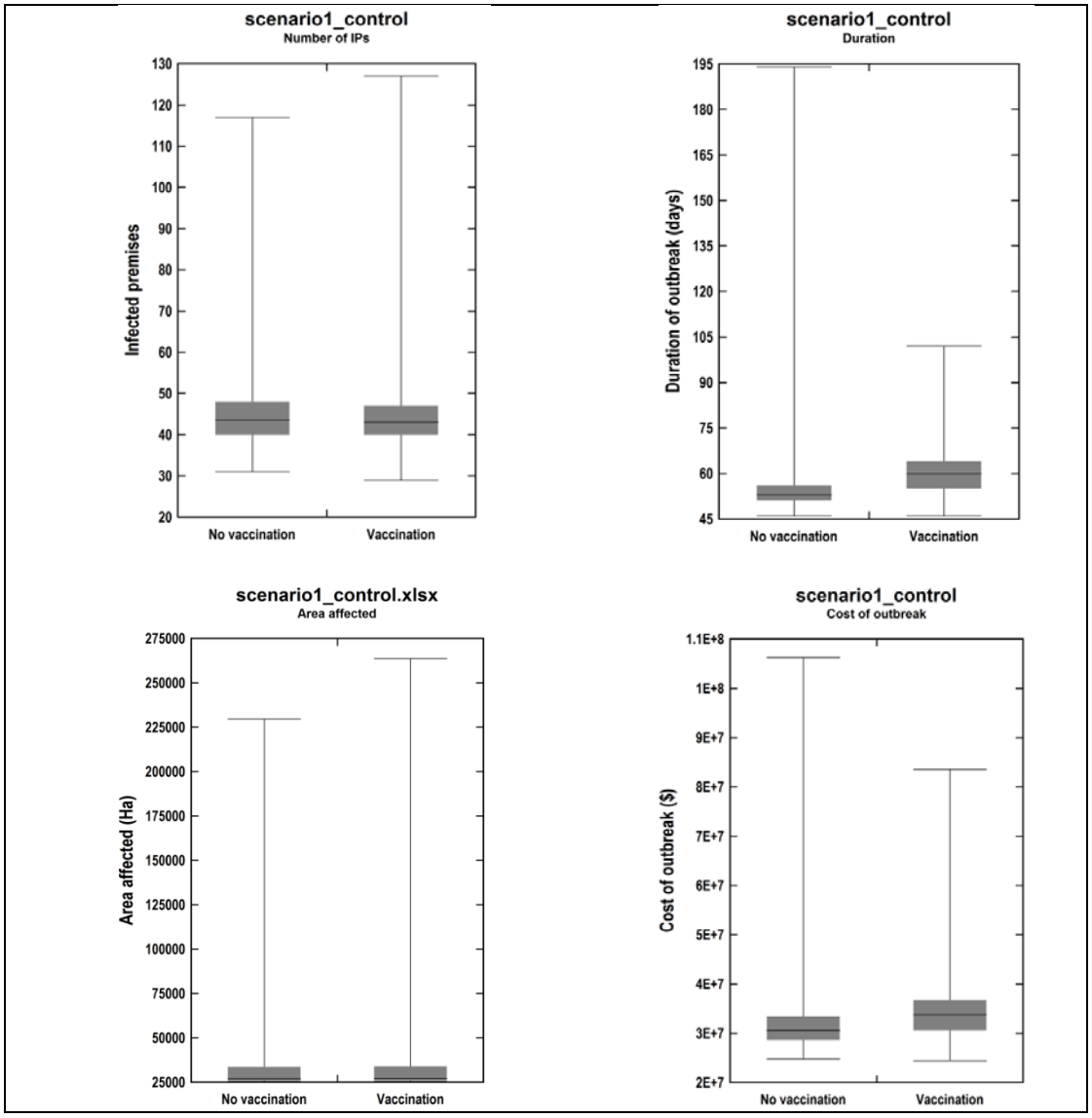


Figure 6: Case study 1 results. Comparison of control strategies

In comparing the two strategies in this case study, there was no significant difference in the number of IPs or the total numbers of animals culled. There were small but significant differences in duration and control costs with the no vaccination strategy performing better in this case study. The vaccination strategy would also result in a small population of vaccinated animals (on average around 5000) that would have to be managed at the end of the outbreak. Under the assumptions of this case study, vaccination does not appear to offer any benefits in terms of disease control.

Table 10: Descriptive statistics for case study 1

Variable	No vacc			Vacc		
	Mean (SD)	Median (Q1, Q3)	Range (min-max)	Mean (SD)	Median (Q1, Q3)	Range (min-max)
IPs (n)	45.08 (8.66)	43.5 (40, 48)	31-117	44.68 (8.26)	43 (40-47)	29-127

Total animals culled (n)	11266 (5975)	9511(8594-11348)	6852-77942	11095 (6608)	9437 (8571, 11103)	6817-134163
VPs (n)	0	0	0	33.33 (14.96)	31 (25-38)	5-140
Total animals vaccinated (n)	0	0	0	4645 (4745)	3922 (3084, 5003)	427-118147
Duration of control program (days)	54.23 (6.96)	53 (51, 56)	46-194	59.89 (7.80)	60 (55-64)	46-102
Size of the infected area (sq km)	31698 (13527)	26883 (25860, 33542)	25452-229360	33006 (20271)	27031 (25886, 33823)	25452-263674
Total cost of control ($'000)	32318 (6853)	30590 (28603, 33429)	24782-106234	34774 (7135(	33800 (30624, 36804)	24440-83548

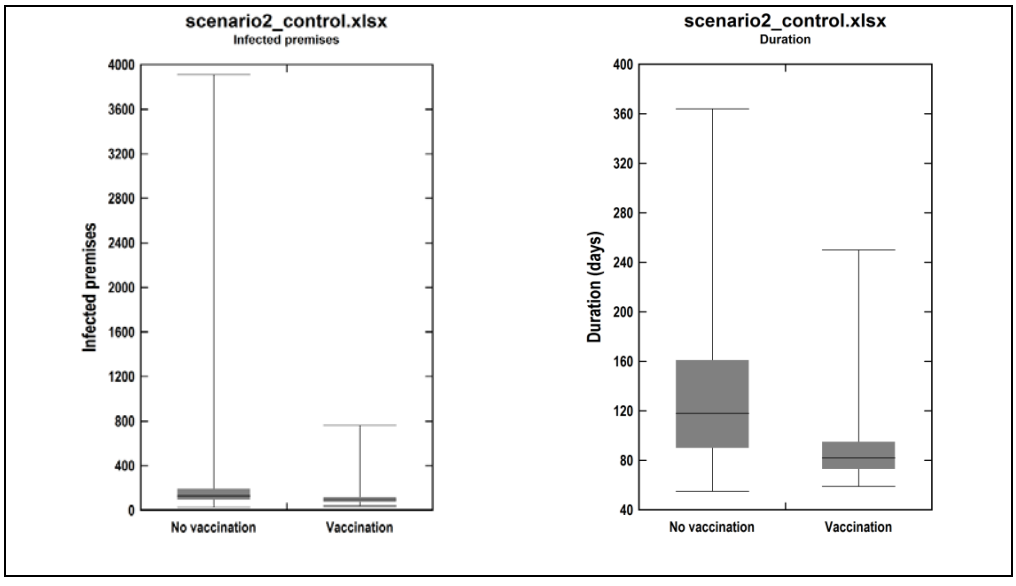
Table 11 Statistical analysis – Case study 1

	No vaccination (mean±S.D.)	**Vaccination (mean±S.D.)**
IPs	45.1 ± 8.7[a†]	44.7 ± 8.3[a]
Duration (days)	54.2 ± 7.0[a]	59.9 ± 7.8[b]
Cost ($ million)	32.3 ± 6.9[a]	34.8 ± 7.1[b]
Animals culled	11265 ± 5978[a]	11095 ± 6611[a]

† Within each row, figures with the same superscript are not significantly different.

5.1.2 Case study 2 (Vic.)

Descriptive statistics for the no vaccination and vaccination strategies are summarised in Figure 7 and Table 12.



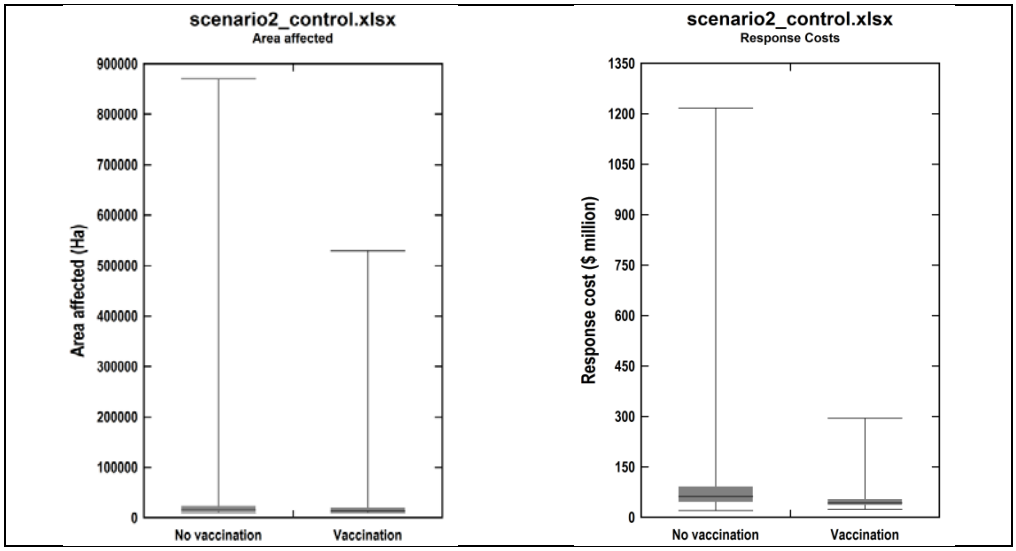


Figure 7: Case study 2 results. Comparison of control strategies

It is apparent from Table 12 that the vaccination strategy performed very well in this case study, being associated with significant reductions in the number of IPs, total numbers of animals culled, duration of the control program, size of the infected area and total control costs. On average, the vaccination strategy reduced the duration of the control program by 48 days (35.5% reduction), the number of IPs by 80 (43.2%) and the cost of the control program by $32 million (39.6%). In addition, vaccination was very effective in reducing the variability in outcome. That is, it reduced the likelihood of getting a very large outbreak. Under the no vaccination strategy, in 24 runs (2.4%) the outbreak was still active at the end of the simulation period of 365 days. When vaccination was used, all outbreaks had been controlled within the simulation period.

Table 12: Descriptive statistics for case study 2

Variable	**No vacc**			**Vacc**		
	Mean (SD)	**Median (Q1, Q3)**	**Range (min-max)**	**Mean (SD)**	**Median (Q1, Q3)**	**Range (min-max)**
IPs (n)	185.0 (229.9)	128 (96, 194)	30-3914	105.2 (47.35)	95 (78, 117)	41-765
Total animals culled (n)	49508 (646350	35236 (25405, 53619)	9398-1359772	30148 (14993)	26512 (21130, 34380)	10977-203234
VPs (n)	-	-	-	213.7 (102.8)	187 (143, 252)	69-859
Total animals vaccinated (n)	-	-	-	45758 (22095)	40293 (30465, 53690)	13366-182214
Duration of control program (days)	134.7 (62.3)	118 (90, 161)	55-364	86.5 (19.5)	82 (73, 95)	59-250
Size of the infected area (sq km)	23647 (41590)	15466 (12001, 22932)	10234-870203	21118 (28789)	14164 (11457, 20137)	10234-528784
Total cost of control ($'000)	80214 (71371)	62081 (45794, 91504)	20597-1217210	48422 (18990)	43756 (36939, 53730)	23914-294453

Table 13: Statistical analysis – Case study 2

	No vaccination (mean±S.D.)	Vaccination (mean±S.D.)
IPs	185.0 ± 230.0[a†]	105.2 ± 47.4[b]
Duration (days)	134.6 ± 62.3[a]	86.5 ± 19.5[b]
Cost ($ million)	80.2 ± 71.4[a]	48.4 ± 19.0[b]
Animals culled	49508 ± 64667[a]	30148 ± 15001[b]

† Within each row, figures with the same superscript are not significantly different.

5.1.3 Case study 3 (WA)

Descriptive statistics for the no vaccination and vaccination strategies are summarised in Figure 8 and Table 14.

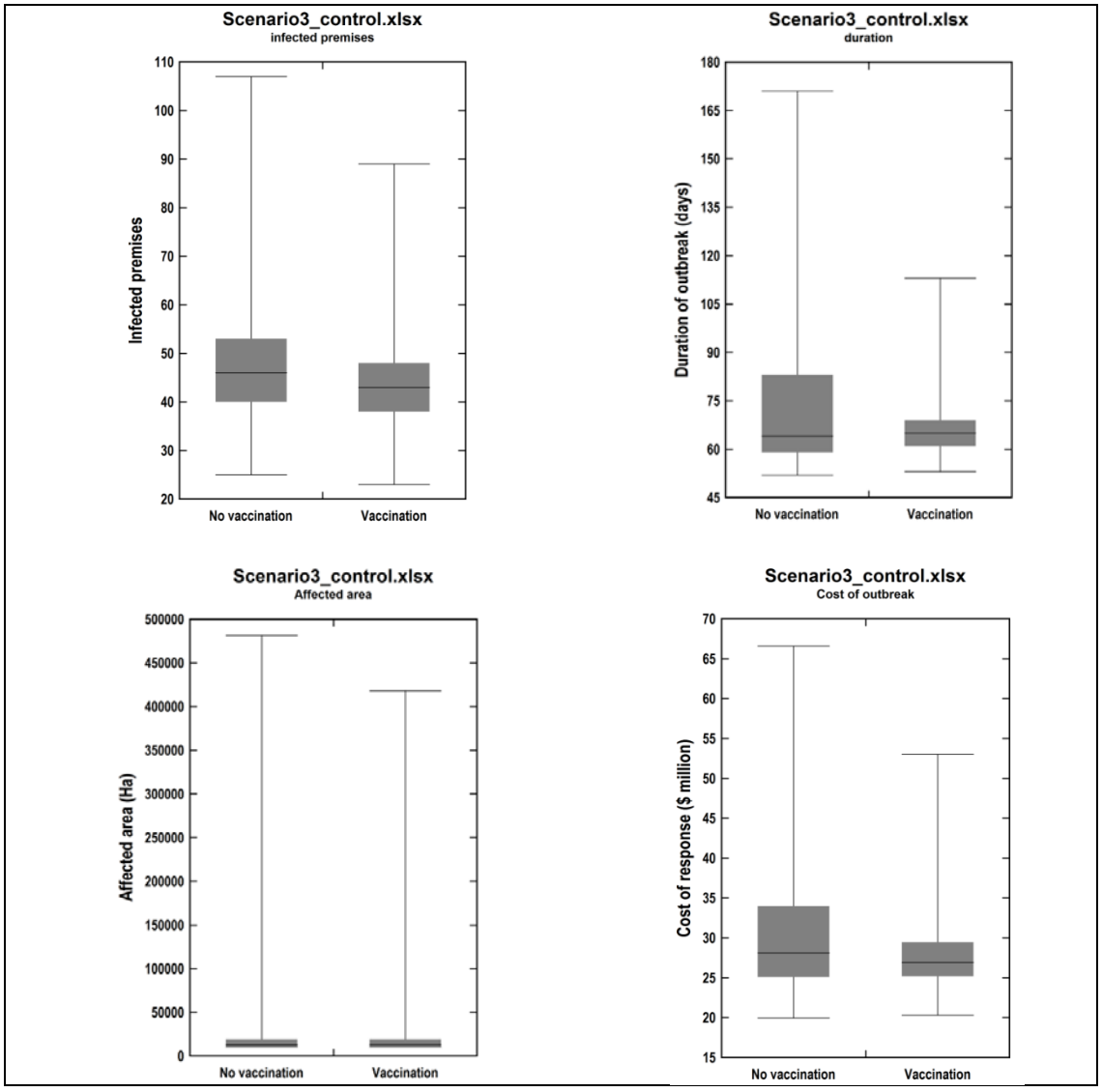


Figure 8: Case study 3 results. Comparison of control strategies

In case study 3, vaccination significantly reduced the size, duration and cost of controlling an FMD outbreak. However, the reductions were quite small e.g. on average duration of the control program was reduced by 8 days (10.8%), the number of IPs by 4 (8.3%) and control costs by about $2.8 million (9.1%). On average there would be around 11,000 (range 3000-42000) vaccinated animals that would have to be managed at the end of the outbreak which will be associated with additional costs.

Table 14: Descriptive statistics for case study 3

Variable	No vaccination			Vaccination		
	Mean (SD)	**Median (Q1, Q3)**	**Range (min-max)**	**Mean (SD)**	**Median (Q1, Q3)**	**Range (min-max)**
IPs (n)	47.55 (11.33)	46 (40, 53)	25-107	43.7 (8.6)	43 (38, 48)	23-89
Total animals culled (n)	16880 (5091)	15414 (13551, 18674)	9892-59978	16014 (4764)	14801 (13019, 17511)	9682-52944
VPs (n)	-	-	-	49.44 (13.25)	47 (41, 56)	19-134
Total animals vaccinated (n)	-	-	-	10679 (3902)	9854 (8047, 12373)	3447-41919
Duration of control program (days)	74.3 (21.6)	64 (59, 83)	52-171	66.2 (8.3)	65 (61, 69)	53-113
Size of the infected area (sq km)	18861 (28714)	13091 (11068, 19288)	10962-481466	18632 (29491)	13305 (11070, 19257)	10962-417929
Total cost of control ($'000)	30459 (7352)	28107 (25091, 33967)	19950-66584	27700 (3969)	26904 (25162, 29442)	20304-53012

Table 15: Statistical analysis – Case study 3

	No vaccination (mean±S.D.)	**Vaccination (mean±S.D.)**
IPs	$47.6 \pm 11.3^{a\dagger}$	43.7 ± 8.6^{b}
Duration (days)	74.3 ± 21.6^{a}	66.2 ± 8.3^{b}
Cost ($ million)	30.5 ± 7.4^{a}	27.7 ± 4.0^{b}
Animals culled	16880 ± 5094^{a}	16013 ± 4766^{b}

† Within each row, figures with the same superscript are not significantly different.

