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Glossary of Acronyms

Acronym	Definition
AADIS	Australian Animal Disease Spread (model)
ABM	Agent-based model
APIQ	Australian Pork Industry Quality (Assurance Program)
ARP	At-risk premises (located inside RAs)
ASF	African swine fever
ASFV	African swine fever virus
AUSVETPLAN	Australian Veterinary Emergency Plan
BQ	Biosecurity Queensland, Department of Agriculture and Fisheries
CA	Control area
CEBRA	Centre of Excellence for Biosecurity Risk Analysis, The University of Melbourne
DAFF	Department of Agriculture, Fisheries and Forestry
DCP	Dangerous contact premises
DCPF	Dangerous contact processing facility
DES	Deserts and xeric shrublands (wildlife region)
DSE	Dry sheep equivalent
EBM	Equation-based model
FMD	Foot-and-mouth disease
FP	Feral Pig
IA	Infected area
IP	(declared) infected premises

LGA	Local government area
MED	Mediterranean forests, woodlands and shrubs (wildlife region)
MLC	Medium-to-large commercial (pig herd)
MON	Montane grasslands and shrublands (wildlife region)
NE	North-east (mega region)
NLIS	National Livestock Identification System
ODE	Ordinary differential equation
OIE	World Organisation for Animal Health
PIC	Property Identification code
PK	Pig keeper (pig herd)
PL	Pastoral (mega region)
POR	Premises of relevance (located inside CAs)
QDAF	Queensland Department of Agriculture and Fisheries
RA	Restricted area
RP	Resolved premises
SC	Small commercial (herd)
SE	South-east (mega region)
SEIRD	Susceptible Exposed Infectious Recovered Deceased (model)
SGT	Specialist gene transfer (pig herd)
SH	Smallholder (herd)
SP	Suspect premises (clinical disease has been reported)
SW	South-west (mega region)
TEF	Temperate broadleaf and mixed forests (wildlife region)
TES	Temperate grasslands, savannas and shrublands (wildlife region)
TP	Trace premises (identified by tracing activities)
TRF	Tropical and subtropical moist broadleaf forests (wildlife region)
VLC	Very large commercial (pig herd)

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Assessing the potential role of feral pigs in an outbreak of foot-and-mouth disease in Australia

Final report on CEBRA Project 23F, prepared for the Department of Agriculture, Fisheries and Forestry

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1 EXECUTIVE SUMMARY

Foot-and-mouth disease (FMD) is a highly contagious and economically important viral disease of cloven-hoofed animals. Australia's freedom from FMD supports a valuable trade in live animals and animal products. An outbreak of FMD would result in the loss of key export markets and cause severe disruption to domestic markets leading to economic losses exceeding A$80 billion and considerable welfare concerns (Buetre, 2013; Department of Agriculture, Fisheries and Forestry, 2022). The prevention of and contingency planning for FMD are important to government, industry, producers and the community.

Understanding the potential spread and control of FMD in Australia is difficult due to a highly contagious multi-host pathogen operating in a heterogeneous environment across multiple jurisdictions. Feral pigs are well known spreaders of FMD in affected countries (Alexandrov et al., 2013; Karniely et al 2020, Fukai et al 2022) and Australia has a large, dispersed feral pig population of 3 to 4 million feral pigs across a range of habitats (West, 2008; Hone, 2020; Bradhurst et al., 2022). There is potential for transmission of FMD between feral pigs and livestock either directly or indirectly through shared grazing and water sources, the degree of which is dependent upon farm biosecurity and feral pig density.

Australia invests considerable resources in preparedness and planning for emergency animal diseases such as FMD. The Australian Animal Disease Spread model (AADIS) (Bradhurst, 2015), is a sophisticated decision-support tool that can be used to look at the risk of disease introduction, establishment and spread, and assess control options in terms of effectiveness, cost, resource management, and post-outbreak consequences. The model is national-scale, spatially explicit, and includes regional, seasonal, and jurisdictional influences on the spread and control of disease (www.aadis.org).

AADIS was originally developed to support FMD preparedness and response (Bradhurst et al., 2015). The model was subsequently expanded to bluetongue (Al-Riyami, 2020; Bradhurst et al., 2018), African swine fever (ASF) (Bradhurst, Garner, Richards, et al., 2022; Bradhurst et al., 2021), *Mycoplasma bovis* (Bradhurst, Burroughs, et al., 2022) and lumpy skin disease (Bradhurst et al., 2024). The AADIS-ASF model simulates the potential spread and control of ASF in both domestic and feral pig populations, and the potential for spillover transmission between the two.

This report describes the development of a new FMD decision support tool that includes the Australian feral pig population and allows exploration of the potential spread and control of FMD in both feral pigs and livestock. The new model is referred to as AADIS-FMD-FP to distinguish it from the original livestock-only national FMD model AADIS-FMD.

The AADIS-FMD-FP model can help stakeholders evaluate:

- how FMD may spread in livestock
- how FMD may spread in the feral pig population including the influence of population density, infectious carcasses, and variable contact rates between groups
- the potential for FMD transmission between livestock and feral pigs and the influence of on-farm biosecurity on spillover
- regional and seasonal influences on FMD outbreaks in both livestock and feral pigs
- candidate control measures in both livestock and feral pigs
- resource management and outbreak costings

Achievements over the course of the project include:

- Improved cattle, small ruminant, and pig herd datasets that considers more recent livestock population statistics and includes updated herd and farm types.
- Better representation of the potential spread of FMD in piggeries through incorporation of the network-based transmission pathway previously developed for the AADIS African swine fever model (AADIS-ASF) (Bradhurst et al., 2021; 2022).
- Introduction of 'risk areas' for individual farms based on herd type and size. Risk areas provide a spatial basis for modelling the relationship between the home range of a feral pig group and nearby farms. When the two intersect, there is the potential for direct and/or indirect contacts between livestock and feral pigs. Prior to this project, farms were only represented spatially within AADIS as single points of latitude and longitude.
- Incorporation of the existing feral pig population layer from the AADIS-ASF model with the following improvements:
    - Updated feral pig distribution

    - Optional random location of a feral pig group within its home cell rather than always being located at the centroid of the home cell
    - Review of seasonal feral pig home ranges by region.
- Modification of the AADIS spillover transmission pathways to consider the dynamic interplay between farm risk areas and feral pig seasonal home ranges.
- Parameterisation of disease transmission variables specific to FMD for the spread of disease within and between feral pig groups, and bidirectionally between feral pigs and domestic herds.
- Implementation of feral pig population control as a part of FMD response, as well as feral pig population recovery following the end of control efforts.
- Incorporation of a national feral pig control difficulty index (CDI) layer which informs the effectiveness of feral pig control efforts according to accessibility and environmental conditions.
- Consultation with feral pig ecologists and jurisdictional and industry stakeholders to ensure the model simulates outbreaks and response measures in a realistic way and obtain advice on outbreak scenarios of interest.