5.2 Post-outbreak surveillance approaches

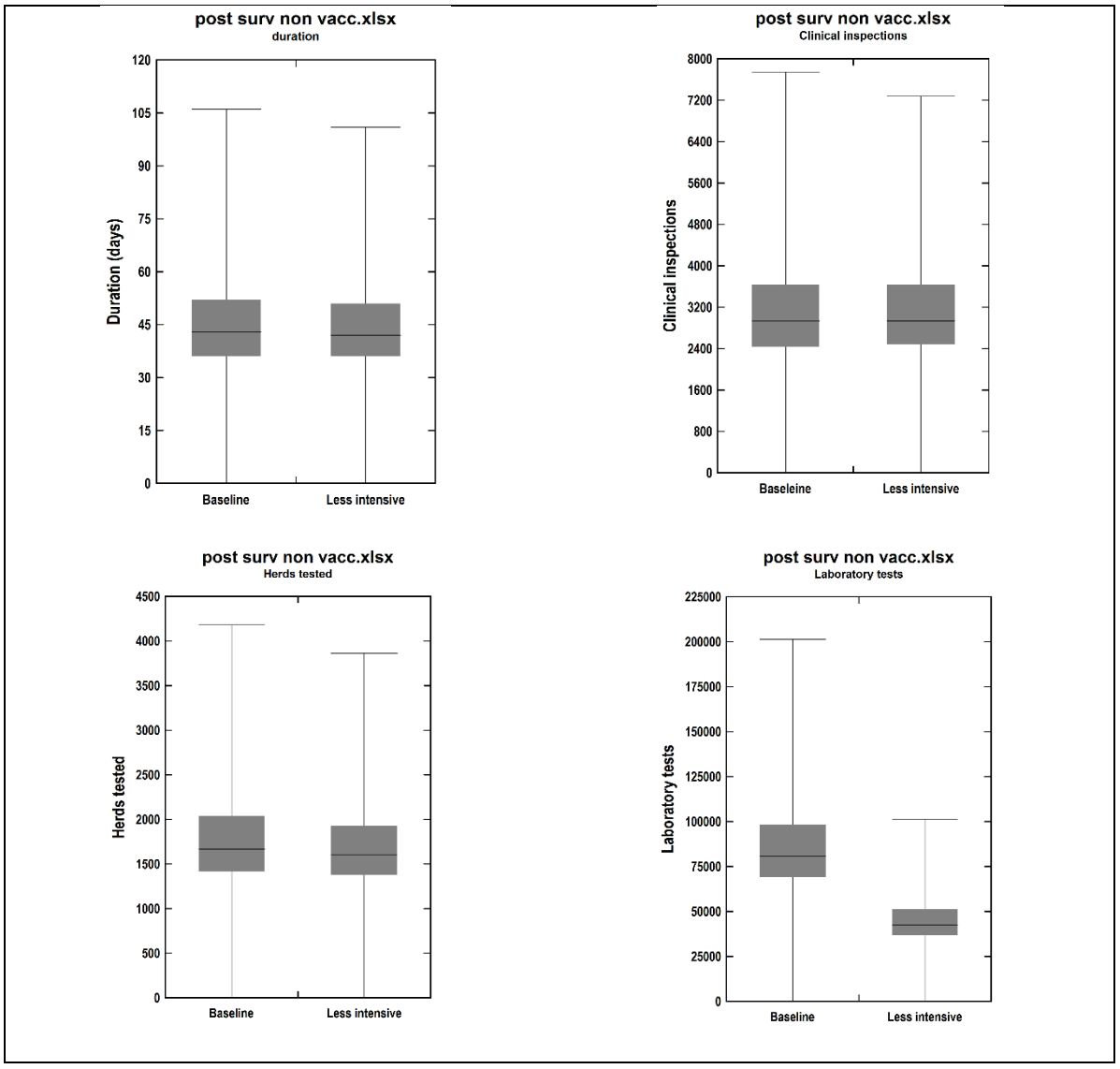
For this study we use the Victorian outbreak scenario (Case study 2) to demonstrate how the modified AADIS model can be used to assess the performance of different post-outbreak surveillance sampling regimes. We compare a baseline surveillance system (based on the approach used in the European Union) with a hypothetical surveillance approach using a reduced sampling intensity as described in Section 4.3.2).

Two situations have been considered:

- Control program without vaccination
- Control program with vaccination

5.2.1 Control program without vaccination

Descriptive statistics for the two post-outbreak surveillance approaches are shown in Figure 9 and Table 16. Under the assumptions used for this study, the post-outbreak surveillance would take around 6 weeks to complete. As all herds in previously infected areas still require clinical inspection, the reduced sampling regime had no significant effect on the time required to complete the surveillance or number of inspections. The reduced intensity sampling regime would significantly reduce the number of samples collected and the cost of the post-outbreak sampling (on average by 47% and 27% respectively) compared to the baseline approach. There would also be a significant reduction in the number of positive herds requiring follow-up. NB in this study there were no residual infected herds in the population so there was no impact of reduced surveillance intensity on missing any infected herds.



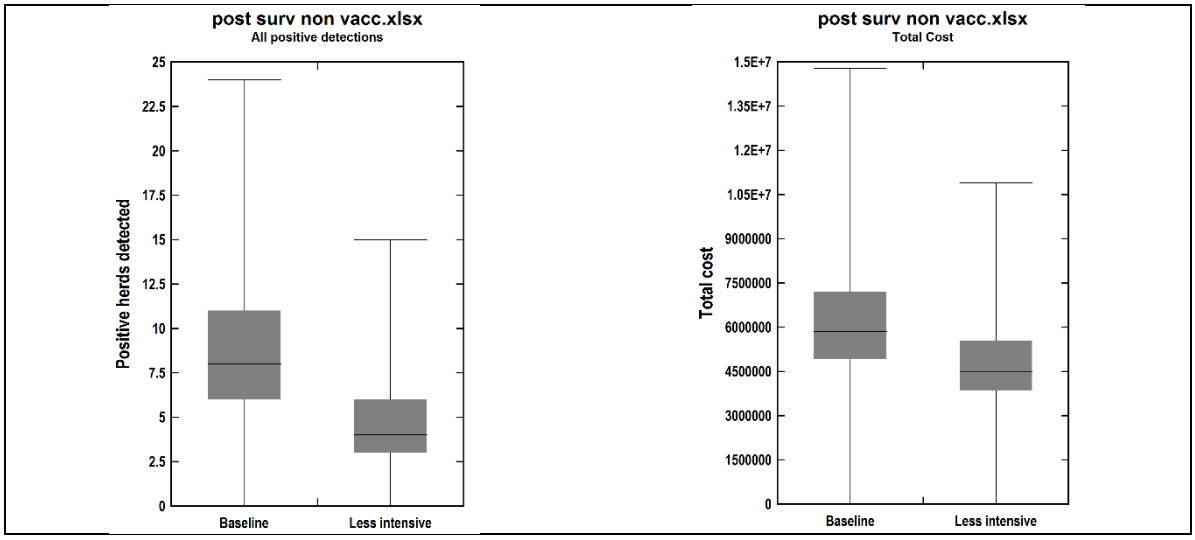


Figure 9: Comparison of baseline and reduced intensity sampling approaches, no vaccination

Table 16: Comparison of two post outbreak surveillance approaches, no vaccination – descriptive statistics

	Baseline			**Reduced intensity**		
	Mean (SD)	Median (Q1, Q3)	Range (min-max)	Mean (SD)	Median (Q1, Q3)	Range (min-max)
Surveillance duration (days)	44.85 (15.1)	43 (36, 52)	0-106	44.36 (13.95)	42 (36-51)	0-101
Surveillance cost ($'000)	6159 (2083.9)	5857.4 (4926.2, 7195.6)	0-14778.4	4772.2 (1531.6)	4481 (3837.9, 5542.2)	0-10891.5
Tot herds tested	1757.5 (582.8)	1664 (1418.5, 2040.3)	0-4181	1693.6 (524.7)	1600.5 (1380, 1927)	0-3863
Total samples	85114 (27796)	80907 (68971, 98389)	0-201341	44923 (13770)	42600 (36687, 51084)	0-101382
Positive herds requiring follow-up	8.5 (3.9)	8 (6-11)	0-24	4.56 (2.6)	4 (3-6)	0-15
Infected herds missed (false negatives)	0	0	0	0	0	0

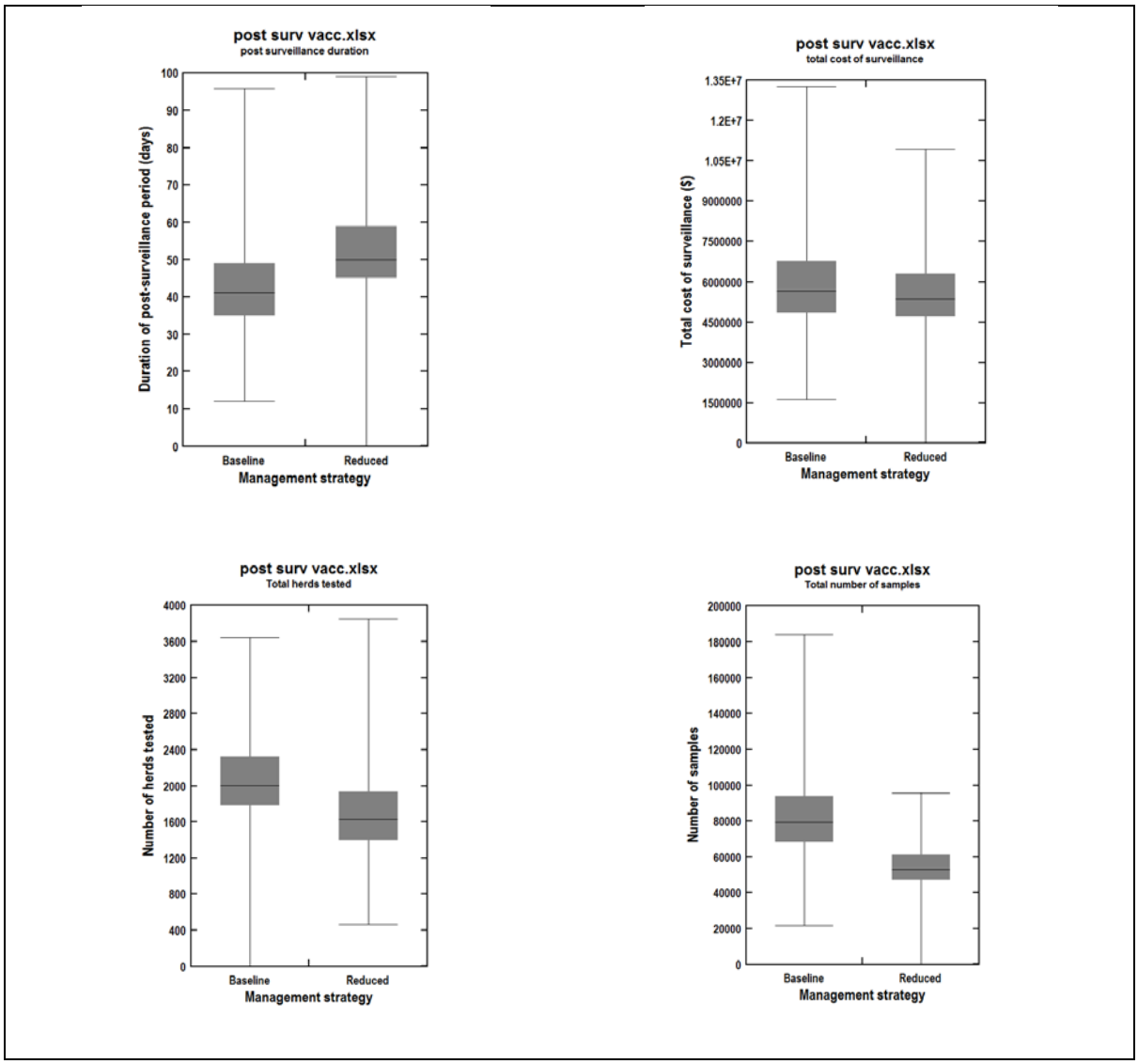
Table 17: Statistical analysis – comparison of surveillance approaches, no vaccination

	Baseline	**Reduced intensity**
Duration	46.2 ± 13.1[a†]	44.5 ± 14.0[a]
No. herds tested	1811 ± 505[a]	1698 ± 527[b]
No of samples collected	87719 ± 23931[a]	45042 ± 13819[b]
No of clinical inspections	3200 ± 983[a]	3133 ± 1053[a]
Cost	6.35 ± 1.81[a]	4.79 ± 1.54[b]
No herds positive	8.77 ± 3.66[a]	4.57 ± 2.61[b]
No of herds missed	0[a]	0[a]

† Within rows, figures with the same superscript are not significantly different

5.2.2 Control program with vaccination

Descriptive statistics for the two post-outbreak surveillance approaches are shown in Figure 10 and Table 18. Under the assumptions used for this study, the post-outbreak surveillance would take around 6 weeks to complete. The reduced intensity approach evaluated here would require fewer herds and samples to be tested with associated reduction in surveillance costs (on average, the number of tests is reduced by 49%, and the cost of surveillance by 24%). There would be fewer positive herds to be followed up with no increase in the number of false negative herds (I.e. infected herds that are missed). NB under both sampling regimes there is the possibility of small numbers of infected vaccinated herds being missed.



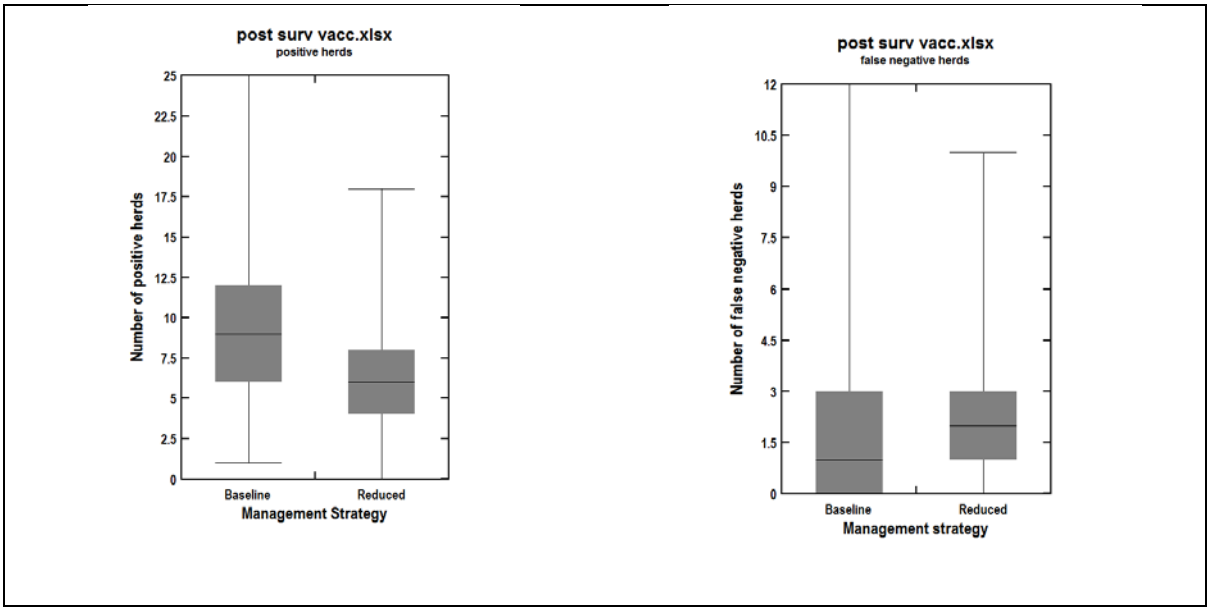


Figure 10: Comparison of baseline and reduced intensity sampling approaches, control with vaccination

Table 18: Comparison of two post outbreak surveillance approaches, control with vaccination – descriptive statistics

	Baseline			**Reduced intensity**		
	Mean (SD)	**Median (Q1, Q3)**	**Range (min-max)**	**Mean (SD)**	**Median (Q1, Q3)**	**Range (min-max)**
Surveillance duration (days)	43.24 (10.39)	41 (35-49)	12-96	42.21 (10.38)	40 (35, 48)	0-91
Surveillance cost ($'000)	5933.3 (1440)	5662.2 (4836.3,6770)	1608.8-13270.9	4527.6 (1150.1)	4236.7 (3705, 5122.5)	0-10316.1
Tot herds tested	1708.9 (410.4)	1630.5 (1401.5, 1936.5)	463-3852	1593.2 (378.1)	1505.5 (1322.8, 1788.3)	0-3484
Total samples	82879 (19492)	79237 (68362, 93855)	21576-184048	42300 (9900)	40004 (35151, 47269)	0-92034
Positive herds requiring follow-up	9.22 (3.92)	9 (6,12)	1-25	4.49 (2.46)	4 (3, 6)	0-17
Infected herds missed (false negatives)	1.86 (2.01)	1 (0-3)	0-12	1.40 (1.43)	1 (0-2)	0-13

Table 19: Statistical analysis – comparison of surveillance approaches, control with vaccination

Variable	**Baseline**	**Reduced intensity**
Duration	43.2 ± 10.4[a†]	42.2 ± 10.4[b]
No. herds tested	1709 ± 411[a]	1593 ± 378[b]
No of samples collected	82879 ± 19502[a]	42300 ± 9900[b]
No of clinical inspections	2954 ± 752[a]	2971 ± 803[a]
Cost	5.93 ± 1.44[a]	4.53 ± 1.15[b]
No herds positive	9.22 ± 3.92[a]	4.6 ± 2.50[b]

No of herds missed	1.86 ± 2.01[a]	1.40 ± 1.53[a]

† Within rows, figures with the same superscript are not significantly different

5.3 Management of vaccinated animals

As the first study had shown vaccination to be beneficial in the Victorian (case study 2) and WA (case study 3) outbreaks only, we use these outbreaks for this study. We compare the three approaches to managing vaccinated animals i.e. vaccinate and retain, vaccinate-and-remove (waste), vaccinate-and-remove (salvage). The three approaches are compared on the basis of the costs incurred:

- Control costs
- Post-outbreak management
- Loss of trade
- Total costs

Control costs include the costs associated with managing the outbreak (operational costs, control centre costs and compensation), post-outbreak management includes surveillance and testing costs and where appropriate costs of slaughtering and disposal of vaccinated animals, including compensation). Loss of trade costs depend on time out of markets. For simplicity in this study, we assume that the time out of markets is directly related to the time until FMD-free status is regained under OIE guidelines. This is an over simplification as, in reality, it is likely to take additional time until export markets are re-gained.