The project undertook case studies of relevant high-risk incursion scenarios. Key findings from the case studies (based on the modelling assumptions) included:

- Impact of feral pigs: In the absence of feral pig control, feral pigs could significantly increase the size, duration, and variability of a domestic outbreak. Spillover transmission between livestock and feral pigs will depend on regional factors, seasonality, feral pig population density, farm type, and on-farm biosecurity.
- Outbreak dynamics: The size, duration, and speed of FMD outbreaks will vary depending on region, season, and the level of interaction between domestic herds and feral pigs. Larger and longer outbreaks are expected in cooler climates and seasons and areas of high farming density and/or feral pig density.
- Provided that an outbreak of FMD is controlled in the livestock population, it is likely to not persist in the feral pig population.
- The higher the density of feral pig populations, the faster and further FMD will spread within these populations.
- The simulation results were coherent and in line with both international FMD experiences and local expectations.

The newly developed AADIS-FMD-FP model is a sophisticated decision support tool for FMD preparedness and planning. However, it is important to note that as AADIS is a data-driven model, modelling results are always dependent on the quality of underlying data. When modelling the potential role of feral pigs in EAD outbreaks, dependent data includes regional and seasonal estimates of feral pig distribution, abundance, home ranges, contact rates between groups, and contact rates with farms. It has previously been shown in the context of ASF that modelling outcomes are sensitive to these data (Bradhurst et al., 2021; 2022). It will be relatively easy to update the AADIS-FMD-FP model with improved feral pig ecological data and parameterisation in step with results from ongoing field studies in Australia on feral pig distribution, abundance, home ranges and contact rates.

The model is not intended to predict how any given FMD incursion will unfold in real time. Given the inherent uncertainty in feral pig ecology and epidemiology on a national scale, the model is best suited for generating a spectrum of plausible FMD outbreaks, against which the cost effectiveness of candidate livestock and feral pig control strategies can be assessed.

2 MODEL DEVELOPMENT

2.1 Domestic herd dataset

The AADIS epidemiological unit of interest for livestock is the 'herd', defined as a group of co-mingling animals under the same production system. A herd has static attributes such as the type of production system, biosecurity rating, geo-location and jurisdiction, and dynamic attributes such as infection and disease status.

In AADIS, a 'farm' is a collection of one or more co-located herds under the same management system. This organisational structure allows AADIS to represent the increased probability of disease transmission between herds that are co-resident on the same farm (e.g., beef & sheep herds on a mixed farm), due to the higher potential for direct contact and indirect contact via shared equipment and personnel.

The AADIS-FMD-FP herd dataset is an evolution of the AADIS-FMD (Bradhurst et al., 2015) and AADIS-ASF datasets (Bradhurst et al., 2021, 2022) (Figure 1). The legacy AADIS-FMD herd dataset was based on the 2012 Agricultural census, and this was updated to the 2021 Agricultural census under AADIS development project C08655. The census included all businesses undertaking agricultural activity recorded on the Australian Bureau of Statistics' Business Register above a minimum threshold of $40,000 in Estimated Value of Agricultural Operations. According to the census, Australia has 44,611 farms with beef cattle, 5,613 farms with dairy cattle and 31,839 farms with sheep. The farm data is stratified by Australian Statistical Geography Standard (ASGS) Statistical Areas level 2 (SA2) (i.e., farms locations are not included). Farm locations in AADIS-FMD were synthesized per SA2 region incorporating a grazing land mask based on Australian Collaborative Land Use and Management Program (ACLUMP) data. The census data provides average populations by Statistical Local Area but does not describe the sizes of individual properties. Herd sizes in the dataset were synthesized based on BetaPERT distributions of herds sizes per herd type per region.

The AADIS-FMD-FP dataset comprises 12 farm types and 11 herd types (Table 1). Improvements made to the herd dataset as part of this project are described in Sections 2.1.1 to 2.1.4.

Table 1. Farm and herd types defined in the AADIS-FMD-FP model.

Farm type	Number of farms	Number of animals per farm mean [5th, med, 95th]	Herd type(s) on farm	Number of animals per herd mean [5th, med, 95th]	Herds per farm	Number of herds
Extensive beef	1500	4405 [522,2526,15630]	Extensive beef	1468 [174, 842, 5210]	3	4,500
Intensive beef	39,204	320 [26,188,1032]	Intensive beef	Per farm size	1	39,204
Feedlot	252	5165 [173,2913,17064]	Feedlot	Per farm size	1	252
Dairy	5588	426 [31,326,1159]	Dairy	Per farm size	1	5,588
Small ruminants	27,312	2147 [80,1397,6784]	Small ruminants	Per farm size	1	27,312
Mixed	3586	2983 [388,2154,8250]	Intensive beef	363 [25,202,1208]	1	3586

			Small ruminants	2620 [164,1785,7870]	1-3	4500
Very large commercial pig	119	23330 [10110,17000,60000]	Very large commercial pig	Per farm size	1	119
Medium to large commercial pig	306	4476 [1700,4000,8963]	Medium to large commercial pig	Per farm size	1	306
Small commercial pig	395	560 [6,550,1359]	Small commercial pig	Per farm size	1	395
Specialist gene transfer pig	6	208 [53,220,366]	Specialist gene transfer pig	Per farm size	1	6
Microscale pig	1064	88 [2,47,320]	Microscale pig	Per farm size	1	1064
Smallholder	76,383	8 [2,5,16]	Smallholder	Per farm size	1	76,383
TOTAL	**155,715**					**163,215**

2.1.1 Cattle

The legacy Mixed Beef/Sheep farm type inherited from the AADIS-FMD model, was renamed as Mixed to provide a more general-purpose farm type for disparate species (i.e., not limited to just beef/sheep). Mixed farms are now comprised of Intensive Beef and Small Ruminant herds. The legacy Mixed Beef and Mixed Sheep herd types were removed. Some Mixed farms inherited from the AADIS-FMD model had only one herd and were subsequently re-classified as either Intensive Beef or Small Ruminant farms.

There were 21 Dairy herds located in regions not known for dairy farming (Lower North and the Arid Zone); these were relocated to the nearest statistical area known for dairy farming.

2.1.2 Sheep

The legacy Sheep herd and farm types from the AADIS-FMD model were renamed Small Ruminants to reflect that they represent both sheep and goats.

2.1.3 Pigs

The legacy AADIS-FMD model had quite a simple representation of pig farms:

- Large-scale commercial with 100 or more sows and good biosecurity
- Small-scale commercial with less than 100 sows and lower levels of biosecurity

It was decided to incorporate the more refined characterisation the pig industry developed for the AADIS-ASF model (Bradhurst et al., 2021; 2022) into the AADIS-FMD-FP model. The AADIS-FMD-FP model categorises piggeries according to the following farms type (Table 2).

Table 2. Pig farm types used in the AADIS-FMD-FP model.

ID	Name	Description
1	Very Large Commercial	1000+ sows kept indoors. APIQ[1] accredited. Routine biosecurity practices and likely to have a secure (pig-proof) perimeter fence. Multiple movements per week to export and domestic processing plants. Vehicle washdown and decontamination between movements likely
2	Medium-to-Large Commercial	151-1000 sows kept indoors. Typically, APIQ accredited. Moderate biosecurity practices and possibility of secure perimeter fencing. Weekly pig movements to domestic and export processing plants using owned vehicles or contractor livestock transport. Possibility of vehicle washdown after movements but decontamination unlikely.
3	Small Commercial	51-150 sows housed indoors or outdoors. Generally, not APIQ-accredited. Low biosecurity practices with no secure perimeter fencing. Regular pig movements to domestic processing plants using owned vehicles. Generally, no vehicle washdown / decontamination.
4	Specialist Gene Transfer	Specialist producers of boar semen. APIQ accredited. Routine biosecurity practices and likely to have a secure (pig-proof) perimeter fence. Vehicle washdown and decontamination between movements likely.
5	Microscale	50 or less sows kept primarily for non-commercial or micro-scale commercial purposes. Not APIQ-accredited. Low biosecurity practices and low awareness of biosecurity. No secure perimeter fencing. Occasional low-biosecurity movements to domestic abattoirs that are recorded under NLIS. This herd type was named Smallholder in the AADIS-ASF model.