5.3.1 Case study 2 (Vic)

Descriptive statistics for the three post-outbreak vaccination approaches are summarised in Figure 11 and Table 20. Under the assumptions of this case study, the vaccinate-and-remove strategies would be associated with higher post-outbreak management costs but lower loss of trade costs. In terms of overall cost, there would be an average savings of around 8% (around $600 million) compared to the vaccinate-and-retain strategies. In this strategy, from a cost point of view there was no advantage of removal with salvage compared to removal to waste. Under the assumption that it is quicker to remove animals under a vaccinate to waste approach compared to a vaccinate and salvage approach (see Section 3.2.2) any savings made through salvage are offset by trade losses associated with longer time remove all vaccinated animals and regain markets.

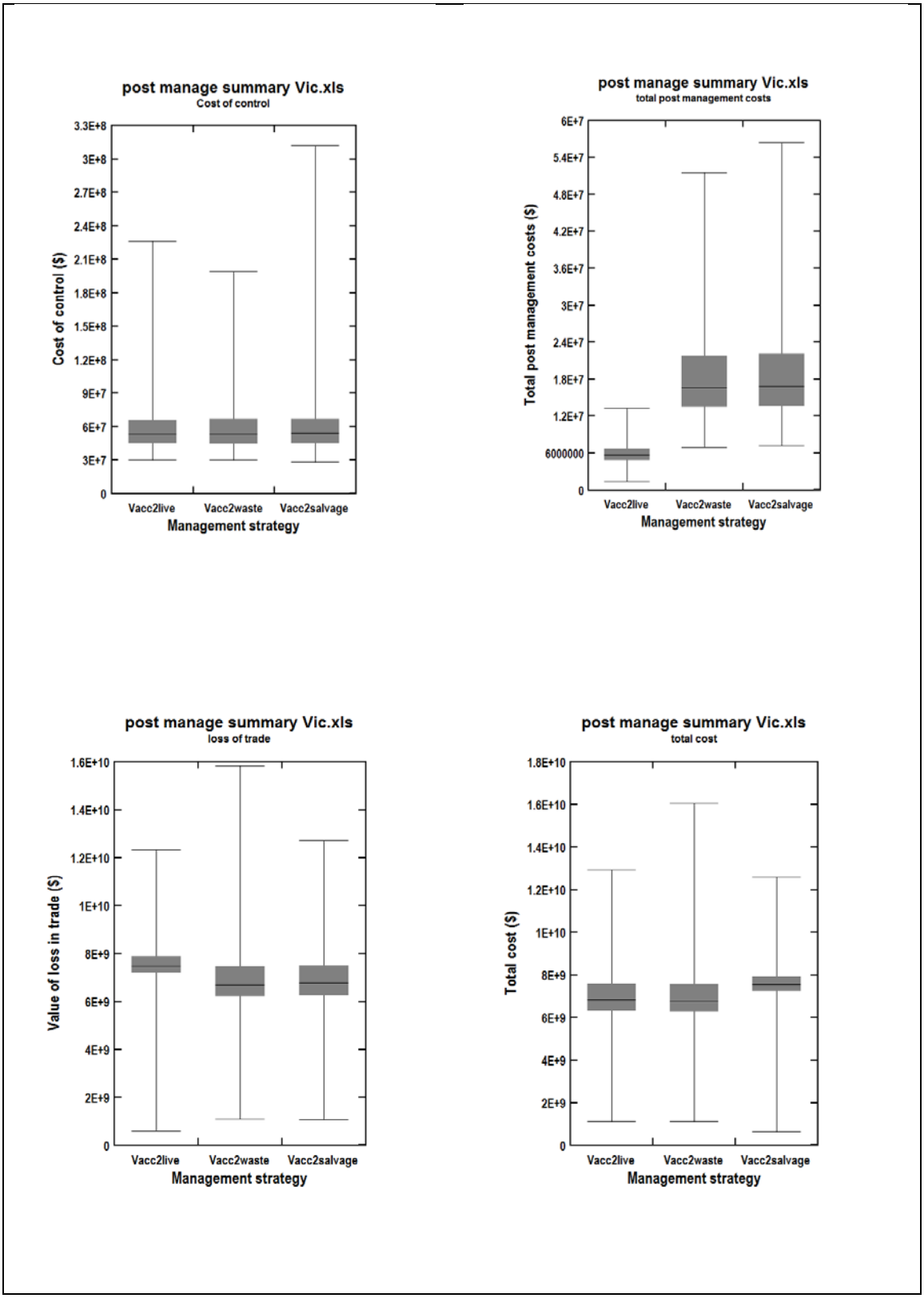


Figure 11: Box-and-whisker plots for costs associated with different post-outbreak management strategies for vaccinated animals under case study 2

Table 20: Comparison of post outbreak management options for vaccinated animals in Case study 2 – descriptive statistics

	Control costs ($m)	Post-outbreak management ($m)	Loss of trade ($m)	Total Costs ($m)
Vaccinate and retain				
Mean (SD)	59 (21.43)	5.93 (1.44)	7597.6 (607.9)	7662.5 (6256.6)
Median (Q1, Q3)	54.22 (45.42, 66.66)	5.66 (4.874, 6.77)	7472.0 (7168,7872)	7536.4 (7225.8, 7936.5)
Range (min-max)	28.55-311.76	1.61-13.27	6656-12320	6695.1-12563
Vaccinate-and-remove (waste)				
Mean (SD)	58.68 (20.24)	18.41 (6.89)	6960.7 (1095.9)	7037.8 (1119.1)
Median (Q1, Q3)	53.66 (44.98, 67.04)	16.60 (13.47, 21.68)	6688 (6208, 7456)	6752.9 (6265, 7548.4)
Range (min-max)	30.53-199.07	7.88-51.47	5344-15808	5384.8-16043.5)
Vaccinate-and-remove (salvage)				
Mean (SD)	58.68 (20.63)	18.78 (7.24)	7007.9 (1082.9)	7083.3 (1106.6)
Median (Q1, Q3)	53.31 (45.38, 65.93)	16.83 (13.60,22.19)	6752 (6240, 7488)	6816.2 (6298.2, 7576.1)
Range (min-max)	30.06,226.48	7.31-56.44	5408-12704	5449.6-12910.1)

Table 21: Statistical analysis – Case study 2

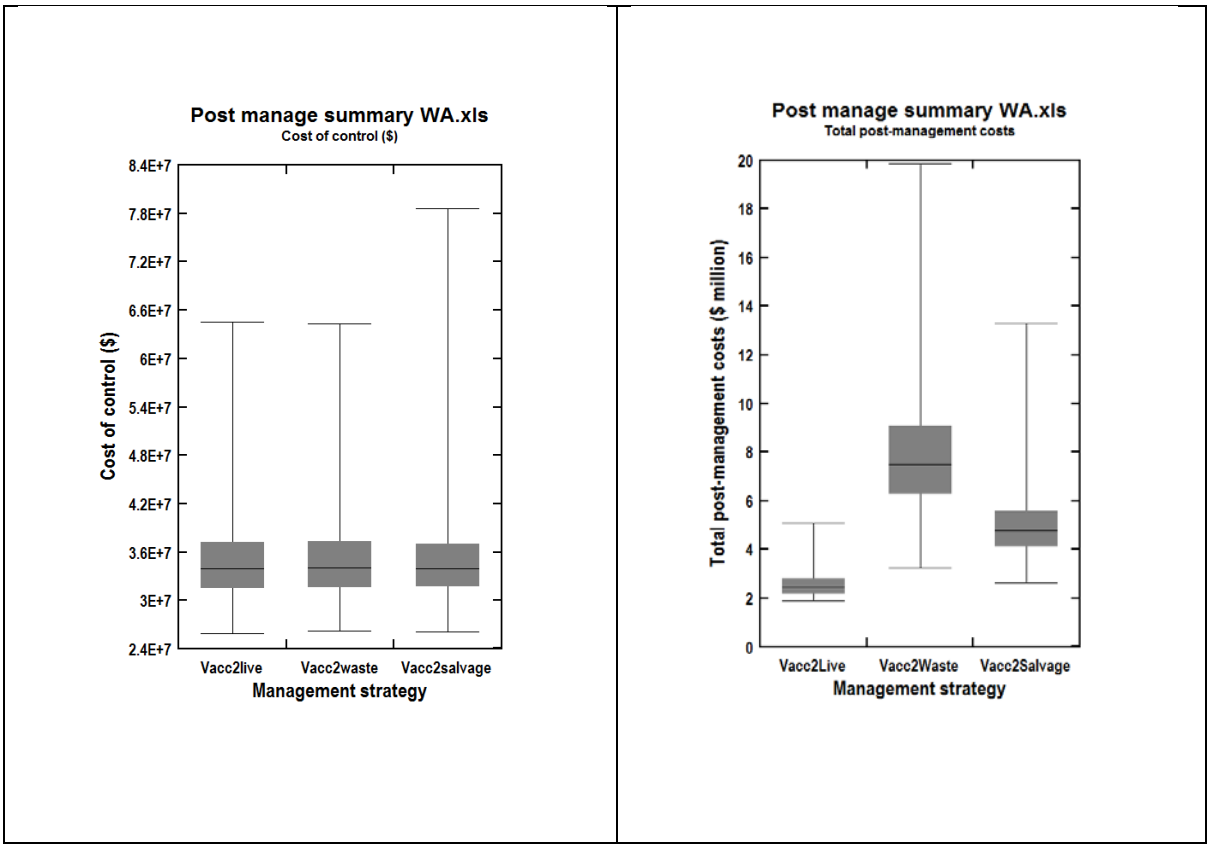
	Vaccinate-and-live	Vaccinate-and-remove (waste)	Vaccinate-and-remove (salvage)
IPs (n)	105 ± 46[a]	104 ± 41[a]	105 ± 41[a]
VPs (n)	211 ± 96[a]	209 ± 97[a]	213± 100[a]
Duration – control (days)	88.7 ± 20.3[a]	87.8 ± 19.2[a]	88.2± 18.2[a]
Cost of control ($m)	59.0 ± 21.4[a]	58.7 ± 20.2[a]	58.7± 20.6[a]
Post surveillance duration (days)	43.2 ± 10.4[a]	41.4 ± 10.2[b]	41.7 ± 10.9[b]
Post management end	130.2 ± 27.2[a]	132.7 ± 32.7[a,b]	134.0 ± 32.3[b]
Post surveillance cost ($m)	3.0 ± 0.8[a]	3.0 ± 0.8[a]	3.1 ± 0.9[a]
Post laboratory costs ($m)	2.9 ± 0.7[a]	2.6 ± 0.6[b]	2.6 ± 0.6[b]
Total post management costs ($m)	5.9 ± 1.4[a]	18.4 ± 6.9[b]	18.8 ± 7.2[b]
Days out of market	237 ± 20[a]	217 ± 34.2[b]	219± 33.8[b]
Loss of trade ($B)	7.6 ± 0.6[a]	6.9 ± 1.1[b]	7.0 ± 1.1[b]
Total Cost ($B)	7.6 ± 0.6[a]	7.0 ± 1.1[b]	7.1 ± 1.1[b]

† within rows, figures with the same superscript are not significantly different

Because the performance of the vaccinate-and-remove approaches will depend on the time taken to slaughter the vaccinated animals, a sensitivity analysis was done. When the rates of removal were doubled, the average total costs under a vaccinate-and-remove (waste) strategy fell to $6359.9m, a saving of $1306.2m compared to the vaccinate-and-retain approach.

5.3.2 Case study 3 (WA)

Descriptive statistics for the three post-outbreak vaccination approaches are summarised in Figure 12 and Table 22. A similar pattern to that with Case study 2 was seen. On average, the vaccinate-and-remove approaches were associated with reductions in overall cost of around 23% (or a saving of around $1600m). On a percentage basis this was a bigger reduction than was seen in Case study 2, which can be explained by the smaller outbreak sizes and fewer vaccinated premises in this case study. With the same removal capacity, the vaccinated population is able slaughtered more quickly and consequently there is a shorter period until FMD-free status is regained. On average, the vaccinated population is able to be removed 52 days earlier in Case study 3 compared to Case study 2.



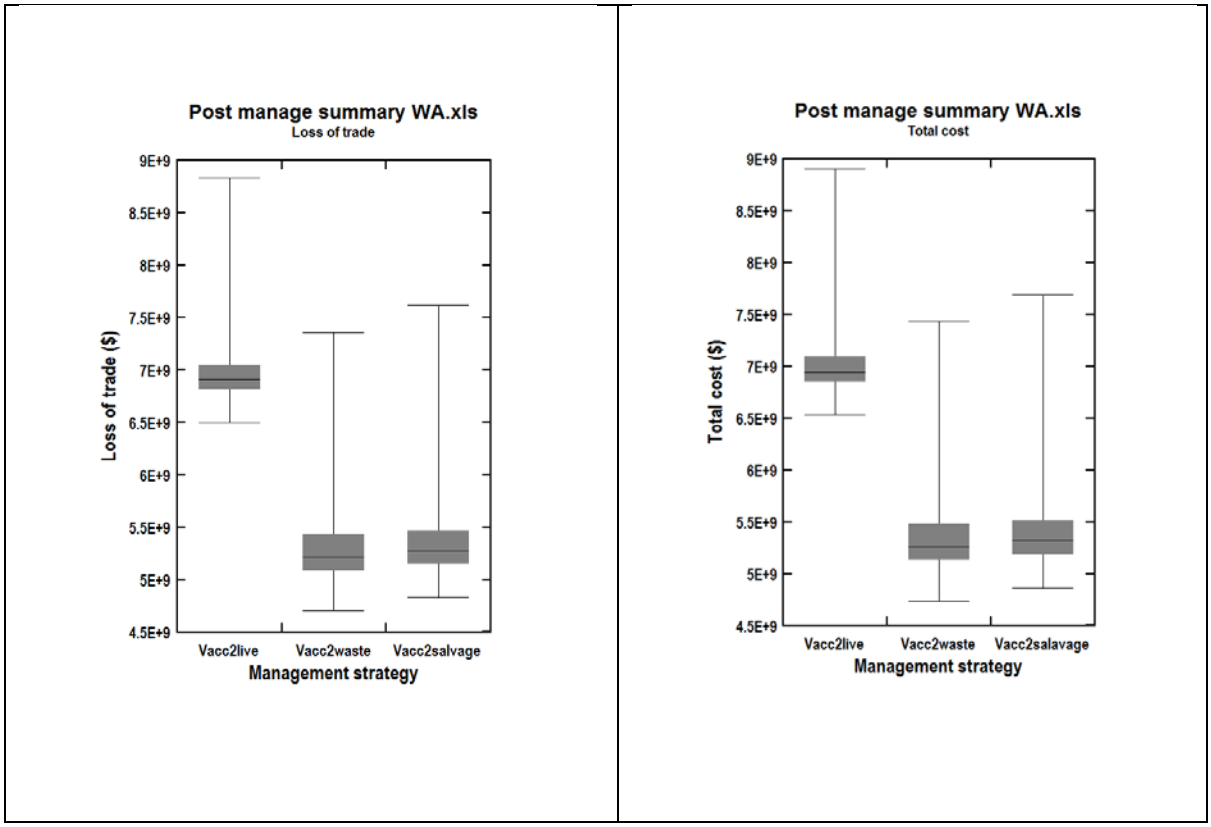


Figure 12: Box-and-whisker plots for costs associated with different post-outbreak management strategies for vaccinated animals under case study 3

Table 22: Comparison of post outbreak management options for vaccinated animals in Case study 3 – descriptive statistics

	Control costs ($m)	Post-outbreak management ($m)	Loss of trade ($m)	Total Costs ($m)
Vaccinate and retain				
Mean (SD)	35.22 (5.51)	2.56 (0.48)	6966 (278.3)	7003.8 (282.4)
Median (Q1, Q3)	33.94 (31.71, 27.02)	2.46 (2.18, 2.81)	6912 (6816-7048)	6947.6 (6849.5, 7094)
Range (min-max)	26.16-78.58	1.9-5.1	6496-8832	6528.7-8903.7
Vaccinate-and-remove (waste)				
Mean (SD)	35.0 (5.25)	7.95 (2.28)	5300.5 (303.3)	5343.4 (308.6)
Median (Q1, Q3)	33.90 (31.46, 37.26)	7.7 (6.28, 9.09)	5216 (5088,5440)	5264.9 (5134.9, 5482.2)
Range (min-max)	25.91-64.55	3.26-19.84	4704-7360	4734.3-7440.4
Vaccinate-and-remove (salvage)				
Mean (SD)	35.11 (5.35)	5.05 (1.34)	5357.4 (323.5)	5397.6 (328.7)
Median (Q1, Q3)	34.0 (31.59, 37.28)	4.77 (4.12-5.58)	5280 (5152, 5472)	5324.9 (5188.6, 5516)
Range (min-max)	26.23-64.28	2.62-13.29	4832-7616	4861.3-7691.3

Table 23: Statistical analysis – Case study 3

	Vaccinate-and-live	Vaccinate-and-remove (waste)	Vaccinate-and-remove (salvage)
IPs (n)	44 ± 9[a†]	44 ± 9[a]	44 ± 9[a]
VPs (n)	51 ± 14[a]	50 ± 14[a]	50 ± 14[a]
Duration – control (days)	68.5 ± 8.4[a]	68.8 ± 8.5[a]	68.7 ± 8.5[a]
Cost of control ($m)	35.2 ± 5.5[a]	35.0 ± 5.2[a]	35.1 ± 5.3[a]
Post surveillance duration (days)	30.8 ± 5.6[a]	29.8 ± 5.3[b]	30.2 ± 5.7[b]
Post management end	97.8 ± 11.9[a]	97.2 ± 12.0[a]	97.7 ± 12.2[a]
Post surveillance cost ($m)	1.7 ± 3.2[a]	1.7 ± 0.3[a]	1.7 ± 0.3[a]
Post laboratory costs ($m)	0.8 ± 0.2[a]	0.7 ± 0.1[b]	0.8 ± 0.1[b]
Total post management costs ($m)	2.6 ± 0.5[a]	7.9 ± 2.3[b]	5.0 ± 1.3[c]
Days out of market	217.6 ± 8.7[a]	165.6 ± 9.4[b]	167.4 ± 10.1[c]
Loss of trade ($B)	7.0 ± 0.3[a]	5.3 ± 0.3[b]	5.4 ± 0.3[c]
Total Cost ($B)	7.0 ± 0.3[a]	5.3 ± 0.3[b]	5.4 ± 0.3[c]

† within rows, figures with the same superscript are not significantly different

6. Discussion

In developing policies and contingency plans for dealing with an FMD outbreak, not surprisingly, animal health authorities have tended to focus on the operational aspects of rapidly containing and eradicating the outbreak. Although this is a critical component of FMD preparedness, it is also important to appreciate that it is the trade effects, especially loss of international market access that will have the greatest economic impact. Beutre et al (2013) found that more than 90% of the economic costs of an FMD outbreak arise from revenue losses caused by immediate and prolonged export bans by Australia's FMD sensitive markets. Thus, it is also essential that our FMD planning takes to account post-outbreak management to facilitate regaining FMD-free status and export market access as rapidly as possible.