2.1.4 Smallholders

The legacy AADIS-FMD Smallholder farm category represents very small-scale non-commercial premises. They are arbitrarily deemed to be an indeterminate mix of 20 or less cattle, sheep, or pigs housed on a property under 20 ha. There have been limited new studies on smallholdings in Australia since the legacy AADIS-FMD herd dataset was created and as such, the Smallholder farms were retained.

Note that in the AADIS-ASF model, the Smallholder category represented small-scale piggeries (50 or less sows) that had one or more movements of animals recorded in Australia's National Livestock Information System (NLIS) during 2019. These farms were re-classified as Microscale Pig in the AADIS-FMD-FP model. The Pig Keeper category from the AADIS-ASF model was not explicitly included in the AADIS-FMD-FP model, as pig keepers were already included under the Smallholder category in the legacy AADIS-FMD model. Figure 1 provides a summary of the merging of the AADIS-FMD and AADIS-ASF herd types into the AADIS-FMD-FP model.

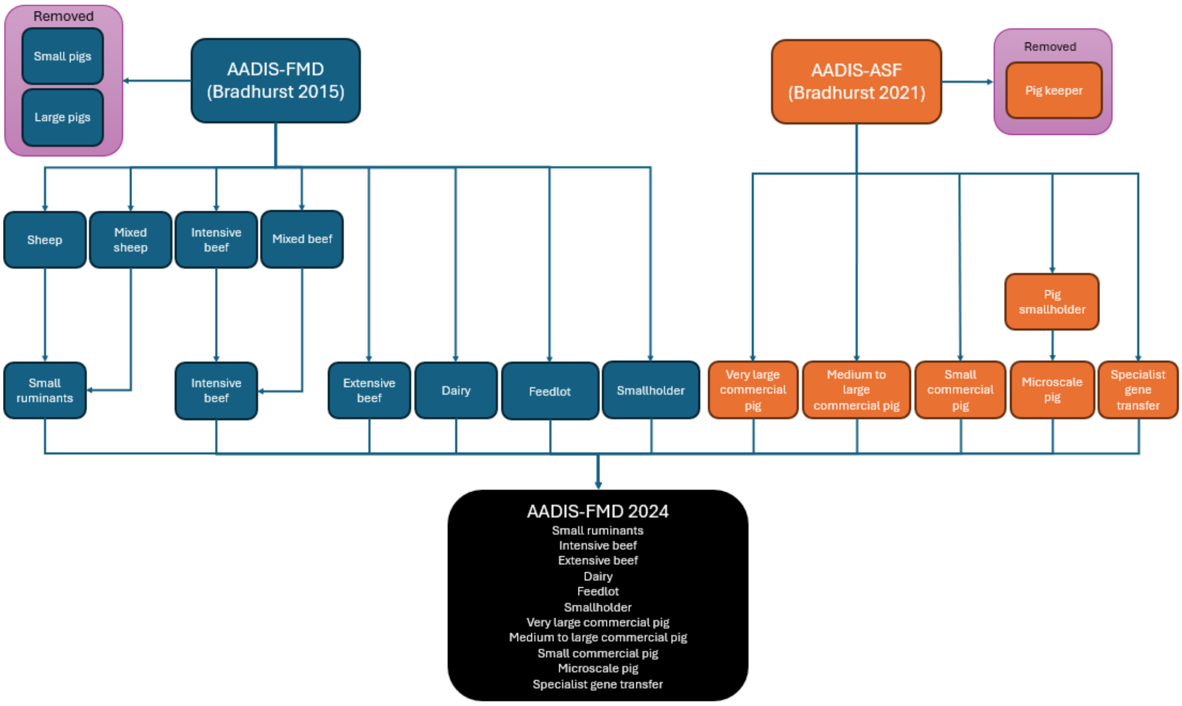


Figure 1. Integration of AADIS-FMD and AADIS-ASF herd types into the new AADIS-FMD-FP model.

2.1.5 Distribution of herd types in Australia

Table 3. Cattle herds per jurisdiction

Jurisdiction	Extensive Beef		Intensive Beef		Feedlot		Dairy	
	Head	Herds	Head	Herds	Head	Herds	Head	Herds
NSW/ACT	19,350	48	3,912,731	14,927	224,868	60	284,912	878
VIC	0	0	2,062,271	10,164	61,992	21	1,444,181	3406
QLD	3,521,529	3327	5,871,358	11,118	1,213,751	137	123,500	501
SA	129,840	132	765,437	2610	39,752	22	111,737	220
WA	1,202,847	456	766,377	2405	53,475	11	109,424	177
TAS	0	0	463,532	1531	6908	1	309,619	406
NT	1,733,331	537	4,017	9	0	0	0	0
Australia	**6,606,897**	**4500**	**13,849,810**	**26**	**1,600,746**	**252**	**2,383,373**	**5588**

Table 3b. Small ruminant and smallholder herds per jurisdiction

Jurisdiction	Sheep		Smallholder	
`	Head	Herds	Head	Herds
NSW/ACT	24,814,883	11,777	182,301	14,566
VIC	15,121,416	8244	146,736	20,548
QLD	4,624,863	2578	58,402	7466
SA	10,347,552	4498	55,902	7500
WA	10,767,384	3706	114119	19495
TAS	2,371,252	1008	34,677	5788
NT	100	1	5506	1020
Australia	**68,047,450**	**31,812**	**597,643**	**76,383**

Table 3c. Pig herds per jurisdiction

Jurisdiction	Very large commercial pig		Medium to large commercial pig		Small commercial pig		Specialist gene transfer pig		Microscale pig	
	Head	Herds	Head	Herds	Head	Herds	Head	Herds	Head	Herds
NSW/ACT	672,312	19	225,772	58	47,488	51	120	1	38,803	392
VIC	649,341	36	368,088	81	42,888	45	469	3	16,303	188
QLD	650,820	25	260,030	60	81,019	240	260	1	16,257	323
SA	341,464	18	304,902	66	28,573	34	401	1	12,532	85
WA	459,385	20	204,950	39	17,227	19	0	0	8700	74
TAS	15,400	1	5797	2	5000	6	0	0	425	1
NT	0	0	0	0	0	0	0	0	85	1
Australia	**2,788,722**	**119**	**1,369,539**	**306**	**222,195**	**395**	**1250**	**6**	**93,105**	**1064**

2.2 Farm risk areas

A farm 'risk area' is defined as the area in which direct or indirect contact with feral pigs might occur. This encompasses paddocks, sheds, internal roads, dams, effluent ponds, dead pits, etc. It is not feasible to include actual farm boundaries in a model of national scale, so a farm's risk area is approximated by a circle with radius *r1* (Figure 2). The size of the risk area is based on

- production system (farm type)
- number of animals (farm size)
- livestock region (Figure 3)

When a farm is comprised of multiple herds then the farm risk area is the sum of the constituent herd risk areas.

Feral pig home ranges are modelled in AADIS-ASF and AADIS-FMD-FP as circles with radius r2 that can vary regionally and seasonally. When feral pigs roam near farms, there is potential for direct or indirect contact with livestock, which can facilitate the spread of disease. In AADIS, spillover transmission may occur if a farm's risk area overlaps with the home range of a feral pig group (Figure 2). The inclusion of spatial risk areas for farms is a significant improvement over the legacy representation of a farm as simply a point of latitude and longitude.

AADIS provides three ways to estimate a herd's risk area :

Method 1: Stocking rates

Stocking rates in terms of head per hectare are defined per herd type, per region (Tables 4-9). This approach considers regional stocking rate differences due to environmental factors like land fertility, water availability, and climate, which affect pasture quality and carrying capacity. Different herd types also have specific land requirements and management practices that influence stocking rates.

herd risk area (ha) = (herd size / stocking rate) * buffer **Equation 1.**

where

herd size = number of animals in the herd
stocking rate = head per hectare
buffer = optional multiplier defined per herd type, per region

The following sources were used to estimate stocking rates for cattle and sheep farms: Elphinstone & Wedlock, 2015; Blackwood et al., 2006; Hassall & Associates, 2006; Pettit, 2011; Meat and Livestock Australia – pers. comms, 2024; Australian Lot Feeders Association – pers comms, 2024; Landscape South Australia, Hills and Fleurieu (2024), NSW Department of Primary Industries, 2022; Northern Territory Govt, 2011.

Method 2: Logarithmic equation

The stocking rate method is not well suited to intensive shed-based production systems. Instead, simple logarithmic curves are used to link herd size to herd risk area per Equation 2.

$$risk\ area\ (ha) = \max\left(minArea, A + B\ln(x)\right)$$ **Equation 2.**

where

x = the number of animals in the herd

minArea = minimum allowable risk area for the herd type (to ensure that the calculated risk area doesn't fall below a realistic estimate),

A, *B* = shape coefficients

Method 3: Constants

In situations where data is scarce (e.g., smallholders), risk areas can be defined as constant values (in hectares) per herd type, per region.

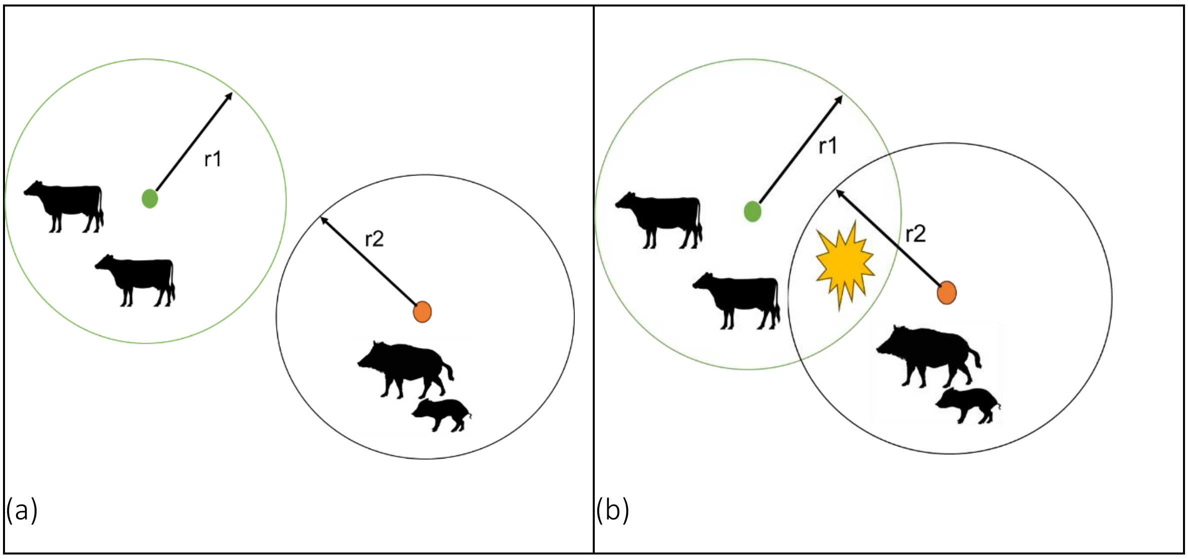
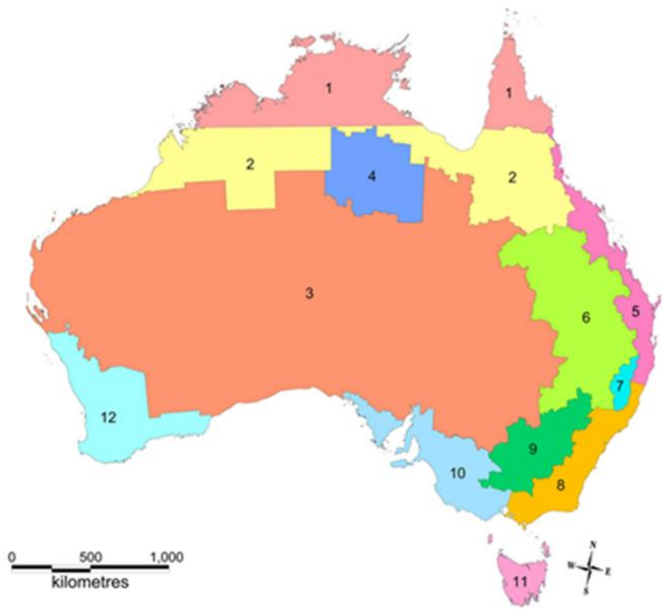


Figure 2. In (a), spillover transmission cannot occur as the farm's risk area (radius *r1*) does not overlap with the feral pig group's home range (radius *r2*). In (b), spillover transmission may occur as the farm's risk area and the feral pig group's home range overlaps.



1. Far North
2. Lower North
3. Arid zone
4. Barkly
5. Tropical NE Coast
6. Central Qld and northern NSW
7. New England
8. Temperate SE Coast
9. Temperate Slopes
10. Mediterranean
11. Tasmania
12. SW WA

Figure 3. Livestock regions.

AADIS mega-regions are groupings of livestock regions per below.

Mega-region ID	Mega-region name	Constituent regions
1	Pastoral	Far North (1), Lower North (2), Arid Zone (3), Barkly (4)
2	North-East	Tropical NE Coast (5), Central Qld & northern NSW (6), New England (7)

3	South-East	Temperate SE Coast (8), Temperate Slopes & plains (9), Mediterranean (10), Tasmania (11)
4	South-West	SW WA (12)

Sections 2.2.1 to 2.2.9 describes the methods used to define risk areas for each herd type. Each method allows minimum and maximum risk areas to be defined per herd type, per region, to ensure that the calculated risk areas do not fall outside reasonable bounds.

2.2.1 Extensive beef farms

The risk area for extensive beef herds was estimated via *stocking rates* defined per region (Equation 1; Table 4). The minimum risk area was set to 500 ha and the maximum set to 2,000,000 ha.

Table 4. Calculated extensive beef farm risk areas by region.

Region	Region name	Average herd size	Stocking rate (head/ha)	Extensive beef farm risk area (ha)		
				Mean	*Min*	*Max*
1	Far North	1762	0.04	132,119	1,500	1,125,300
2	Lower North	1330	0.04	99,779	1,500	1,384,950
3	Arid zone	1301	0.22	97,603	25,050	63,1575
4	Barkly Tableland	8953	0.08	335,723	22,0125	50,8950

Note: All extensive beef farms have three herds.