Two important issues that need to be considered are surveillance approaches to support proof of freedom and the related issue of how to manage vaccinated animals when vaccination has been used as part of the control program. In both cases, there are different approaches and strategies that could be considered. From a policy perspective it would be very useful if managers had access to decision support tools that could be used to test strategies and evaluate different approaches in terms of effectiveness and cost-effectiveness.

Determining the best approach to regaining FMD-free status will depend on the nature of the outbreak, the type of control program used (particularly whether vaccination has been used or not) and an economic evaluation of the different options. In this project, we have modified the AADIS model (Bradhurst et al. 2015, Bradhurst et al., 2016) which is being used in Australia to support FMD planning and preparedness to specifically enable post-outbreak management issues to be studied. To address the issue of post outbreak surveillance to support proof of freedom we have added a module that enables different sampling and testing regimes to be evaluated taking into account different design criteria, diagnostic test performance and resourcing levels.

The use of terminology like ‘testing to demonstrate freedom from infection’ is misleading and it has been suggested that it should be replaced with something like ‘testing to substantiate freedom from infection’ (Paton et al. 2006). It is possible to estimate the probability of freedom (Schuppers et al. 2012). This can be done by testing for the presence of infection in a herd by sampling a suitable number of animals, and if they are all negative, we can conclude with a certain level of confidence that the herd is not infected at the design prevalence. The design prevalence at the animal level may be thought of as the minimum prevalence that would occur if the disease were present in a herd. The design of a surveillance program is a compromise between cost and logistics of implementing an intensive sampling program, the cost-information ratio of additional samples and the level of acceptable risk for the disease of concern (Schuppers ate al. 2012). The level of acceptable risk may vary by country, by pathogen and over time. For FMD, with its high economic impact this is typically low, which is reflected in the design prevalence in protocols like the EU FMD directive. It could be argued that in unvaccinated populations a higher design prevalence (with associated savings in time and sampling costs) would be adequate. For a highly contagious disease like FMD, it it might be expected that a large proportion of an initially naıve population would seroconvert to the disease, if it were present (Martin et al. 2007). The situation is less clear in vaccinated populations. The likely prevalence of infection in in FMDV-infected vaccinated herds is not well quantified (Paton et al. 2006). Under some circumstances it could be quite low, so inevitably an intensive surveillance approach will be required.

Surveillance programs need to take into account the performance characteristics of the diagnostic tests. When testing a large number of samples, (false) positive results will be obtained, even using tests with high specificity. In designing a surveillance plan, specificity of the testing procedure can be increased by using confirmatory tests, but it is still inevitable that some false positives can be expected. Simply removing them is not an option as finding reactors that have not been shown to be free of infection implies a failure to demonstrate freedom from infection (Paton et al.2006).Thus, the surveillance plan should include a follow-up protocol. This should include resampling and testing for evidence of active infection using virological methods. Both the OIE code and EU Directive require that all herds with sero-reactors be followed up and classified as free or containing infection. Follow-up of reactors will require demonstrating the absence of transmission of FMD virus in vaccinated populations where this is defined as ‘demonstrating changes in virological or serological evidence indicative of recent infect ion, even in the absence of clinical sign’s (OIE 2016). The OIE code further states ‘in the absence of infection and transmission, findings of small numbers of seropositive animals do not warrant the declaration of a new outbreak and the follow-up investigations may be considered complete’ (OIE 2016).

There is increasing interest in using emergency vaccination for the control of FMD to avoid the need for large scale culling of animals (Paton 2006). However, under current international guidelines there is a significant economic disincentive to a vaccinate-and-retain policy because of the longer waiting period before FMD-free status can be regained compared to the situation where vaccinated animals are removed from the population (OIE 2016). Understandably the disposal of healthy vaccinated animals just for the purpose of regaining markets has been identified as an area of concern (Geale et al. 2015). There is interest in seeing whether there may be scope to reduce the time periods under a vaccinate-and-retain policy (Geale et al. 2015) and in June 2017 an OIE ad hoc working group met to consider this issue. For countries with significant exports of livestock and livestock products it is important to have appropriate tools to evaluate the costs and benefits of different approaches to

facilitate regaining FMD-free status as rapidly as possible. To address the issue of vaccination we added functionality to AADIS to enable different approaches to managing vaccinated animals at the end of an outbreak to be studied.

The focus of this project was on building capability to provide sound technical advice and economic evidence to support policies on post-outbreak management to facilitate return to trade. Several studies were done to test the modifications to AADIS and demonstrate how the model can be used to quantify and compare the performance and impact of different approaches to managing vaccinated animals and doing post-outbreak surveillance. Three outbreak scenarios in different regions of Australia were considered.

Initially, the model was run to compare control strategies based on stamping out with or without vaccination. Vaccination used with stamping out provided no improvement over stamping out on its own in the Qld case study scenario, provided a small but significant improvement in the WA case study and was highly effective in reducing the size and duration of the outbreak in the Victorian case study. This finding highlights that when it comes to considering the use of vaccination, a 'one size fits all' approach is not appropriate. The performance of control strategies in terms of containing and eradicating FMD will be affected by assumptions about the performance of control measures (e.g. compliance with movement restrictions, effectiveness of tracing) and availability of resources to implement the measures. Where resources are adequate to maintain effective surveillance and infected premises operations then vaccination is unlikely to offer any advantages in terms of disease control over a stamping out strategy on its own (Abdalla et al., 2005; Roche et al., 2013; Garner et al., 2014). The WA outbreak was associated with delayed detection. The Victorian outbreak occurred in a high density livestock area with high potential for spread as evidenced by the wide distribution of outbreak sizes under the stamping out alone strategy.

In the second demonstration study we showed how the modified model can be used to compare surveillance approaches, in previously infected areas, to support regaining FMD free status after an outbreak. Compared to a baseline surveillance based on the European Union Directive, a reduced sampling intensity approach used with a control program not involving vaccination, could significantly reduce the number of samples collected and the cost of the post-outbreak sampling. There would also be a significant reduction in the number of positive herds requiring follow-up. To recover FMD-free status, there should only be herds in the population that are sero-negative or seropositive exclusively from the administration of inactivated vaccine. There should be no danger of carriers or undetected disease/infection.

It was reassuring that under the assumptions used in this study, there were no residual herds under the non-vaccination control program i.e. the control measures put in place were effective in finding and removing all FMD-infected farms. This was not the case when a vaccination-and-retain policy was used. With an emergency (suppressive ring) vaccination strategy as applied in these studies, there is a high likelihood that some vaccinated herds will be exposed to infection before or soon after vaccination. Under these situations vaccination cannot be relied upon to prevent infection although it might suppress clinical signs in these herds. Residually infected vaccinated herds were not uncommon in the simulations. In the Victorian case study there were up to seven infected and vaccinated herds present after completion of the control program. Post-outbreak surveillance

programs cannot be guaranteed to find all of these herds. Even with the baseline (EU) surveillance approach involve testing of all vaccinated animals, on average two true positive herds would be missed under the Victorian case study scenario. 'Small' herds have been identified as a particular problem for FMD surveillance programs after emergency vaccination (Paton et al. 2006). This is because it is not possible to compensate for imperfect test sensitivity by increasing the number of animals tested. Options for dealing with small herds include (a) not vaccinating them in the first place (b) applying a vaccinate-and-remove policy for small herds (Paton et al. 2006, Anon 2007). Animal health authorities should consider carefully whether vaccination of small herds is necessary under Australian conditions. In this study we elected not to vaccinate small herds. It could be argued that small herds pose a relatively low risk of spreading infection, it is likely to be time consuming to vaccinate these herds and if vaccine is limited, larger herds would be a higher priority (Paton et al. 2006). Having said this, socio-political pressure could make it difficult to implement a non-vaccination policy for small herds under an emergency FMD vaccination program.

The third demonstration study showed how the model can be used to quantify the costs of managing the vaccinated population at the end of an outbreak. Three approaches were compared: (a) vaccinate-and-retain; (b) vaccinate-and-remove (slaughter to waste) and (c) vaccinate-and-remove (slaughter and salvage). For the Victorian case study, the vaccinate-and-remove strategies would be associated with higher post-outbreak management costs but lower loss of trade costs. In terms of overall cost, there would be an average savings of around 8% (around $600 million) compared to the vaccinate-and-retain policy. In this case study, from a cost point of view there was no advantage of removal with salvage compared to removal to waste. This finding assumes that it takes longer to remove (process) animals under a slaughter and salvage approach then a slaughter and waste approach. Any savings made through salvage are offset by trade losses associated with longer time required to remove all vaccinated animals, and regain markets. A similar pattern was seen with the WA case study, although, on average, the vaccinate-and-remove approaches were associated with bigger reductions in overall cost on a percentage basis than was seen in the Victorian case study. This can be explained by the smaller outbreak sizes and fewer vaccinated premises in this case study. With the same removal capacity, the vaccinated population is able slaughtered more quickly and consequently there is a shorter period until FMD-free status is regained.

It is apparent that the findings in relation to the relative performance of vaccinate-and-remove compared to vaccinate-and-retain policies will be influenced by the rate at which vaccinated animals can be removed, since the 3-month waiting period before FMD-free status can be regained starts from when the last vaccinated animal is removed (OIE 2016). In the case of vaccinate-and-retain, the six-month delay until FMD-free status can be regained starts from when the last animal is culled or the last vaccination, whichever comes first (OIE 2016). For this study, we have conservatively estimated that 1000 cattle, 5000 sheep or 2000 pigs can be slaughtered (removed through abattoirs) per day. In a large outbreak, it could take some time (many weeks or months) to remove all the vaccinated animals. To illustrate how the relative performance of a vaccinate-and-retain policy compared to vaccinate-and-remove policy is influenced by removal rate, a sensitivity analysis involving removal rate was done. For the Victorian case study, when the rates of removal were doubled, the average total costs under a vaccinate-and-remove (waste) strategy fell to $6359.9m, a saving of $1306.2m compared to the vaccinate-and-retain approach. This finding indicates that if a

vaccinate-and-remove policy is to be applied, consideration should be given to removing vaccinated animals as quickly and as expeditiously as possible. Given that there will be no commercial reason for abattoirs to purchase and slaughter vaccinated animals, consideration will have to be given as to how incentives and subsidies might need to be applied. In addition, the issue of compensation for owners of vaccinated animals that are compulsorily removed will need to be addressed.

It is important to appreciate that in this project we have concentrated on structured surveillance in previously infected areas. The approach does not give an overall probability of being free. In presenting a case for disease freedom, in reality, a range of surveillance activities will contribute to supporting the case for freedom. To present case for being FMD free when multiple sources of surveillance data are used a number of techniques like scenario tree modelling approach (Martin et al. 2007) could be considered to quantify the probability of being free.

47

In addition, the total costs of post-outbreak surveillance are under-estimated here since, although we have identified them, we haven't added in the cost of follow-up investigations for all the positive herds. This will be added to the model following consultation with jurisdictional animal health agencies about the type of investigation and additional testing that would be done in these circumstances. Future enhancements to the model could include algorithms for classifying herds as true or false positives based on the number of reactors found (Cannon 2001). This involves defining a threshold value for the number of positive test results above which the herd is declared positive without retesting. Backer et al. (2012b) used this approach in their modelling study, although, this approach has not been considered compatible with EU directive 2003/85/EC (Anon. 2007).

Note also that the calculation of trade losses in these studies is based on the minimum expected time to regain FMD free status under the OIE guidelines (OIE 2016). This is very simplistic and does not account for the additional time that would be required to negotiate the re-opening of closed export markets (Beutre et al. 2013). Although this approach may be considered adequate to explore relative differences between policies, more work would be required, taking into account different countries' attitudes and approaches to FMD risk, to more realistically estimate the actual time out of markets and the actual costs of the different policies.

This project has developed and demonstrated modelling functionality to support policy development around important issues to facilitate regaining FMD free status and regaining market access after an FMD outbreak. However, the limited nature of these studies and uncertainty around some parameters (especially around some of the costings) means that more work is required before it is possible to provide clear advice and guidelines to disease managers. It is anticipated that the current MLA-CSIRO FMD project funded under the Rural R&D for Profit Program will provide the opportunity to collect better background information, including cost and economic data, and to run a comprehensive set of FMD simulation studies under which different approaches to outbreak control and post-outbreak management can be studied under a wide range of outbreak scenarios.

References

ABARES (2013) Australian Commodities Statistics 12(2) 134-135. http://www.daff.gov.au/abares/publications_remote_content/publication_series/australian_commodities Accessed 8 Jan 2014.

Abdalla A, Beare S, Cao L, Garner G and Heaney A (2005) *Foot and mouth disease: Evaluating alternatives for controlling a possible outbreak in Australia*. ABARE eReport 06.6, Canberra, April

Akashi H. (2012) The 2011 foot and mouth disease outbreak in Miyazaki Prefecture. *Journal of Disaster Research* 7: 252-257.

Anon. (2007) Report of Workshop on the design and interpretation of post foot-and-mouth disease (FMD) – vaccination serosurveillance by NSP tests Part I (dense cattle-pig countries). 23-25 January 2007. EPIZONE, EFMD (FAO).

Arnold ME, Paton DJ, Ryan E, Cox SJ and Wilesmith JW (2008) Modelling studies to estimate the prevalence of foot-and-mouth disease carriers after reactive vaccination. *Proceedings Royal Society B* 275: 107–115

Australia Animal Health Australia (2014) Disease strategy: foot-and-mouth disease (version 3.4). In: Australian Veterinary Emergency Plan (AUSVET-PLAN), third ed. Standing Council on Primary Industries, Canberra, ACT.

Backer JA, Hagenaars TJ, Nodelijk G and van Roermund HJ (2012a) Vaccination against foot-and-mouth disease I: Epidemiological consequences*, Preventive Veterinary Medicine* 107: 27-40.

Backer JA, Engel B, Dekker A and van Roermund HJW (2012b) Vaccination against foot-and-mouth disease II: Regaining FMD-free status. *Preventive Veterinary Medicine* 107: 41-50.

BDA Group. (2009). *The full cost of landfill disposal in Australia*. BDA Group, Canberra, Australia.

Buetre B, Wicks S, Kruger H, Millist N. Yainshet A, Garner G, Dunca, A, Abdalla A, Trestrail C, Hatt M, Thompson LJ and Symes M. (2013) *Potential socioeconomic impacts of an outbreak of foot-and-mouth disease in Australia*, ABARES research report, Canberra, September. CC BY 3.0.

Blower, S. and Dowlatabadi, H. Sensitivity and uncertainty analysis of complex models of disease transmission – an HIV model, as an example. International Statistical Review 1994; 62, 229-243.

Bouma, A, et al. The foot-and-mouth disease epidemic in The Netherlands in 2001. Preventive Veterinary Medicine 2003; 57: 155-166.

Bradhurst RA, Roche SE, Kwan P and Garner MG (2015) A hybrid modelling approach to simulating foot-and-mouth disease outbreaks in Australian livestock. *Front. Environ. Sci*., 19 March 2015 | http://dx.doi.org/10.3389/fenvs.2015.00017

Bradhurst RA, Roche SE, East IJ, Kwan P and Garner MG (2016) Improving the computational efficiency of an agent-based spatiotemporal model of livestock disease spread and control. *Environmental Modelling & Software* 77: 1-12

Brocchi E, Bergmann IE, Dekker A, Paton DJ, Sammin DJ, Greiner M, Grazioli S, De Simone F, Yadin H, Haas B, Bulut N, Malirat V, Neitzert E, Goris N, Parida S, Sorensen K and De Clerq K (2006) Comparative evaluation of six ELISAs for the detection of antibodies to the non-structural proteins of foot-and-mouth disease virus*. Vaccine* 24: 6966-6979.

Cameron A (1999) *Survey Toolbox for Livestock Diseases – A Practical Manual and Software Package for Developing Countries*. Australian Centre for International Agricultural Research, Canberra, Australia. 49

Cannon RM and Roe RT (1982) Livestock Disease Surveys. A Field Manual for Veterinarians. Bureau of Rural Science.

Cannon RM (2001) Sense and sensitivity – designing surveys based on an imperfect test. *Preventive Veterinary Medicine* 49: 141-163.

Caporale V, Giavanni A and Zepeda C (2012) Surveillance strategies for foot and mouth disease to prove absence of disease and absence of virus circulation. Rev. sci. tech. Off. Int. Epiz. 31(3): 747-759.

Commonwealth of Australia (2015) Agricultural Competitiveness White paper, Canberra.

Davies, G. The foot and mouth disease (FMD) epidemic in the United Kingdom 2001. Comparative Immunology, Microbiology & Infectious Diseases 2001; 25:331–343.

Dubé C, et al. A comparison of predictions made by three simulation models of foot-and-mouth disease. New Zealand Veterinary Journal 2007; 55, 280-288.

East IJ, Martin PAJ, Langstaff I, Iglesias RM, Sergeant ESG and Garner MG (2015, accepted for publication) Assessing the delay to detection and the size of the outbreak at the time of detection of incursions of foot and mouth disease in Australia. Preventive Veterinary Medicine 123:1-11.

European Union (2003) Council Directive 2003/85/EC of 29 September 2003 on Community measures for the control of foot-and-mouth disease repealing Directive 85/511/ EEC and Decisions 89/531/EEC and 91/665/EEC and amending Directive 92/46/EEC.

Feir-Walsh, B.J. and Toothaker, L.E. (1974) An empirical comparison of the ANOVA F-test, normal scores test and Kruskal-Wallis test under violation of assumptions. Educational and Psychological measurement. 34: 789-799.

Garner, M. G., Allen, R. T., and Short, C. (1997), *Foot-and-mouth disease vaccination : a discussion paper on its use to control outbreaks in Australia*. Bureau of Resource Sciences, Canberra.

Garner MG, Bombarderi N, Cozens M, Conway ML, Wright T, Paskin R and East IJ (2014), Estimating Resource Requirements to Staff a Response to a Medium to Large Outbreak of Foot and Mouth Disease in Australia. *Transboundary and Emerging Diseases*. doi: 10.1111/tbed.12239

Garner MG, Hamilton SA. Principles of Epidemiological Modelling. Revue Scientifique et Technique Office International des Epizooties 2011; 30, 407-416.

Geale DW, Barnett PV, Clarke GW,Davis J and Kasari TR (2015). A review of OIE country status recovery using vaccinate-to-live versus vaccinate-to-die foot-and-mouth disease response policies II: waiting periods after emergency vaccination in FMD free countries. *Transboundary and Emerging Diseases*. Doi: 10.1111/tbed. 12165.

Keeling MJ, Woolhouse ME, May RM, Davies G and Grenfell BT (2003) Modelling vaccination strategies against foot-and-mouth disease. *Nature* 421: 136-142.

Kitching RP and MacKay DKJ. (1998). New developments in foot-and-mouth disease diagnosis (IAEA-TECDOC--1055). International Atomic Energy Agency (IAEA).

Kittelberger R, Mackereth GF, Sewell M, Keall J, Clough R, Pigott C and O'Keefe JS (2008) Specificity of non-structural protein enzyme-linked immunosorbent assays for the detection of serum antibodies against foot-and-mouth disease virus in a target population *New Zealand Veterinary Journal* 56: 227-232.

Kobayashi M, et al. A dynamic, optimal disease control model for foot-and-mouth disease: I. Model description Preventive Veterinary Medicine 2007; 79, 257–273

Martin PAJ, Cameron AR and Greiner M (2007) Demonstrating freedom from disease using multiple complex data sources 1: A new methodology based on scenario trees. *Preventive Veterinary Medicine* 79: 71–97.

Martin PAJ, Langstaff I, Iglesias RM, East IJ, Sergeant ESG, Garner MG (2015) Assessing the efficacy of general surveillance for detection of incursions of livestock diseases in Australia. Preventive Veterinary Medicine http://dx.doi.org/doi:10.1016/j.prevetmed.2015.06.017

Matthews K. (2011) *A review of Australia's preparedness for the threat of foot and mouth disease*. Australian Government Department of Agriculture, Fisheries and Forestry, Canberra. http://www.daff.gov.au/ animal-plant-health/pests-diseases-weeds/animal/fmd/review-foot and-mouth-disease

McClaskey J, Fox J, Marsh TL, Nutsch A, Kastner J, Doering O and Foster K (2004). Economic and cost considerations. In: Carcass Disposal: A Comprehensive Review. Report of the National Agricultural Biosecurity Center Consortium, USDA APHIS Cooperative Agreement Project, Kansas State University.

MLA (2016) *Market snapshot – Beef*, MLA Industry Insight Series, Meat and Livestock Australia, Sydney.

Moonen P and Schrijver R (2000) Carriers of foot-and-mouth disease virus: a review. *Veterinary Quarterly* 22: 193-197.

OIE (2012) *Manual of Diagnostic Tests and Vaccines for Terrestrial Animals*. 7th Edition,. Paris: World Organisation for Animal Health 2012 (http:// http://www.oie.int/international-standard-setting/terrestrial-manual/access-online/)

OIE (2016) *Infection with foot and mouth disease virus*. Chapter 8.8. In:Terrestrial Animal Health Code Edition 25. Paris: World Organisation for Animal Health, 2016 (http://www.oie.int/en/international-standard-setting/terrestrialcode/).

Parida S (2009) Vaccination against foot-and-mouth disease: strategies and effectiveness. *Expert Review of Vaccines* 8: 347-365.

Parthiban ABR, Mahapatra M, Gubbins S and Parida S (2015) Virus excretion from foot-and-mouth disease virus carrier cattle and their poptential in causing new outbreaks. PLOS One. DOI10.1371/journal .pone.0128815. June 25 2015.

Paton DJ, de Clerq K, Greiner M, Dekker A, Brocchi E, Bergmann I, Sammin DJ, Gubbins S and Parida S (2006). Application of non-structural protein antibody tests in substantiating freedom from foot-and-mouth disease virus infection after emergency vaccination of cattle. *Vaccine* 24: 6503-6512.

Paton DJ, Füssel A-E, Vosloo W, Dekker A and De Clercq K (2014) The use of serosurveys following emergency vaccination, to recover the status of "foot-and-mouth disease free where vaccination is not practised". Vaccine 32: 7050–7056.

Roche SE, Garner MG, Wicks RM, East IJ, de Witte K (2013). How do resources influence control measures during a simulated outbreak of foot and mouth disease in Australia? *Preventive Veterinary Medicine* 113: 436–446.

Roche SE, Garner MG, Sanson RL, Cook C, Birch C, Backer JA, Dube C, Patyk KA, Stevenson MA, Yu ZD, Rawdon TG and Gauntlett F. (2014) Evaluating vaccination strategies to control foot-and-mouth disease: a model comparison study. *Epidemiology and Infection* 143: 1256-1275

Sakamoto K (2012) Mechanism of FMD outbreaks and its control in Asian region. *Journal of Disaster Research* 7: 258-263.

Salt JS (1993) The carrier state in foot and mouth disease – an immunological review. *The British Veterinary Journal* 149: 207-233.

Sanson RL, Rawdon T, Owen K, Hickey K, van Andel M and YU ZD (2017) Evaluating the benefits of vaccination when used in combination with stamping out measures against hypothetical introductions of foot-and-mouth disease into New Zealand: a simulation study *New Zealand Veterinary Journal* 65: 124-133.

Sanson RL, et al. Foot and mouth disease model verification and 'relative validation' through a formal model comparison. Revue Scientifique et Technique Office International des Epizooties 2011; 30, 527-540.

Schmider, E., Ziegler, M., Danay, E., Beyer, L. And Buhner, M. (2010) Is It Really Robust? Reinvestigating the Robustness of ANOVA against violations of the normal distribution assumption. *Methodology* 6(4):147–151.

Schuppers ME, Stegeman JA, Kramps JA and Stärk KDC (2012) Implementing a probabilistic definition of freedom from infection to facilitate trade of livestock trade: Putting theory into praxis for the example of bovine herpes virus-1. *Preventive Veterinary Medicine* 105: 195-201. 51

Sergeant ESG (2017) *Epitools epidemiological calculators*. Ausvet Pty Ltd. Available at http://epitools.ausvet.com.au

Tomassen FH, de Koeijer A, Mourits MC, Dekker A, Bouma A and Huirne RB (2002). A decision-tree to optimise control measures during the early stage of a foo-and-mouth disease epidemic. *Preventive Veterinary Medicine* 54: 301-324

USDA (2015) Foot-and-mouth disease (FMD) response ready reference guide – Overview of FMD freedom and vaccination. http://www.aphis.usda.gov/animal_health/emergency_management/downloads/fmd_rrg_freedom_and_vaccination.pdf. Accessed 3 May 2017.

Willeberg P (2012) Simple decision tools informed by model predictions when considering FMD emergency vaccination strategies. 2012 Open Session of the EuFMD Standing Technical Committee. Jerez, Spain, 29-31 October 2012. http://www.fao.org/fileadmin/user_upload/eufmd/docs/Open_Session2012/Appendices/12_Simple_decisions_tools_informed_by_model_predictionswhen_considering-FMD_emergency__P-Willeberg_P.Willeberg.pdf

CEBRA FMD post-outbreak surveillance: Workshop report

Monday 29 August 2016
M.2.02, 18 Marcus Clarke St, Canberra

Purpose

This workshop was held to enable stakeholder discussion around the CEBRA project: "Incorporating economic components in Australia's foot-and-mouth disease (FMD) modelling capability and evaluating post-outbreak management to support return to trade". The workshop brought together policy-makers, disease-managers, researchers and an industry representative to discuss the requirements for enhancing the Australian Animal Disease Model (AADIS) to enable simulation modelling of foot-and-mouth disease post-outbreak surveillance in Australia.

Agenda

A copy of the agenda is at attachment A.

Participants

A list of participants and their affiliation is at attachment B.

Pre-workshop discussion document

A copy of the pre-workshop discussion document is at attachment C.

Objectives of the workshop

1) Identify the key requirements to address post-outbreak management issues both where vaccination has and has not been used in the response. Considerations include diagnostic tools, surveillance strategies and approaches to managing vaccinated animals.
2) Agree on a small set of study scenarios to test AADIS modifications.

Morning session - presentations:

In the morning session, the group was presented with background information relevant to the CEBRA project. The facilitator (Nick Housego) opened the workshop with a welcome and a brief statement on the purpose for the day. The aim of the morning session was to inform participants of elements for consideration relevant to simulating the cost of post-outbreak surveillance, outline current approaches, and highlight areas of uncertainty.

Context setting introduction

Robyn Martin welcomed everyone to the workshop and commented that the degree of complexity surrounding the project was reflected by the combination of skills in the room (virologists, other technical experts such as software engineers, epidemiologists, economists; as

well as federal and jurisdictional disease-managers and decision-makers, policy-makers and an industry representative). She outline how the department has actively invested in epidemiological simulation modelling with the development of 'AusSpread' by Graeme Garner, and recently AADIS by Richard Bradhurst. Our collaborations with CEBRA have enabled us to address questions that can inform preparedness and response policies. We recognise FMD as an important economic disease, and we know that we need to look beyond the technical aspects of control to address issues of how we would recover from an outbreak. We must also consider animal welfare and the public perception of response activities. There are key issues around post-outbreak surveillance and vaccination about which we need to be proactive, in order to make balanced assessments of our options in 'peace-time', not during the heat of a response. Thorough consideration of these issues in advance will enable us to robustly simulate various strategies, which should enhance our decision-making capability and enable return to trade as quickly as possible in the event of an outbreak.

Robyn introduced our four key questions for the day. In the event of an Australian FMD outbreak:

1) What surveillance will be necessary to demonstrate freedom?
2) How will we manage vaccinated animals?
3) What economic information do we need to make decisions about the most cost-efficient management strategy?
4) What can't we control?

Background and evolution of the project

Graeme Garner discussed the need for consideration of how best to manage a vaccinated population subsequent to an FMD outbreak in Australia, and presented an overview of the department's FMD simulation modelling and related CEBRA work to date. He outlined that the purpose of the current project and workshop is to identify the functionality required to address post-outbreak management issues with the AADIS model, in order to enable simulation of the most cost-efficient approach of returning to trade. Graeme also outlined a new CSIRO led 'Rural R&D for Profit' project that will build on the model development that occurs during this CEBRA project.

Economics of FMD management

Tom Kompas talked about previous CEBRA work that looked at the economics of FMD surveillance in Australia. He explained how their models allowed investigation of the inevitable trade-off between cost of testing and cost of the outbreak. Bulk milk testing was not found to be economical for pre-incursion/early detection surveillance, but in an outbreak it could be very useful and likely to be cost-efficient. Tom outlined the three options for managing vaccinated animals: vaccinated-to-live, vaccinate-to-remove (to waste) or vaccinate-to-remove (to salvage). Discussion after Tom's presentation highlighted the need for "market access" to be considered on a more subtle scale that binary i.e. there would be loss of market share that would require modelling.

OIE proof-of-freedom requirements

Wilna Vosloo outlined the current global situationin relation to FMD, and the requirements to be met to regain FMD-free status with the OIE following an outbreak in a non-endemic country. If vaccination is not used, there is a three month waiting period (after removal of the last infected animal) before application to regain free status can be made. With vaccination, as long

as all vaccinated animals are removed, this period does not increase , but if vaccinated animals are retained, the waiting period increases to six months (and surveillance is required to demonstrate no evidence of infection in the remaining vaccinated population). Recent experience is that all the non-endemic countries that have used emergency vaccination have followed a vaccinate-to-remove policy and then re-applied for status of: "Free country/zone where vaccination is not practiced". The NSP ELISA has high specificity, but is less sensitive in vaccinated cattle that have been subsequently infected (therefore you need to survey more animals; potentially all of them). The point was made that lost trade will most likely not return based on OIE approval alone, but on bilateral missions and subsequent negotiations. It is more complex to prove freedom when vaccination is used, and you cannot trade vaccinated animals in FMD-free markets. Carrier animals are low risk but not no risk; don't find antibodies after a point in time (they are completely cleared).

Overview and demonstration of the AADIS model

Richard Bradhurst described the development of the AADIS model and the technical aspects of its capability. It is a national scale model that uses herds as the unit of interest and is highly computationally efficient. It is described as a hybrid model, combining a population-based model (equation based – EBM) to represent within-herd spread and an individual-based model (agent based – ABM) to represent between-herd spread and the control and eradication of disease. Richard demonstrated the model for the group, stepped through a simulation, talked through the elements that the user can parameterise and manipulate, as well as discussing approaches to analysis of the model output.

Proof-of-freedom surveillance:

Whole group discussion:

Clare Death and Richard Bradhurst stepped through a hypothetical FMD outbreak scenario prepared using the AADIS model. This scenario revolved around a small outbreak that did not involve the use of vaccination, designed to stimulate discussion about the baseline process of surveillance that would be required when preparing a proof-of-freedom dossier to submit to the OIE. Even though this CEBRA project will be based on the assumption that vaccination will be used, it was considered appropriate to first consider 'baseline' proof-of-freedom surveillance and then discuss how this would vary following vaccination.

There was a consensus that jurisdictions would await CCEAD direction and approval of their proposed surveillance strategies, and that there would be an expectation from trading partners that we have national level surveillance data regardless of how small/localised the outbreak was. The group did not feel that making efforts to compartmentalise the outbreak would be beneficial if it drew resources away from control and general proof of freedom efforts. In relation to proof-of-freedom surveillance, there would be a great deal of data including exclusion testing results (from clinical investigations and tracing) collected during the control phase.. We would emphasise the importance and quality of our livestock traceability system and use this to support a lack of epidemiological evidence of any further spread outside the known infected areas.

It was thought that we would use evidence from enhanced clinical surveillance in abattoirs and saleyards nationwide. In addition, jurisdictions becoming confident enough to start accepting

trade from each other would provide a large amount of data (and confidence to trading partners). There was concern expressed around how to manage feral animals, wildlife, and lack of reporting and compliance in peri-urban smallholders. There was general confidence that our laboratory capability will be adequate to cope with the volume of samples, but that collecting the samples would likely take longer than processing them.

Management strategies following emergency vaccination

Breakout group discussions:

Clare and Richard presented a second hypothetical scenario using the AADIS model. This scenario was larger and involved the use of emergency vaccination in the control period. Participants were divided into 3 groups to discuss the different strategies for managing vaccinated animals. They were asked to consider how proof-of-freedom surveillance would differ from baseline, and they were asked not to focus on concerns out of their control such as political pressures, trading partner reactions, etc. Groups then presented their thoughts back to the group. The 3 scenarios were:

1) Vaccinate-to-remove (to waste)
2) Vaccinate-to-remove (to salvage, domestic consumption, etc.)
3) Vaccinate-to-live

Vaccinate-to-remove (to waste)

- Policy: The group raised the concern that there isn't any legislation that enables authorities to compulsorily acquire and slaughter non-infected vaccinated animals, and expressed uncertainty about the policies for managing offspring of vaccinates and collection of genetic material from vaccinates. There were also questions about whether vaccinates could be culled before the 21-day mark, and about which species would require surveillance.
- Surveillance/sampling strategy (resources/logistics): The group discussed whether or not animals would be transported to slaughter facilities and then disposed of and, if so, what would be the movement restrictions and pre-movement sampling required? It was acknowledged that disposal capacity, methods and costs would vary by region and jurisdiction. In relation to proof-of-freedom surveillance strategy, it was noted that there would be exclusion data gained during the process of suppressive ring vaccination, as stock would all be clinically examined. The group also felt that there would inevitably need to be a buffer zone of tested animals around the vaccination zone.
- Diagnostics: It was thought that we should utilise pooled sampling methods such as bulk milk testing in high density/high risk areas.
- Public perception: It was thought that the public perception of destroying healthy animals to waste rather than salvage would be even more negative/difficult to "sell", and that there would be environmental considerations with mass disposal. It was thought that if vaccination was limited to high risk areas then the numbers of animals requiring destruction, and the subsequent public backlash, would be less.
- Costs/economic variables we must account for:
    - Cost of identifying vaccinated animals.
    - Surveillance costs.
    - Pre-movement sampling.
    - Transport costs (need the CA/RA to include abattoir, can the model ensure this?)
    - Destruction and disposal costs (abattoir throughput).

- Compensation costs (market value or future genetic potential?).
- Legal challenge costs and subsequent delays.
- Public communication costs.
- Need to model the welfare cull process.

Vaccinate-to-remove (to salvage)

- Policy: The group felt that salvage to domestic consumption would only be a viable option in a small outbreak, and suspected that it would not be cost effective considering the extra processing costs and the reduced price of the product. To enable slaughter for domestic consumption, we would also need to make sure that declared areas included abattoirs. It was thought that domestic abattoirs wouldn't be able to handle the volume, and that there may be some unwillingness for export abattoirs to be involved due to perceived risk of contamination.
- Surveillance/sampling strategy (resources/logistics): The group agreed that there would need to be census sampling of all vaccinates and their offspring, as well as in-contact animals, and that pre-movement surveillance would be required. This targeted surveillance would be required before any vaccinated animals were moved, in addition to on-going passive surveillance at abattoirs. There was consensus that once vaccinates are removed, the proof-of-freedom survey is no different to a non-vaccination strategy.
- Diagnostics: It was thought that sampling costs would be lower than a vaccinate-to-live strategy, but it would be necessary to follow up all reactors.
- Public perception: The group expressed uncertainty about whether the domestic market would buy products from vaccinated animals, and emphasised that there would need to be a great deal of public communication.
- Costs/economic variables we must account for:
  - Survey visit (teams) and laboratory costs.
  - Pre-movement inspection and testing costs.
  - Salvage value of animals.
  - Abattoir/knackery capacity and compensation to facilities that process FMD animals.
  - Management of product for human consumption – infrastructure, storage, supply chains, etc.