2.2.2 Intensive beef farms

The risk area for intensive beef herds was estimated via *stocking rates* defined per region (Equation 1; Table 5). The minimum risk area was set to 100 ha and the maximum set to 50,000 ha.

Table 5. Calculated intensive beef farm risk areas by region.

Region	Region name	Average herd size	Stocking rate (head/ha)	Intensive beef farm risk area (ha)		
				Mean	*Min*	*Max*
1	Far North	237	0.04	5,915	825	16,350
2	Lower North	373	0.04	9,331	575	38,275
3	Arid zone	391	0.22	9,773	300	24,950
5	Tropical NE Coast	291	0.4	728	100	9,350
6	Central Qld and northern NSW	615	1.3	482	100	5,625
7	New England	401	1.1	373	100	3,006
8	Temperate SE Coast	214	1.4	178	100	1,899
9	Temperate Slopes	227	1.4	186	100	1,336
10	Mediterranean	259	1.125	247	100	2,323
11	Tasmania	303	1.4	239	100	2,518
12	SW WA	307	0.93	340	100	2,524

2.2.3 Feedlots

The following advice on typical feedlot areas was sourced from MLA:

i) Pen area = maximum number of cattle multiplied by the stocking density.
ii) Stocking density = 12 m²/head (833.33 head/ha)
iii) Total feedlot complex area = at least three times the pen area.

Further advice was received from representatives of the Australian Lot Feeders Association:

iv) Feedlots typically stock at 80% capacity; thus, the maximum number of cattle will be the herd size * 1.2
v) Additional land will be needed for effluent irrigation and solid manure disposal, as well as a buffer zone between the feedlot development and nearby sensitive receptors. The buffer also accounts for areas where cattle may be held for short periods prior to induction and movement to feedlot pens. Following consultation with the Australian Lot Feeder's Association, a 100% buffer was applied to the calculated total feedlot complex area.

The risk area for feedlot herds was estimated via *stocking rates* defined per region (Equation 1; Table 6). The minimum risk area was set to 10 ha and the maximum set to 6000 ha. A buffer multiplier of 7.2 was applied to account for iii), iv) and v) above. Co-located farming operations (i.e. grazing cattle) were not considered in estimates.

Table 6. Calculated feedlot risk areas by region.

Region	Region name	Average herd size	Stocking rate (head/ha)	Feedlot risk area (ha)		
				Mean	*Min*	*Max*
2	Lower North	2,890	833.33	26.66	10.00	60.19
3	Arid zone	9,894	833.33	85.48	10.11	385.11
5	Tropical NE Coast	11,467	833.33	99.93	10.00	701.08
6	Central Qld & northern NSW	7,472	833.33	65.28	10.00	354.30
7	New England	3,603	833.33	31.17	10.00	51.51
8	Temperate SE Coast	3,769	833.33	32.57	11.75	93.64
9	Temperate Slopes	2,933	833.33	27.32	10.00	175.85
10	Mediterranean	2,257	833.33	20.91	10.00	76.95
11	Tasmania	6,908	833.33	59.69	59.69	59.69
12	SW WA	4,861	833.33	42.95	10.00	162.23

2.2.4 Dairies

The risk area for dairy herds was estimated via *stocking rates* defined per region (Equation 1; Table 7). The minimum risk area was set to 100 ha and the maximum set to 5,000 ha.

Table 7. Calculated dairy farm risk areas by region.

Region	Region name	Average herd size	Stocking rate (head/ha)	Dairy farm risk areas (ha)		
				Mean	*Min*	*Max*
5	Tropical NE Coast	264	1.2	238	100	1,408
6	Central Qld and northern NSW	198	1.3	182	100	892
7	New England	171	1.3	158	100	436
8	Temperate SE Coast	392	1.5	276	100	2,793
9	Temperate Slopes	379	1.5	262	100	1,431
10	Mediterranean	470	1.1	430	100	4,078
11	Tasmania	763	2.5	310	100	1,157
12	SW WA	618	0.8	779	100	4,874

2.2.5 Small ruminant farms

The risk area for intensive beef herds was estimated via *stocking rates* defined per region (Equation 1; Table 8). The minimum risk area was set to 100 ha and the maximum set to 1,000,000 ha.

Table 8. Calculated small ruminant farm risk areas by region.

Region	Region name	Average herd size	Stocking rate (head/ha)	Small ruminant farm risk area (ha)		
				Mean	*Min*	*Max*
1	Far North	44	0.04	1,092	200	2,500
2	Lower North	1,420	0.04	35,490	250	126,425
3	Arid zone	4,297	2	2,150	100	12,406
5	Tropical NE Coast	109	3.6	109	100	1,064
6	Central Qld & northern NSW	1,694	12	177	100	1,634
7	New England	1,732	10	195	100	1,050
8	Temperate SE Coast	1,420	8	208	100	1,451
9	Temperate Slopes	2,075	7	310	100	1,450
10	Mediterranean	2,133	9	256	100	3,366
11	Tasmania	2,352	11	244	100	1,846
12	SW WA	2,863	7.5	394	100	2,549

2.2.6 Mixed farms

The risk area for mixed farms (Table 9) was estimated using the previously described methods for intensive beef herds and small ruminant herds.

Table 9. Calculated mixed farm risk areas by region.

Region	Region name	Average herd size	Mixed farm risk area (ha)		
			Mean	*Min*	*Max*
3	Arid zone	1,857	5,731	3,168	9,266
5	Tropical NE Coast	1,337	2,563	2,563	2,563

6	Central Qld and northern NSW	1,301	664	200	4,318
7	New England	576	319	312	327
8	Temperate SE Coast	1,518	624	200	1,798
9	Temperate Slopes	1,231	566	200	3,131
10	Mediterranean	1,460	469	200	1,781
12	SW WA	1,926	906	200	3,024

2.2.7 Pig farms

The *logarithmic equation* method was used for commercial piggeries. The parameter values (Table 10) were estimated by fitting curves to limited empirical data (Sara Willis, Kirsty Richards & Zane Wilkinson, pers. comms., November 2024) and will be refined as more information becomes available.

The *constants* method was employed for specialist gene transfer herds and microscale piggeries.

Table 10. Parameters for calculating the risk areas of pig farms

Pig farm type	Min risk area (ha)	Max risk area (ha)	*A*	*B*
Very large commercial	150	500	100	20
Medium to large commercial	75	250	40	10
Small commercial	50	100	30	5
Specialist gene transfer	40	40	N/A	N/A
Microscale	20	20	N/A	N/A

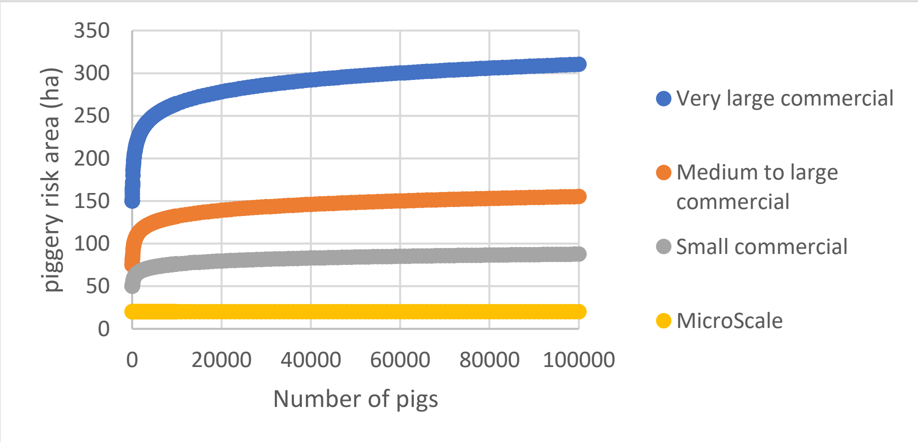


Figure 4. Calculated risk areas for piggeries.

Table 11. Calculated risk areas for very large commercial piggeries by region.

Region	Region name	Average herd size	**Very large commercial piggery risk area** (ha)		
			Mean	*Min*	*Max*
5	Tropical NE Coast	14,533	291	284	296
6	Central Qld and northern NSW	31,575	303	289	331

8	Temperate SE Coast	10,235	285	285	285
9	Temperate Slopes	26,661	299	267	325
10	Mediterranean	19,529	296	282	316
11	Tasmania	15,400	293	293	293
12	SW WA	22,969	298	284	318

Table 12. Calculated risk areas for medium to large commercial piggeries by region.

Region	Region name	Average herd size	Medium to large commercial piggery risk area (ha)		
			Mean	*Min*	*Max*
2	Lower North	2500	118	118	118
3	Arid zone	3800	122	122	122
5	Tropical NE Coast	4208	122	115	129
6	Central Qld and northern NSW	4151	122	113	132
7	New England	2336	118	118	118
8	Temperate SE Coast	3506	121	113	127
9	Temperate Slopes	4480	123	113	132
10	Mediterranean	4546	123	113	132
11	Tasmania	2899	119	116	123
12	SW WA	5255	124	115	132

Table 13. Calculated risk areas for small commercial piggeries by region.

Region	Region name	Average herd size	Small commercial piggery risk area (ha)		
			Mean	*Min*	*Max*
2	Lower North	261	54	50	65
3	Arid zone	1000	65	65	65
5	Tropical NE Coast	475	58	50	67
6	Central Qld and northern NSW	272	55	50	67
7	New England	900	64	64	64
8	Temperate SE Coast	917	64	61	67
9	Temperate Slopes	958	64	61	67
10	Mediterranean	882	64	61	66
11	Tasmania	833	63	62	65
12	SW WA	907	64	61	67

2.2.8 Smallholders

Smallholder herds were estimated to operate on a fixed land area of 20 hectares (Table 14) (Hernández-Jover et al., 2014). A range of land areas was not utilised due to lack of available real data on smallholders.

Table 14. Calculated risk areas for smallholders by region.

Region	Region name		Smallholder risk area (ha)

		Average herd size	*Mean*	*Min*	*Max*
1	Far North	5	20	20	20
2	Lower North	7	20	20	20
3	Arid zone	8	20	20	20
5	Tropical NE Coast	8	20	20	20
6	Central Qld and northern NSW	11	20	20	20
7	New England	11	20	20	20
8	Temperate SE Coast	9	20	20	20
9	Temperate Slopes	12	20	20	20
10	Mediterranean	7	20	20	20
11	Tasmania	6	20	20	20
12	SW WA	6	20	20	20

2.3 Transmission of FMD in livestock

2.3.1 Within-herd spread

AADIS considers a herd to be homogeneous and 'well-mixed' from a disease transmission point of view, i.e., all members of a herd are biologically equivalent and equally likely to contract a disease (Keeling and Rohani, 2008). When a herd becomes infected, it acquires an SEIRD (susceptible, exposed, infectious, recovered, deceased) compartmental equation-based model (EBM) that predicts the herd's infected, infectious and clinical prevalence over time. The parameterisation of the EBM considers herd type, herd size, and FMD strain (PanAsia type O), and is provided in Appendix C. Further details on the within-herd EBM can be found in Bradhurst 2015; Bradhurst et al., 2015 and Bradhurst et al., 2021.

2.3.2 Between-herd spread

AADIS employs a stochastic and spatially explicit agent-based model (ABM) to represent the spread of disease between domestic herds (Bradhurst 2015; Bradhurst et al., 2015; 2016). The levels of infected and infectious prevalence predicted by a herd's EBM inform the likelihood that disease will spread between herds. The AADIS-FMD and AADIS-FMD-FP models both employ the following spread pathways:

- Local spread (short-range catch-all spread within 3km of an infected herd)
- Direct spread (direct contacts due to movements of infected animals)
- Saleyard spread (amplification of infection arising from marketing systems)
- Indirect spread (indirect contacts via environment or movement of fomites)
- Airborne spread (viral plumes emanating from large pig herds)

The parameterisation of the above pathways in the AADIS-FMD-FP model is the same as the AADIS-FMD model and is not described in this report. Details can be found in Bradhurst 2015; Bradhurst et al., 2015; Capon et al., 2021.

2.3.3 Directed spread

In the legacy AADIS-FMD model, the direct spread of FMD via live animal movements was modelled stochastically based on trends derived from historical movement data. This approach was ill-suited to the Australian pig industry where commercial animal movements are typically more directed and predictable, for example, routine transfers between sites of a vertically integrated operation and periodic consignments for specific domestic pork markets. A new network-based 'directed' spread pathway was developed for the AADIS-ASF model that replays historical movements of pigs as recorded in NLIS. This provides much more realistic estimations of the direct transmission of infection between piggeries and between piggeries and abattoirs/saleyards.

As part of this project, the directed spread pathway developed for the AADIS-ASF model was incorporated into the AADIS-FMD-FP model. Movements emanating from commercial and microscale pig herds are modelled with the directed spread pathway while movements out of beef, dairy, small ruminant and smallholder herds are modelled with the legacy stochastic direct spread pathway. The choice between direct spread and directed spread is determined by the 'directed movements' Boolean attribute in the Herd Type table.

2.4 Domestic Control Measures

Australia's response strategy to an outbreak of FMD is outlined in the AUSVETPLAN Response Strategy for FMD (Animal Health Australia, 2024). The default response is to control and eradicate FMD in the shortest time possible to regain FMD-free status, whilst minimising socioeconomic impacts. The key simulated control measures in livestock are movement controls, surveillance, tracing, and infected premises operations (valuation, destruction, disposal, and decontamination). Control measures are configured and resourced per jurisdiction. Details on the implementation of domestic control measures can be found in Bradhurst 2015; Bradhurst et al., 2015; Capon et al., 2021; Bradhurst et al., 2021 and Bradhurst et al., 2022. Selected parameterisation of the AADIS-FMD-FP control measures is provided in Appendix E.

Inherited AADIS-FMD cost estimates (per herd type) for surveillance, destruction, disposal, disinfection, compensation, and vaccination were adjusted for inflation to the 2023/24 financial year and incorporated into the AADIS-FMD-FP model. The revised values are not provided in Appendix E as control costs were not included in the case studies.

2.5 Feral pigs

The feral pig population layers previously developed for the AADIS-ASF model (Bradhurst et. al., 2021; 2022) were incorporated into the AADIS-FMD-FP model. These layers provide monthly estimates of feral pig distribution and abundance relative to seven wildlife regions (Figure 5; Table 15).