Vaccinate-to-live

- Policy: The general feeling was that this strategy would be very difficult and very expensive, and that it would be unlikely to represent value for money. Which generation of offspring from the vaccinated zones would we be able to call "unaffected"? The difficulties with permanent identification and compliance relating to ongoing movement restrictions for vaccinates were raised. It was noted that we need a national policy for vaccinated animals, including thresholds for action if some animals within test positive to non-structural protein (NSP) tests. There was discussion about distribution maps for feral animals, but the thought was that we would use commercial herds as sentinels to demonstrate lack of disease in free-ranging animals, in addition to incentives for hunters to participate in surveillance.
- Surveillance/sampling strategy (resources/logistics): Census surveillance of all vaccinates would be required and follow-up surveillance would be required to check on reactors/potential carriers. Suppressive vaccination would mean many vaccinated animals will also be exposed to infection, so they will seroconvert and test positive to NSP tests.

- Diagnostics: There would be a role for new technologies if this route was chosen i.e. PCR tests on pooled samples to demonstrate absence of circulating virus. This could also be used during an outbreak to add confidence that an in-contact (DCP) farm was never infected, which would add to the strength of a post-outbreak proof-of-freedom dossier.
- Public perception: It was acknowledged that this would be an easier story to sell to the public, but we would want to be able to explain how expensive it could be for Australia. It could be seen as an opportunity to retain rare and genetically valuable stock. However there was uncertainty about whether consumers would want milk/beef from vaccinates, or would these products be diverted to pet food, etc.?
- Costs/economic variables we must account for:
    - Disposal of unwanted product or costs of extra treatment (e.g. milk).
    - Number of tests required and costs of each test i.e. costs of surveillance.
    - Length of time before return to "free" status i.e. cost of being out of markets.
    - Ongoing monitoring and tracing costs of vaccinates.
    - Discounted value of products from vaccinates i.e. what is the salvage value? What is the value of exporting to non-sensitive markets?
    - Disposal of reactors.
    - Would need to know which species we planned to vaccinate in which areas to assess cost of vaccination program and subsequent management costs.
    - Transport costs.
    - Compensation claims by sideline industries.
    - Compliance costs.
    - Costs of public communication.
    - Legal costs.
    - Cost of retaining a low value animal.
    - The longer we are of markets potentially the harder it will be to regain access.

What can't we control?

- Domestic market acceptance of meat (can aim to have good communication, but hard to predict response).
- Market price of products from vaccinated animals.
- Abattoir capacity and location – need to model these aspects.
- Trading partner reactions/requirements; impact on reputation.
- Public perception of FMD as a health threat.
- Political lobbying and pressures.
- Difficult to control vaccinated animals long term i.e. compliance.

Afternoon session: case studies for modelling

Participants were divided into 3 groups to discuss a case study, which they then proposed for consideration. Each group was asked to think about the incursion scenario and the outbreak scenario, and for each of these situations each of the three management scenarios (i.e. vaccinate-to-live, vaccinate-to-remove to waste or salvage) could be modelled to enable comparison of costs.

1 – Gippsland, Victoria

This group would like to see a large outbreak modelled in Gippsland, Victoria, with detection on Day 14, where outbreak management involved culling of IPs but not DCPs. The state is initially the CA, until delimiting surveillance and tracing are completed, with a minimum RA of 3km.

Vaccination would occur in cattle only (plus sheep on mixed properties). They would like to model a central national vaccination repository, and suppressive outwards-in ring vaccination with 3km radius (or they suggested a vaccine "buffer line" down the side of Gippsland). They would like to consider modelling the use of the ADF and IAHER capability if possible.

2 – Bunbury, WA

Incursion via the port in Fremantle (contaminated stockfeed/malicious intent), with detection of Day 21. The scenario ideally involves the disease being detected in sheep at an abattoir, following a saleyard event. Assume no jurisdictional sharing initially, but perhaps later once other states are comfortable that they are free. Initially the entire state would be the CA, reducing to most of the southern half of the state; the RA size would have to be scoped during the standstill. There would be targeted vaccination, of cattle (and sheep on mixed properties) only. Would like to model giving resource teams two days off after five days on. Would like to model all samples/serology being managed in state.

3 – Darling Downs, Qld

A modification of Exercise Slapstick. The group would like it to include a large piggery and a saleyard event, perhaps Roma. Vaccination would involve a 3km suppressive ring of cattle only (no pigs or sheep vaccinated, and uncertainty about feedlots – could we model providing incentives to cull instead?), only 100,000 doses available. The RA would initially be 20km, the CA would start at 10km then reduce to 5km. The group are keen to have cross-border cost sharing modelled.

Timeline

A timeline of the project moving forward was shared:

- A workshop report will be prepared and circulated for comment.
- The project team will distil the information needs into functional requirements for the model development.
- Sep – Oct 2016: Modifications to AADIS to incorporate post-outbreak management
- Nov – Dec 2016: Complete model simulations **SHARE WITH GROUP**
- Jan – Mar 2017: ANU to run economic analysis on model output
- Apr – May 2016: Generate final project report
- Jun 2017: Project conclusion

The group agreed that they would like to be informed about the results that are obtained from their case study suggestions.

Participants were thanked for their attendance and the meeting was closed at 15:30.

Attachment A- Agenda

CEBRA FMD post-outbreak surveillance workshop: Agenda

29 August 2016 – Room M.2.02

Department of Agriculture and Water Resources, 18 Marcus Clarke St, Canberra

Time	Activity	Lead
8:25	Meet in foyer for security sign-in	Clare Death
8:30	Introduction and housekeeping	Facilitator
8:45	Context: why we are here today	Robyn Martin
9:00	Background and evolution of the project	Graeme Garner
9:15	Economics of FMD management	Tom Kompas
9:30	OIE proof-of-freedom requirements	Wilna Vosloo
9:45	Overview and demonstration of the AADIS model	Richard Bradhurst
10:15	**Morning tea**	
10:45	Proof-of-freedom surveillance	Facilitated discussion
11:30	Surveillance following vaccination: variations	Group discussions
12:30	**Lunch (working lunch)**	
1:15	Focus on our 4 key questions	Group discussions
2:00	Highlight uncertainties & discuss main considerations requiring modelling	Facilitated discussion
	Afternoon tea	
2:30	Proposed case studies: what economic information do we require?	Facilitated discussion
3:15	Wrap-up & next steps	Facilitator

3:45	**Finish**

Attachment B- Participants and affiliation

Name	Contact details:
Facilitator: Nick Housego	Department of Agriculture and Water Resources Nick.Housego@agriculture.gov.au
Allison Crook	Biosecurity Queensland, Department of Agriculture and Fisheries **Allison.Crook@daf.qld.gov.au**
Belinda Wright	Animal Health Australia bwright@animalhealthaustralia.com.au
Bill Matthews	Department of Agriculture and Water Resources Bill.Matthews@agriculture.gov.au
Clare Death	Department of Agriculture and Water Resources Clare.Death@agriculture.gov.au
Corissa Miller	Department of Agriculture and Water Resources Corissa.Miller@agriculture.gov.au
Graeme Garner	Department of Agriculture and Water Resources Graeme.Garner@agriculture.gov.au
Iain East	Department of Agriculture and Water Resources Iain.East@agriculture.gov.au
Iain Mclaren	Department of Economic Development, Jobs, Transport and Resources Iain.Mclaren@ecodev.vic.gov.au
Justin Toohey	Cattle Council of Australia justin@j2e.com.au
Haidee Hudson	Department of Agriculture and Water Resources Haidee.Hudson@agriculture.gov.au
Richard Bradhurst	Centre of Excellence for Biosecurity Risk Analysis (CEBRA)

	Richard.Bradhurst@unimelb.edu.au
Robyn Martin	Department of Agriculture and Water Resources Robyn.Martin@agriculture.gov.au
Sal Thompson	Department of Agriculture and Water Resources Sal.Thompson@agriculture.gov.au
Tim Capon	CSIRO Tim.Capon@csiro.au
Tom Kompas	Centre of Excellence for Biosecurity Risk Analysis (CEBRA) Tom.Kompas@unimelb.edu.au
Van Ha Pham	Australian National University ha.pham@anu.edu.au
Wilna Vosloo	Australian Animal Health Laboratories (CSIRO) wilna.vosloo@csiro.au

Apologies: Sam Hamilton, Jef Hammond

Workshop discussion groups:

Green (VTR - waste)	Blue (VTR – salvage)	Red (VTL)
Clare Death Iain Mclaren Justin Toohey Robyn Martin Tim Capon	Belinda Wright Bill Matthews Corissa Miller Iain East Tom Kompas Wilna Vosloo	Allison Crook Graeme Garner Honor Calnan Sal Thompson Van Ha Pham

Attachment C- Pre-workshop discussion paper

'Incorporating economic components in Australia's FMD modelling capability and evaluating post-outbreak management to support return to trade'

Prepared by Clare Death and Graeme Garner

Background

Foot-and-mouth disease (FMD) is recognised as the single greatest disease threat to Australia's livestock industries (Matthews 2012). Early detection of an incursion, effective control of an outbreak and rapid return to trade are essential to minimise the economic impact of diseases like FMD. Australia's policy for an FMD response is to contain, control and eradicate the disease in order to re-establish the FMD-free status of Australia as quickly as possible, while minimising social and financial disruption. The Australian Veterinary Emergency Plan (AUSVETPLAN) states that the 're-establishment of trade for affected industries would be of the highest priorities of disease response efforts' (Animal Health Australia 2014).

Although vaccination is increasingly being recognised as an important tool to assist in containing and eradicating FMD outbreaks (Roche et al. 2014), it will make achieving recognition of free status more difficult—keeping vaccinated animals in the population will delay the period until FMD-free status is regained under the World Organisation for Animal Health (OIE) guidelines and add additional complications to the post-outbreak surveillance program. If vaccination is used in the control program subsequent actions will depend on how the vaccinated population is managed.

There is no agreed approach to post-outbreak management of vaccinated animals in AUSVETPLAN with the options being to: (1) allow vaccinated animals to remain in the population to live out their normal commercial lives (*vaccinate-to-live*); (2) remove all vaccinated animals from the population (*vaccinate-and-remove*). Under option 2, vaccinated animals could be subject to (a) slaughter to waste i.e. remove and dispose of vaccinated animals; or (b) slaughter and salvage i.e. attempt to sell either raw or processed product from vaccinated animals. For (b) there may be some residual value of products that could offset some of the costs.

Determining the best approach to regaining FMD-free status will depend on the nature of the outbreak and an economic evaluation of the different options. There have been studies looking at the importance of early detection, (e.g. Martin et al. 2015, East et al. 2015) and Australia has nationally agreed plans for responding to FMD (Animal Health Australia 2014). However, there has been relatively little investigation of post-outbreak management and return to trade despite the major component of the costs associated with an FMD outbreak being the time out of markets (Beutre et al 2013).

To support policy development on FMD, the Department of Agriculture and Water Resources has invested in developing sophisticated FMD modelling capability (initially through AusSpread and more recently through the Australian Animal Disease Spread Model – AADIS). However, along with most epidemiological models in use, outbreak simulations in AADIS end when the

last infected premises has been removed and therefore it has limited capability to address post-outbreak issues.

The focus of this project is to address this limitation in order to enable studies to support policies that enhance early return to trade. This CEBRA project will explore and identify the components and elements required in decision-support systems to support post-outbreak management. The project will expand the department's modelling capability to represent post-outbreak activities (surveillance for proof of freedom, management of vaccinated animals) and economic components. This project compliments work planned under a longer-term Rural R&D for Profit funded project being run by CSIRO. The main focus of this study will be to identify and prototype the modelling capability required to be able to study post-outbreak management issues around surveillance and vaccination. Given the time and resource constraints this project will only look at a small number of selected scenarios for demonstration purposes. In contrast the CSIRO project will provide an in-depth assessment and analysis of a more extensive range of post-outbreak management to regain FMD-free status and early return to trade.

Purpose of the workshop

At the workshop, stakeholders will:

1) Identify the key requirements to address post-outbreak management issues both where vaccination has not and has been used in the response. Considerations include:

- diagnostic tools
- surveillance strategies
- approaches to managing vaccinated animals.

Discussion will focus on the information required by decision-makers e.g. we might need to know:

- How effective are our diagnostic tools?
- What level of assurance is provided by different surveillance strategies/approaches?
- What are the cost/resource implications?
- What is the risk that residual infection/sero-positive animals may remain in the population?
- What are the costs and benefits of different approaches to managing vaccinated animals?

This information will be used to build post-outbreak module(s) to be added to AADIS

2) Agree on a small set of study scenarios to test AADIS modifications:

- The type of outbreak(s) (source, location, time to detection and management response).
- The type/scope of the post-outbreak surveillance.
- The approaches to managing vaccinated animals to be considered.

The outcomes from (1) will be used to modify the AADIS model with addition of new post-outbreak module(s). It is important that we have a good understanding of needs, expectations, technical requirements, etc. so that this module is designed with sufficient flexibility to enable us to assess different surveillance/management regimes in terms of costs and effectiveness.

The outcomes from (2) will be used to set up some plausible study scenarios to test the ability of the modified model to produce useful information and insights to support policies on post-outbreak issues.

Discussion will focus around technical and policy areas that may require further clarity. We are keen to brainstorm and come to a consensus on the key issues e.g.:

- What information do disease managers need to make decisions on:
  - Appropriate surveillance approaches to support proof of freedom.
  - How to best manage vaccinated animals (when vaccination has been used in a response).
- What are the socio-economic factors that need to be considered?

Modelling work to date, and current baseline scenarios

Previous work using AADIS in international modelling comparison studies (via the Quads EpiTeam) and CEBRA projects has enabled detailed exploration of appropriate model configuration for studying the potential value of vaccination in Australian FMD outbreaks. Vaccination has been shown to be most effective when:

- disease is spreading actively
- resources are inadequate to maintain effective surveillance and stamping out operations
- used early in a response.

Much of our previous work has focused on outbreaks starting in south-eastern Australia as this region is considered at higher risk for introduction, establishment and spread of FMD (although we have also recently looked at a number of QLD outbreak scenarios). The size of an outbreak will be influenced by time of year that an incursion occurs and the time taken for the first case to be reported.

Some other considerations when using vaccination are:

- Type of vaccine and vaccination strategy i.e. retrospective, suppressive vs protective (generally suppressive ring vaccination has been found to be more effective), size of vaccination rings?
- Species to be vaccinated (all species vs limited to specific species or farm types)?
- All areas or restricted to pre-specified 'high risk' areas?
- Vaccine doses available (limited to our bank vs assuming more vaccine will be able to be accessed). How will vaccine be divided amongst jurisdictions?
- Vaccination capacity (rate at which animals can be vaccinated). Do we assume lay vaccinators will be used?
- Management of vaccinated animals (compulsory ID, movement restrictions, etc.)
- What restrictions (if any) will apply to vaccinated animals after the outbreak.

Post-outbreak surveillance scenarios

Following an outbreak of FMD, surveillance will be required to demonstrate that infection has been eradicated from the population and enable any remaining movement restrictions to be lifted within the country (Attachment C1). Proof of freedom will be needed to satisfy trading partners and regain access to international markets. To regain its FMD-free status after an outbreak Australia will need to meet international animal health guidelines which include

minimum time periods since the last case of disease, and appropriate surveillance aimed at identifying disease and FMD infection or transmission, including presence of carriers if a vaccinate-to-live policy is undertaken (OIE 2015). The AUSVETPLAN FMD strategy, Appendix 2, sets out some principles for designing a post-outbreak surveillance program but lacks clear guidance on how to go about this (Animal Health Australia 2014).

> *'To provide confidence that FMDV is no longer circulating a comprehensive surveillance program will be required. This will need to be carefully designed and followed to ensure that it produces sufficient data that are reliable and acceptable to the OIE and international trading partners, while avoiding a program that is excessively costly and logistically complicated. The surveillance program will build on surveillance, tracing and diagnostic testing done during the control phase. The post-outbreak surveillance program should include clinical and serological surveillance, and targeted and random components.'*

Some of the potential approaches we could consider include:

- looking at what other countries have done
- EU directives
- new technical approaches (diagnostic tests, use of containment zones, etc.).

Workshop outcomes

At the end of the workshop we hope to have reached a consensus on the key issues and assumptions that stakeholders believe require consideration in the new post-outbreak decision-support modules of the AADIS model. The project will then be able to follow-up with development of new modules to enable post-outbreak management approaches to be studied.

References

Animal Health Australia (2014) Disease strategy: foot-and-mouth disease (version 3.4). Australian Veterinary Emergency Plan (AUSVETPLAN), Edition 3, Agriculture Minister's Forum, Canberra, ACT.

Anon (2003) Council Directive 2003/85/EC on Community measures for the control of foot-and-mouth disease repealing Directive 85/511/EEC and Decisions 89/531/EEC and 96/665/EEC and amending Directive 92/46/EEC. Official Journal of the European Union L306, Volume 46, 22 November 2003.

Bradhurst RA, Roche SE, Kwan P and Garner MG (2015) A hybrid modelling approach to simulating foot-and-mouth disease outbreaks in Australian livestock. *Frontiers in Environmental Science*, 19 March 2015 dx.doi.org/10.3389/fenvs.2015.00017

Buetre B, Wicks S, Kruger H, Millist N, Yainshet A, Garner G, Dunca, A, Abdalla A, Trestrail C, Hatt M, Thompson LJ and Symes M (2013) Potential socioeconomic impacts of an outbreak of foot-and-mouth disease in Australia, ABARES research report, Canberra, September. CC BY 3.0.

Commonwealth of Australia (2015) Agricultural Competitiveness White paper, Canberra (agwhitepaper.agriculture.gov.au).

East IJ, Martin PAJ, Langstaff I, Iglesias RM, Sergeant ESG and Garner MG (2015) Assessing the delay to detection and the size of the outbreak at the time of detection of incursions of foot and mouth disease in Australia. *Preventive Veterinary Medicine* 123: 1-11.

OIE (2015) Terrestrial Animal Health Code Edition 24. Paris: World Organisation for Animal Health, 2015, oie.int/en/international-standard-setting/terrestrialcode/). Accessed 20 December 2015.

Martin PAJ, Langstaff I, Iglesias RM, East IJ, Sergeant ESG, Garner MG (2015) Assessing the efficacy of general surveillance for detection of incursions of livestock diseases in Australia. *Preventive Veterinary Medicine,* dx.doi.org/doi:10.1016/j.prevetmed.2015.06.017

Roche SE, Garner MG, Sanson RL, Cook C, Birch C, Backer JA, Dube C, Patyk KA, Stevenson MA, Yu ZD, Rawdon TG and Gauntlett F (2014) Evaluating vaccination strategies to control foot-and-mouth disease: a model comparison study. *Epidemiology and Infection* 143: 1256-1275

Attachment C1: Considerations for post-outbreak management

To accommodate post-outbreak surveillance, the model will need to 'keep track' of all recovered animals that are not removed during control operations and all vaccinated herds, including their infection status and any animal movements.

Different approaches to accommodate post-outbreak management need to be considered depending on whether vaccination is used or not.

1 **Proof-of-freedom surveillance:**
   i. will need to occur whether or not vaccination has been used in order to regain market access, and questions will include:
      - When does the outbreak end (does surveillance start 30 days after the last IP has been culled/vaccinated (EU; Anon 2003))?
      - What is the role of new technologies?
      - How much surveillance nationally (outside of the control/restricted areas)?
      - What is the process for managing reactors? Thresholds? Repeat visits?
   ii. will need to incorporate an adequate sampling design to satisfy the OIE and trading partners, and could consist of a combination of:
      - active sampling of a valid sub-sample of the national livestock population
      - active clinical surveillance in the RA and CA (and outside of these areas?).
      -

2 **Vaccinate-to-live: additional surveillance**
   i. Census based surveillance required to check for circulating virus and/or carriers:
      - When will surveillance of vaccinated populations start?
      - What movement restrictions apply to vaccinated herds after the outbreak?
      - Do we need to test offspring of vaccinated animals?
      - Would animals be disposed of on farm or via abattoir/knackery?
      - Consider reduced value of product and/or lack of desire to purchase?
      - What is the process for managing reactors? Thresholds? Repeat visits?
   ii. Potential for 'multistage/risk-based' surveillance (+/- containment zones):

- If vaccinated properties/jurisdictions zoned, can the rest of country return to trade?
- How much should we consider re: alternatives to census surveillance?
- If animals live out their natural life, is there ongoing surveillance?
-

3 Vaccinate-to-remove

i. Disposal on farm (waste)

ii. Disposal to salvage (including domestic consumption?):

- When will proof-of-freedom surveillance start? After last vaccinate removed? Concurrently?
- Will this still require census surveillance?
- What is the process for managing reactors? Thresholds? Repeat visits?
- Will testing be required to enable transport?
- Consider value of product/s and need for incentives/compensation?
- What is the capacity of abattoirs to be used?

➔ following removal of vaccinated animals, proceed with proof-of-freedom surveillance

Economic analysis

Throughout the workshop, we will be asking for contributions regarding the economic and any animal welfare implications associated with the above options for managing FMD vaccinated animals. Identifying the costs and benefits of each will highlight aspects that require modelling. The following table lists some of these potential considerations:

Approach	**Benefits**	**Costs**
Vaccinate-to-live	• Reduced cost of removing animals: (slaughter, disposal, compensation) • Reduced loss of genetics • Continuity of production • Producer goodwill • Vaccinated animals have a value (less than non-vaccinated)	• Longer time to achieve FMD-free status • Delayed return to markets • Additional surveillance costs • Separate slaughter and product processing chains • Additional product processing costs • Record keeping and information management • Finding new markets • Compensation for discounted value of vaccinated animals/products
Vaccinate-to-remove (waste)	• Shorter time to achieve FMD-free status • Earlier return to markets	• Compensation for mandatory acquisition and slaughter of stock • Vaccinated animals have no value • Animal processing and disposal costs • Production loss • Loss of genetics • Producer resentment
Vaccinate-to-remove (salvage)	• Shorter time to achieve FMD-free status • Earlier return to markets	• Compensation for mandatory acquisition and slaughter of stock • Production loss

	• Vaccinated animals have some value (less than non-vaccinated animals; NB some classes of slaughtered animals will have negligible value)	• Loss of genetics • Producer resentment • Animal processing costs • Additional product processing costs • Finding new markets

Appendix 2

Summary of European Union FMD Directive (Council Directive 2003/85/EC) surveillance requirements

Removal of measures in protection zone (Article 36) and surveillance zone (Article 44)

Specifies minimum time periods from killing and safe disposal of all animals on infected holdings and completion of preliminary cleansing and disinfection

Specifies that survey has been concluded with negative results in holdings keeping susceptible animals

Survey (Annex III)

To include clinical inspection and serological sampling

Surveillance after an outbreak should commence at least 21 days after removal of animals from infected holdings and preliminary cleansing and disinfection has been carried out.

Sampling within holdings

- Sheep and goats: 5% prevalence with 95% confidence

Sampling in protection zones:

- 5% prevalence 95% confidence
- All holdings

Sampling in surveillance zones:

- Multistage sampling adequate
- 95% confidence of detecting at least one infected holding if the estimated prevalence was 2% equally distributed throughout the zone
- Sheep and goats: 5% within-herd prevalence with 95% confidence. NB if <15 sheep and goats in a herd then all should be sampled

Vaccination (Articles 56, 61)

A survey to be carried out no earlier than 30 days after completion of emergency vaccination

Survey will include clinical inspection and laboratory testing of all susceptible animals in all herds in the vaccination zone

Testing for infection with FMDV using NSP antibody test or by another approved method

All vaccinated animals of susceptible species and their non-vaccinated offspring in all herds in the vaccination zone.

Article 61 specifies that following eradication with vaccination, free status can only be recovered:

- Provided requirements in OIE FMD code are met
- At least 3 months have elapsed since the slaughter of the last vaccinated animal and serological surveillance has been carried out in accordance with the Directive (Article 70)
- At least 6 months has elapsed since the last outbreak or completion of emergency vaccination (when vaccinated animals are not removed) and a serological survey based on NSP antibody testing has demonstrated absence of infection as specified in the DSirective (Article 70)

Appendix 3

Workshop on the design and interpretation of post Foot-and-Mouth Disease (FMD)-vaccination serosurveillance by NSP tests

Post-outbreak design criteria

All large ruminants should be tested in a vaccinated population

Have to consider on a cluster by cluster basis

Protection zone

- Cattle: clinical surveillance all herds/all animals
- Sheep/goats: sample all herds/(95:5) animals
- Pigs: clinical surveillance all herds/all animals

Surveillance zone

- Cattle: Clinical surveillance all herds/all animals
- Sheep/goats: sampling 95:2 of herds, 95:5 animals within herds
- Pigs: clinical surveillance all herds/all animals

Vaccination zone

1. <u>All animals vaccinated</u>
    - Cattle: sample all herds, all animals. Alternative all herds/ (95:5 animals)
    - Sheep/goats: sample all herds/all animals
    - Pigs: sample all herds/95:5 animals (sampling all pigs considered impractical)
2. <u>Cattle only vaccinated</u>
    - Cattle: clinical surveillance all herds + sample all herds/ <=50 animal then all; >50 animals then 95:5 animals OR
    - Sample all herds/all animals

- Sheep/goats: clinical surveillance all herds + sample all herds/(95:5 animals)
- Pigs: clinical surveillance all herds/all animals

Appendix 4

Modelling positive and negative herds found during post-outbreak surveillance

1. *Detecting residual infected herds if they are sampled (true positives)*.

If a residual herd is sampled we need to determine if it is found or not. This will depend on the within herd seroprevalence and number of animals tested. Probability that at least one animal in a sample from a residual herd tests positive is given by $1-(1-p)^n$ (Canon and Roe 1982)

Where:

p= herd seroprevalence on testing day
n= number of animal sampled

We will have to adjust prevalence to take into account the sensitivity (Se) of the laboratory test used i.e. the apparent prevalence (= true prevalence*Se)

Probability of detecting a residual herd

$$prob = 1-(1-p*Se)^n$$

In a two test regime (screening test followed by confirmatory test) we have to factor in the reduction in overall sensitivity. SE can be approximated by:

$$Se = Se_1*Se_2$$

For example, in the case of an unvaccinated population this might involve initial testing with SP-ELISA followed by confirmatory testing with NSP ELISA or VNT. If $Se_1 = 0.99$ and $Se_2 = 0.92$ then overall sensitivity Se = 0.91

Although this approach is a useful approximation, it assumes that test results are independent and in practice one should allow for sensitivity co-variance (*c*) where *c* is the probability of both tests being positive (Paton et al. 2006). That is:

$$Se = Se_1*Se_2+c$$

Published values for six commercial NSP ELISAs have found generally low values of sensitivity covariance, commonly around 0.1 or lower, with actual values depending on the combination of tests used (Brocchi et al. 2006).

2. *Generating false positive herds*

Because we are testing lots of animals with tests that are not perfect we can expect false positive results. If a negative herd is tested, the probability that at least one animal in a sample from that herd will test positive is given by

$$prob = 1- Sp^n$$

In a two test regime (screening test followed by confirmatory test) we have to factor in the increased specificity. This can be approximated by:

$$Sp = 1-(1-Sp_1)(1-Sp_2)$$

For example, in the case of an unvaccinated population this might involve initial testing with SP-ELISA followed by confirmatory testing with NSP ELISA or VNT. If test 1 has specificity (SP_1) of 0.98 and test 2 (SP_2) of 0.98 then overall specificity is

$$Sp = 0.996$$

Although this approach is a useful approximation, it assumes that test results are independent of each other. In practice, one should allow for covariance specificity (*d*) where *d* is the probability that both tests are negative (Paton et al. 2006). That is:

$$Sp = 1-(1-Sp_1)(1-Sp_2)-d$$

Published values for six commercial NSP ELISAs have found generally very low values of specificity covariance (0-0.009) with the actual value depending on the combination of tests used (Brocchi et al. 2006).

3. Estimating true negative and false negative herds

Because the computer has perfect knowledge of the true status of all herds in the population, once the true positive and false positive herds have been determined, the numbers of true negative and false negative herds can be calculated by subtraction.

Case Study Scenario Parameter Settings

Case Study 1 – Darling Downs, Queensland	**Value**
1. Scenario	
- Scenario start month	May
Seeding	
- Seed herd type	Large piggery: #108909
- Seed herd LGA	Lockyer Valley
Control	
- First detection mode	Fixed
- Detection day (Day 0 = beginning of outbreak = 4 latently infected animals in the seed herd)	Day 21
- Detection species type	Cattle (preferentially)
2. Resources *	
- National resource pool enabled	false
- Surveillance teams (initial, maximum, time to maximum)	5, 40, 21 days
- Cull teams (initial, maximum, time to maximum)	1, 25, 28 days
- Assume lay vaccinators	true
3. Vaccination	
- Start day 14	true
- Species: Cattle only (no feedlots)	3 km
- Outer radius of vaccination ring	true
- Suppressive vaccination, outside in	true
- Only vaccinate new IPs (no retrospective vaccination)	true
- National vaccine bank enabled	
4. Movement restrictions and size/temporality of zones	
- National livestock standstill	72 hr
- Initial CA	Entire state
- Initial RA	20 km
- CA after 14 days	10 km
- RA after 14 days	5 km
5. IP operations	
- Culling of IPs	true
- Culling of DCPs	false
- Ring culling	false

Case Study 2 – Gippsland, Victoria	**Value**
6. Scenario	
- Scenario start date	September
Seeding	
- Seed herd	Small piggery: #108386
- Seed herd LGA	215 (South Gippsland)
Control	
- First detection mode	Fixed
- Detection day (Day 0 = beginning of outbreak = 4 latently infected animals in the seed herd)	Day 14
- Detection herd type	any
7. Resources	

- National resource pool enabled (in an attempt to reflect the availability of the Australian Defence Force and the International Animal Health Emergency Reserve)	false
- Surveillance teams (initial, maximum, time to maximum)	3, 50, 21 days
- Cull teams (initial, maximum, time to maximum)	1, 25, 28 days
- Assume lay vaccinators	true
8. Vaccination	
- Species: Cattle and sheep on mixed sheep/cattle properties only	true
- Vaccine start day (post detection)	14
- Outer radius of vaccination ring	3 km
- Suppressive vaccination, outside in	true
- Only vaccinate new IPs (no retrospective vaccination)	true
- High risk areas only (user_defined_criteria)	true
- National vaccine bank enabled	true (500,000 doses)
9. Movement restrictions and size/temporality of zones	
- National livestock standstill	72 hr
- Initial CA	Entire state
- Initial RA	10 km
- CA after 14 days	10 km
- RA after 14 days	3 km
10. IP operations	
- Culling of IPs	true
- Culling of DCPs	false
- Ring culling	false

Case Study 3 – Bunbury, Western Australia	**Value**
11. Scenario	
- Scenario start date	May
Seeding	
- Seed herd	Sheep/beef mixed: #93268
- Seed herd LGA	434 (Harvey)
Control	
- First detection mode	Fixed
- Detection day (Day 0 = beginning of outbreak = 4 latently infected animals in the seed herd)	Day 30
- Detection herd type	Sheep (preferentially)
12. Resources	
- National resource pool enabled	False
- Surveillance teams (initial, maximum, time to maximum)	4, 30, 21 days
- Cull teams (initial, maximum, time to maximum)	1, 20, 28 days
- Assume lay vaccinators	true
13. Vaccination	
- Species: Cattle and sheep on mixed sheep/cattle properties only	true
- Outer radius of vaccination ring	3 km
- Suppressive vaccination, outside in	true
- Only vaccinate new IPs (no retrospective vaccination)	true
- National vaccine bank enabled	true (500,000 doses)

14. Movement restrictions and size/temporality of zones	
- National livestock standstill	72 hr
- Initial CA	Entire state
- Initial RA	LGA
- CA after 14 days km	25
- RA after 14 days km	10
- CA after 28 days km	10
- RA after 28 days km	3
15. IP operations	
- Culling of IPs	true
- Culling of DCPs	false
- Ring culling	false

Software updates in support of CEBRA project 1604D

Database

AADIS uses the PostgreSQL relational database to store datasets such as the national herd population, weather data and animal movement patterns. An AADIS database is comprised of approximately 40 tables with each table having a corresponding CSV input file. A user updates the database by editing the CSV file corresponding to the table of interest and then rebuilding the entire database (to ensure relational integrity between tables). A user may only add/delete/modify rows of an existing table. The creation of a new database table or the addition of new columns to an existing table is a software development activity. The following software updates were carried out to support the new post-outbreak management functionality:

Post-Outbreak Surveillance table

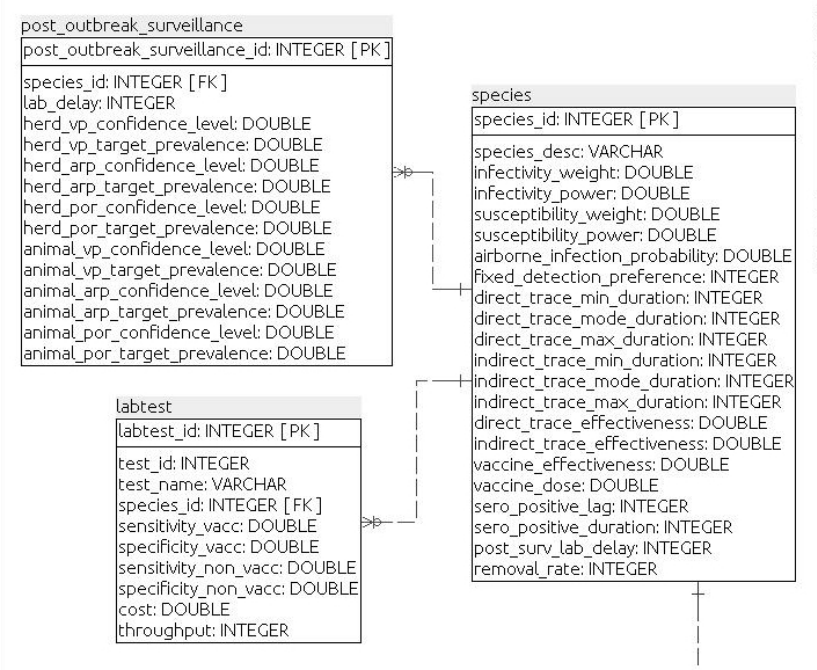


Figure 1: Post-Outbreak Surveillance and Labtest database tables

A new Post-Outbreak Surveillance table (figure 1) was created with the following (per species) attributes:

- lab results delay - the time needed (in days) for laboratory test results to become available after a surveillance visit has concluded.

- herd VP confidence level - the confidence level at which to test a cluster of VP herds. A value of 0 means test no herds in the cluster. A value of 100 means test all herds in the cluster. A value of 95, for example, means test sufficient herds such that we are 95% confident that the desired target prevalence (e.g., 5%) would be detected.
- herd VP target prevalence - the target prevalence at which to test a cluster of VP herds (per above).
- herd ARP confidence level - the confidence level at which to test a cluster of ARP herds. A value of 0 means test no herds in the cluster. A value of 100 means test all herds in the cluster. A value of 95, for example, means test sufficient herds such that we are 95% confident that the desired target prevalence (e.g., 5%) would be detected.
- herd ARP target prevalence - the target prevalence at which to test a cluster of ARP herds (per above).
- herd POR confidence level - the confidence level at which to test a cluster of POR herds. A value of 0 means test no herds in the cluster. A value of 100 means test all herds in the cluster. A value of 95, for example, means test sufficient herds such that we are 95% confident that the desired target prevalence (e.g., 5%) would be detected.
- herd POR target prevalence - the target prevalence at which to test a cluster of POR herds (per above).
- animal VP confidence level - the confidence level at which to sample animals in a VP herd. A value of 0 means sample no animals in the herd. A value of 100 means sample all animals in the herd. A value of 95, for example, means sample sufficient animals such that we are 95% confident that the desired target prevelance (e.g., 2%) would be detected.
- animal VP target prevalence - the target prevalence at which to sample a VP herd (per above).
- animal ARP confidence level - the confidence level at which to sample animals in an ARP herd. A value of 0 means sample no animals in the herd. A value of 100 means sample all animals in the herd. A value of 95, for example, means sample sufficient animals such that we are 95% confident that the desired target prevelance (e.g., 2%) would be detected.
- animal ARP target prevalence - the target prevalence at which to sample an ARP herd (per above).

- animal POR confidence level - the confidence level at which to sample animals in a POR herd. A value of 0 means sample no animals in the herd. A value of 100 means sample all animals in the herd. A value of 95, for example, means sample sufficient animals such that we are 95% confident that the desired target prevelance (e.g., 2%) would be detected.
- animal POR target prevalence - the target prevalence at which to sample a POR herd (per above).