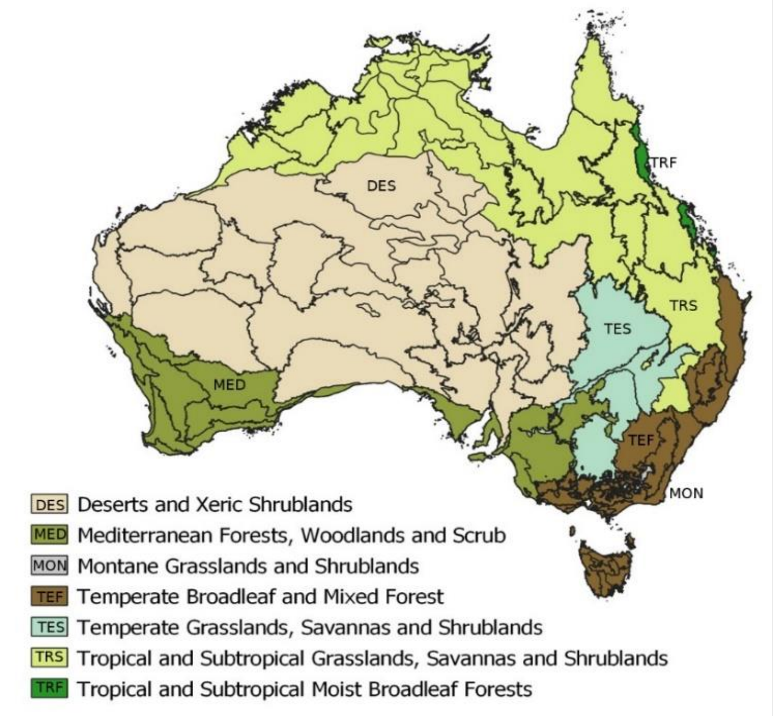


Figure 5. Wildlife regions used by the AADIS-ASF model (Department of Sustainability, Environment, Water, Population and Communities, 2021)

Table 15. Wildlife regions used by the AADIS-ASF model (adapted from Department of Sustainability, Environment, Water, Population and Communities, 2021)

Region	Name	Description
DES	Deserts and xeric shrublands	Annual rainfall varies greatly and generally is exceeded by evaporation. Temperature extremes are typical with searing daytime heat and cold nights due to limited insulation from humidity and cloud cover.
MED	Mediterranean forests, woodlands and shrubs	Hot and dry summers, while winters tend to be cool and moist.
MON	Montane grasslands and shrublands	High elevation (montane and alpine) grasslands and shrublands in south-eastern Australia including the Australian Alps and parts of Tasmania.
TEF	Temperate broadleaf and mixed forests	Moderate climate and high rainfall that give rise to unique eucalyptus forests and open woodlands.

TES	Temperate grasslands, savannas and shrublands	Cooler and wider annual temperatures than tropical grasslands. Much of this region has been converted to sheep rearing and wheat cropping, and only small fragments of the original eucalypt vegetation remains.
TRS	Tropical and subtropical grassland, savannas and shrublands	Tropical areas with rainfall levels that do not support extensive tree cover. Examples are the Kimberley, Top End, and Cape York savannas.
TRF	Tropical and subtropical moist broadleaf forests	Low variability in annual temperature and high levels of rainfall. Dominated by semi-evergreen and evergreen deciduous tree species. Australia has a small and scattered areas of this type of forest in Queensland and Norfolk Island. These forests are of particular interest for the high degree of endemism of their plant (many with ancient lineages) and animal species.

Following input from feral pig experts at a project workshop, the following updates were carried out on the distribution and abundance layers.

2.5.1 Key updates in feral pig distribution and abundance.

The AADIS-FMD-FP model has refined the spatial distribution of feral pigs as follow:

- **Tasmanian region**: The Tasmanian feral pig population was adjusted in the AADIS-FMD-FP feral pig layers (Figure 6) reflecting the current understanding that there are no feral pigs present on the main island. The feral pig population on Flinders Island was, however, retained reflecting their occurrence and management under the Feral Pig Management Plan.
- **Randomized feral pig group locations**: Prior to this project, the AADIS-ASF model positioned feral pig groups at the centroid of their home cell, and this resulted in a lack of variability in their simulated home ranges over time (Figure 7). A new option was added to the AADIS-FMD-FP model for feral pig groups to be allocated at random locations inside their home cell (Figure 8). The randomly assigned location can either be retained for all simulation runs or re-allocated at the start of each run. This improvement was also retrofitted to the AADIS-ASF model.

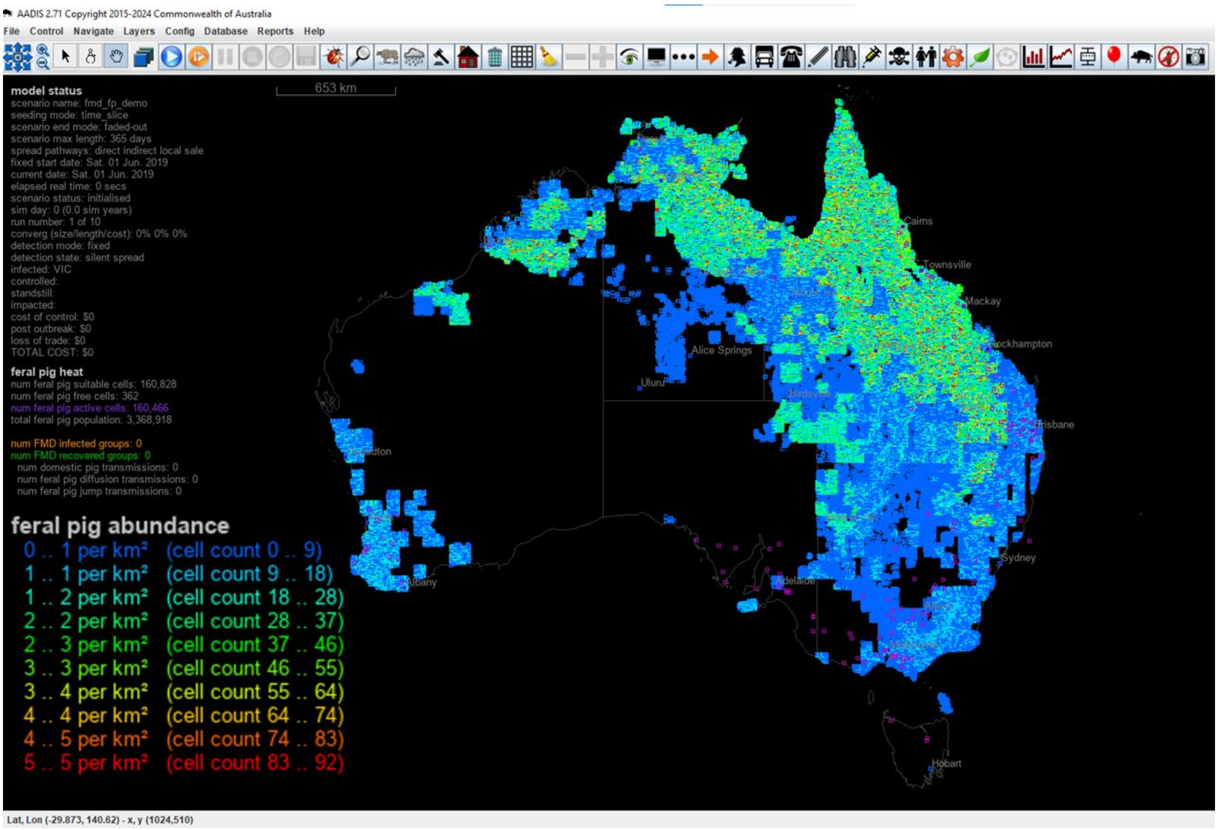


Figure 6. A heat map of modelled feral pig distribution and abundance in AADIS-FMD-FP.