Labtest table

A new Labtest table (figure 1) was created with the following attributes:

- lab test ID – primary key
- test ID – test identifier (e.g. 2 corresponds to C-ELISA) (secondary key)
- species ID – species identifier (secondary key)
- sensitivity (vaccination) - sensitivity of the test when vaccination has been used
- specificity (vaccination) - specificity of the test when vaccination has been used
- sensitivity (non-vaccination) - sensitivity of the test when vaccination has not been used
- specificity (non-vaccination) - specificity of the test when vaccination has not been used
- cost - cost of the test (in $AUD)
- throughput – not currently used

Species table

The Species table (figure 1) was updated with the following new (per species) attributes:

- sero positive lag - number of days after infection that a herd becomes serologically positive.
- sero positive duration - duration in days that a herd remains serologically positive.
- post-outbreak lab results delay - the time needed (in days) for laboratory test results to become available after a surveillance visit has concluded.
- removal rate - the daily rate at which vaccinates can be removed from the population.

Herd Type table

The Herd Type table (figure 2) was updated with the following new (per herd type) attributes:

- post-outbreak surveillance priority – surveillance visits are carried out in one cluster at a time with VP herds having priority over ARP herds, and ARP herds having priority over POR herds. A second level priority (1..7) assigned per herd type is used to determine which herds have priority within the VP, ARP and POR groupings in a cluster.
- cull cost – the cost of culling a single animal of a specific herd type.

- disposal cost - the cost of disposing a single animal of a specific herd type.
- disinfect cost – the cost of disinfecting the premises for a specific herd type.
- compensation cost – the cost of compensating the removal of a single animal of a specific herd type.
- vaccination cost - the cost of vaccinating a single animal of a specific herd type.
- vaccination to waste cull cost - the cost of culling a single vaccinated animal of a specific herd type for waste purposes
- vaccination to waste disposal cost - the cost of disposing a single vaccinated animal of a specific herd type for waste purposes.
- vaccination to salvage cull cost - the cost of culling a single vaccinated animal of a specific herd type for salvage purposes.

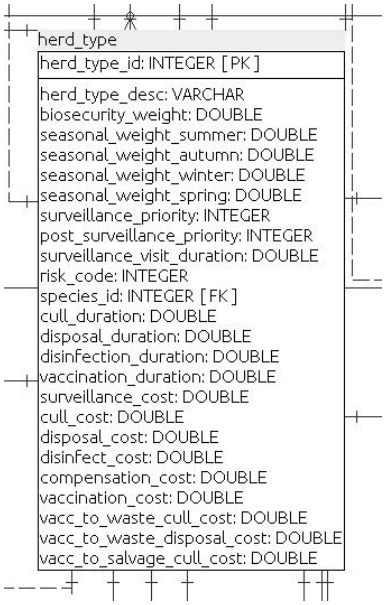


Figure 2: Herd Type database table

Resources table

The Resources table (figure 3) was updated with the following new attribute:

- post surveillance resources - the number of post-outbreak surveillance teams available per jurisdiction.

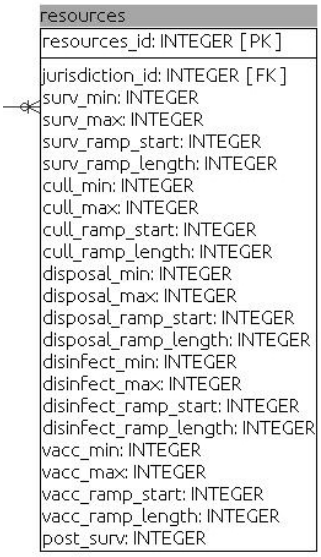


Figure 3: Resources database table

Configuration files

Scenario configuration file

The scenario configuration file was updated with the following new parameters:

- post-outbreak management enabled - determines whether post-outbreak management is enabled or disabled.
- post-outbreak management of vaccinates policy – options are: vaccinate to waste, vaccinate to salvage or vaccinate to retain.
- post-outbreak management trigger day - number of days from the declaration of the last IP (or VP, which ever is later) to the commencement of post-outbreak surveillance.
- post-outbreak management surveillance radius - radius (in km) used to construct the post-outbreak surveillance clusters. A cluster is formed from the set of RPs that are within two radius' of at least one other RP in the cluster, and comprise all properties that were at one stage during the outbreak a VP, ARP or POR, and lie within one radius of any RP in the cluster.
- post-outbreak management non vaccination screening test ID - the ID of the lab test to use for screening tests of non-vaccinated herds. The ID indexes into a row in the Labtest DB table.

- post-outbreak management non vaccination confirmatory test ID - the ID of the lab test to use for confirmatory tests of non-vaccinated herds. The ID indexes into a row in the Labtest DB table.
- post-outbreak management vaccination screening test ID - the ID of the lab test to use for screening tests of vaccinated herds. The ID indexes into a row in the Labtest DB table.
- post-outbreak management vaccination confirmatory test ID - the ID of the lab test to use for confirmatory tests of vaccinated herds. The ID indexes into a row in the Labtest DB table.
- return to trade waiting period when stamping out only – waiting period in days after the last premises was culled until trade may be resumed (when vaccination was not employed).
- return to trade waiting period when vaccinating to remove - waiting period in days after the last vaccinated herd was removed until trade may be resumed (when a vaccination policy of 'vaccination to waste/salvage' was employed).
- return to trade waiting period when vaccinating to retain - waiting period in days after the later of the last infected herd removal and the last herd vaccination, until trade may be resumed (when a vaccination policy of 'vaccination to remove' was employed).

Disease configuration file

The disease configuration file was updated with the following new parameters:

- control program costing enabled – determines whether the control program and post-outbreak management are costed.
- daily control centre cost - the daily cost of running one State Disaster Control Centre (SDCC) and one Local Disaster Control Centre (LDCC) per jurisidiction.
- daily loss of trade cost - daily cost attributed to the loss of trade.

Agent-based model

Post-Outbreak Surveillance class

A new Post-Outbreak Surveillance component was added to the AADIS agent-based model (ABM) environment (figure 4). It is responsible for:

(a) determining when to commence post-outbreak surveillance according to the configured trigger day,

(b) defining the post-outbreak surveillance clusters based on the configured post-outbreak surveillance radius,

(c) scheduling surveillance visits to VP, ARP and POR herds in each cluster according to the configured target prevalence and confidence levels,

(d) conducting the scheduled surveillance visits taking into account the finite pool of post-outbreak surveillance teams available per jurisdiction,

(e) conducting screening and confirmatory lab tests on animals according to the configured sampling regimes for VP, ARP and POR herds,

(f) determining the number of true/false positives and true/false negatives arising from the lab tests.

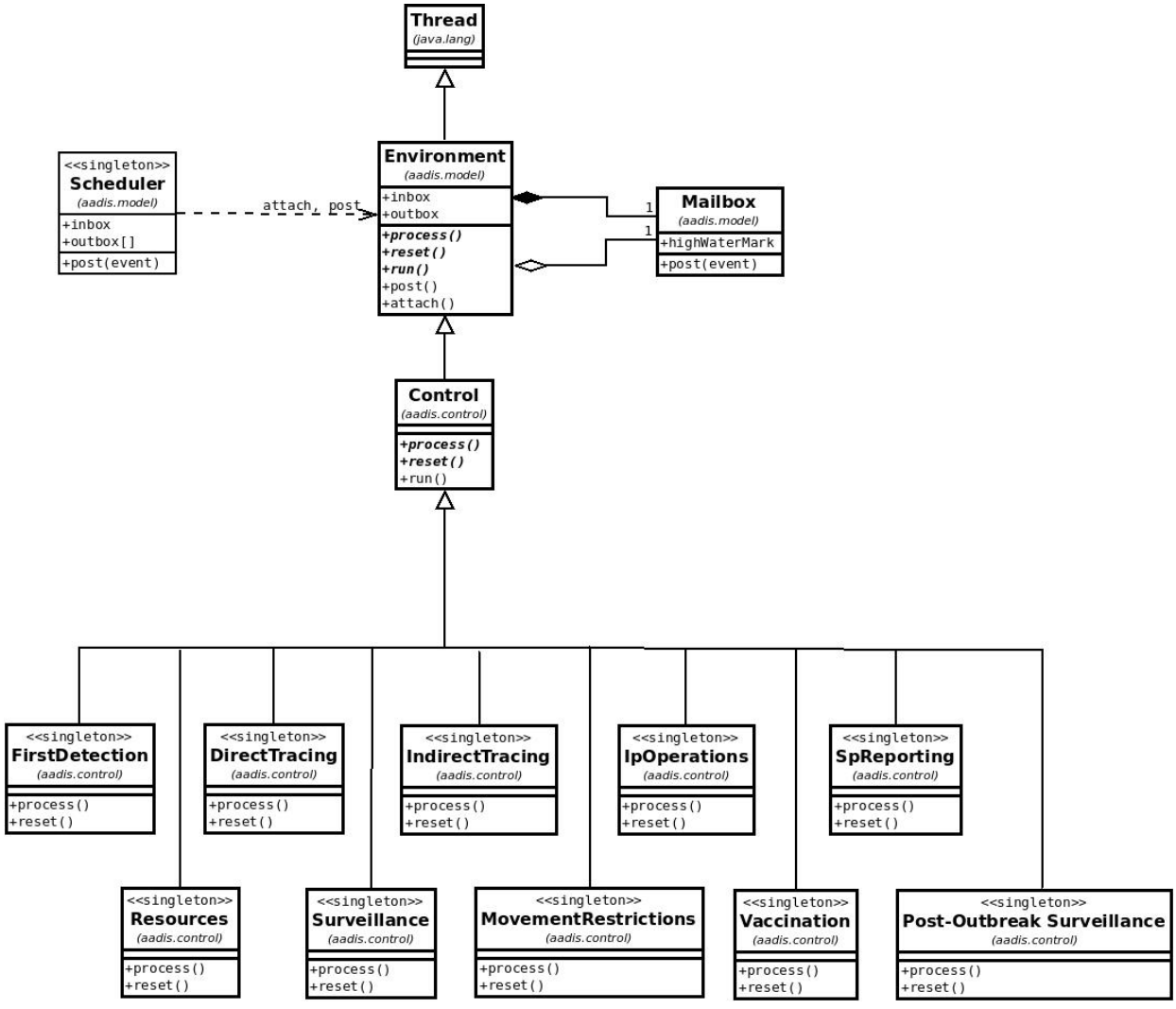


Figure 4 : Control subsystem

Economics

A new Economics subsystem was created that currently just contains the new Cost Manager class. The subsystem may later house other classes to support further economic functionality.

Cost Manager class

The Cost Manager class is responsible for daily calculation of:

(a) surveillance, culling, disposal, disinfection, vaccination and compensation costs incurred during the control program,

(b) surveillance, lab test, vaccinate removal and compensation costs incurred during the post-outbreak management program,

(c) control centre costs,

(d) loss of trade (cost and duration).

Visualisation & Graphical User interface

- The Declared Farms layer was updated to dynamically depict the formation of the post-outbreak surveillance clusters (Figure 5) and the completion of surveillance visits over time.
- The Surveillance Monitor, Surveillance Queue Monitor and Team Resources Monitor were updated to reflect how the rate of completion of post-outbreak surveillance visits is constrained by the available teams for the jurisdiction (Figure 5).
- The Surveillance Dialog was updated with a new pane for post-outbreak surveillance. This allows manual overrides of the configured post-outbreak surveillance trigger day, radius, lab test IDs and lab results delay.
- The Model Status pane was updated to dynamically reflect the daily cumulative cost of the control program, post-outbreak management and loss of trade (Figure 5).
- The Declared Farms Visualisation Layer was updated to depict all premises that returned true or false positive result during the post-outbreak surveillance program (Figure 6).
- The Declared Farms Visualisation Key was updated to report the number of true and false positive test results that arose from the post-outbreak surveillance program (Figure 6).
- The Farm Popup was updated to report the post-outbreak surveillance visit status of the subject premises (Figure 6).

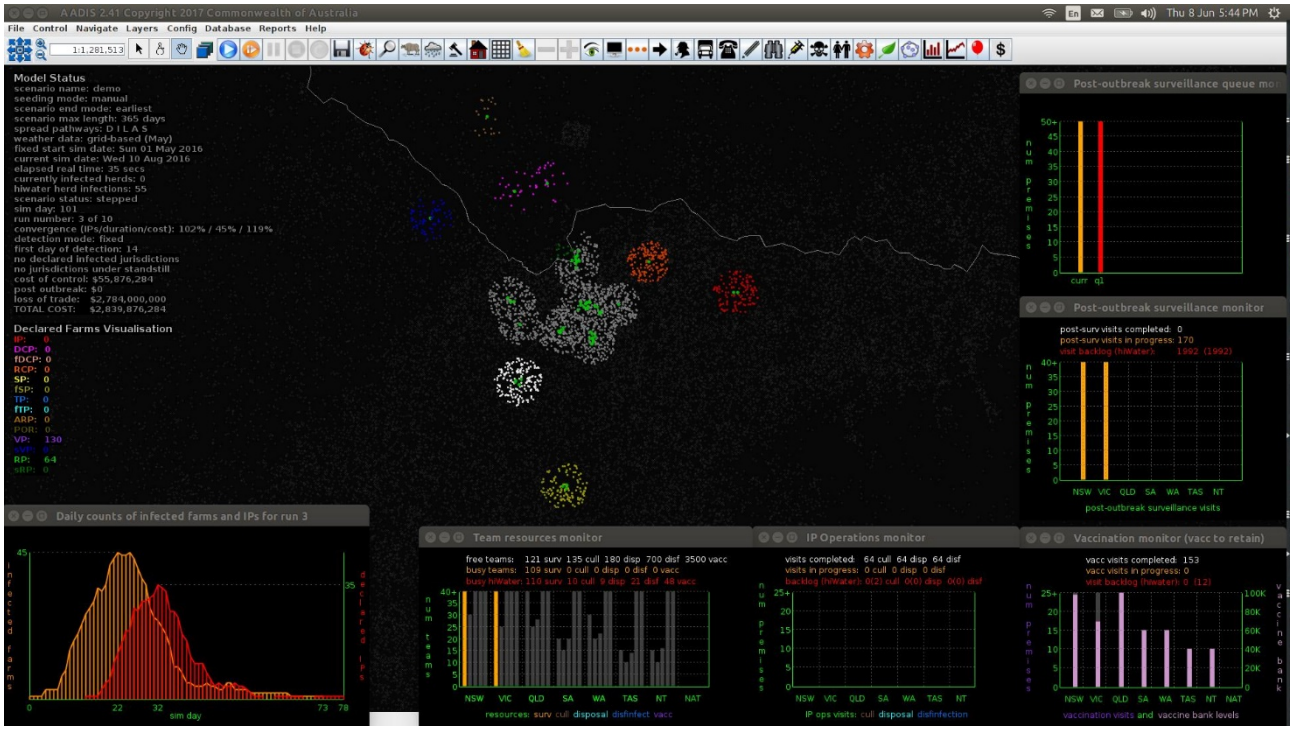


Figure 5: Post-outbreak surveillance clusters

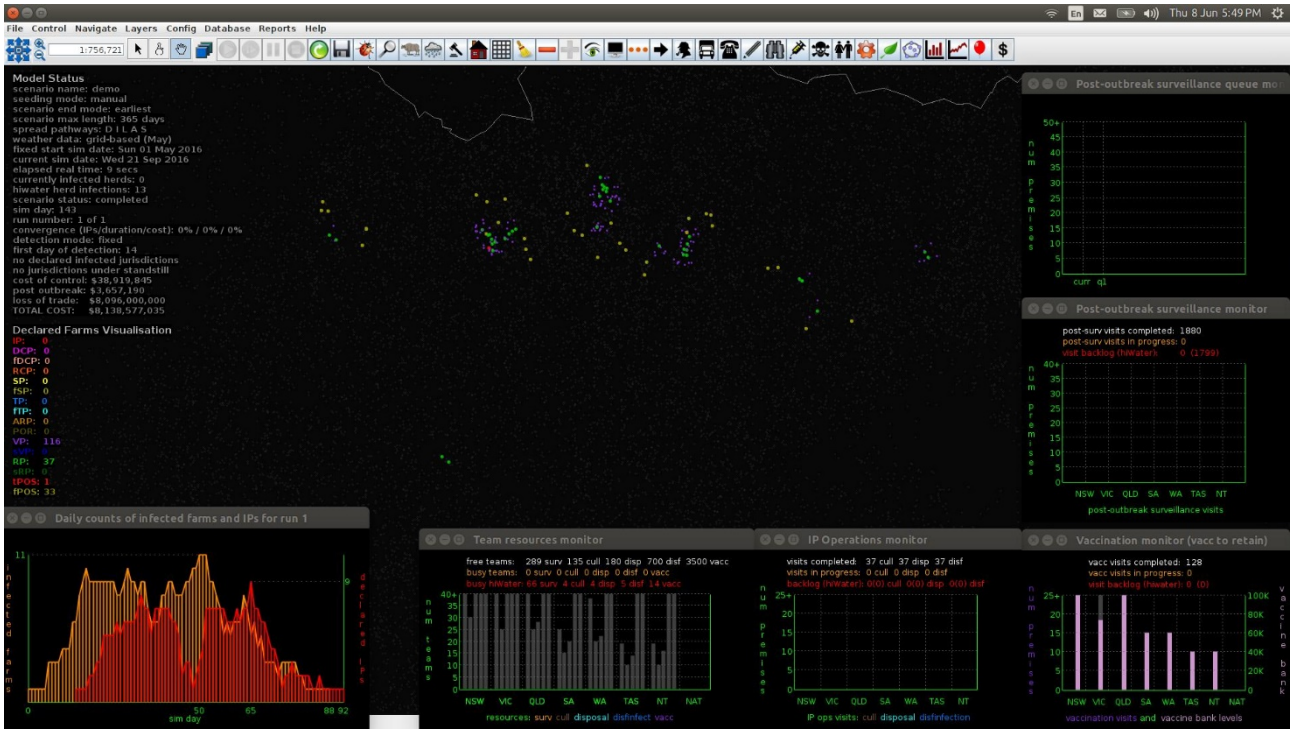


Figure 6: Post-outbreak surveillance true/false positive test results

Reports

The Control Report class was updated to report:

- duration and cost of the control program
- duration and cost of post-outbreak management

- post-outbreak surveillance test results
- loss of trade duration and cost

Documentation

The AADIS configuration guide (accessible via the Help menu) was updated with descriptions of all new user configurable parameters.