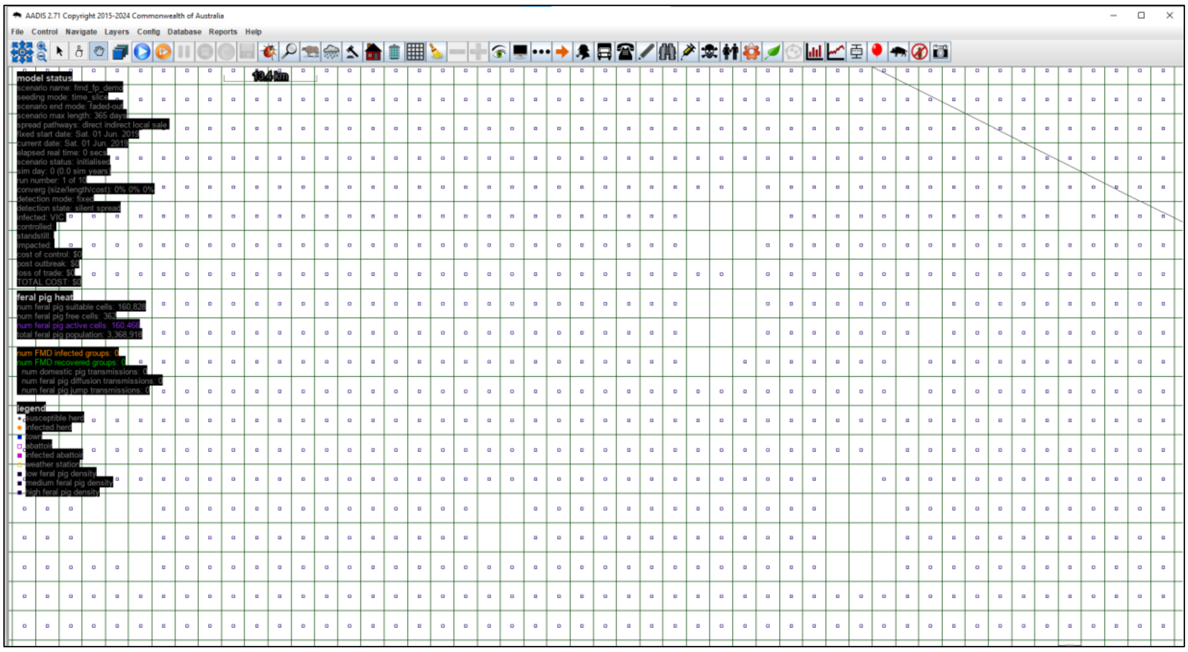


Figure 7. Example of an initial feral pig distribution where groups are located at the centroid of populated cells.

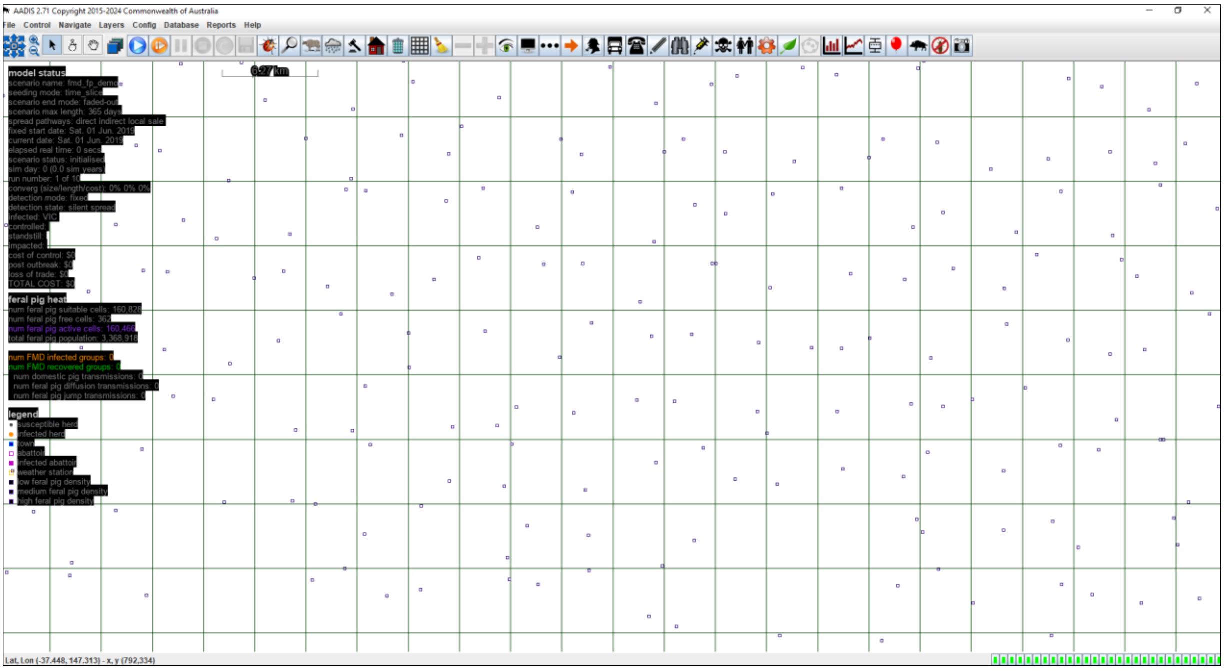


Figure 8. Example of an initial feral pig distribution where groups are located randomly inside populated cells.

2.5.2 Statistical summary of the national feral pig dataset

The number of cells with a modelled feral pig population is summarized by wildlife region in Table 16. The total modelled area of Australia, based on terrestrial cells, is 7.73 million km², aligning closely with the official reported figure of 7.69 million km². After removing feral pig populations from Tasmania (while retaining them on Flinders Island), the modelled occurrence of feral pigs in Australia now covers 2.57 million km², approximately 33.3% of the land area. This coverage is lower than the 3.46 million km² estimate from West et al. (2008) but remains broadly consistent with recent estimates of feral pig distribution and abundance (Hone, 2020). Note that Figures 6 and 10, and Table 16 illustrate the modelled occurrence of feral pigs, not the broader habitat suitability, which would encompass a larger area.

Table 16. Statistical summary of modelled feral pig distribution by wildlife region.

Wildlife Region	Area	Number of cells	Approx. total area (km²)	Populated area (km²)	Populated area (%)	Average density in populated areas (pigs/km²)
DES	Central	222,783	3,564,528	262,352	7.36%	0.84 – 1.37
MED	South	52,170	834,720	191,760	22.97%	0.46 – 0.72
MON	Central	869	13,904	12,928	92.98%	0.57 – 0.90
TEF	South	37,737	603,792	305,458	50.59%	0.36 – 0.56
TES	Central	34,445	561,120	329,424	59.77%	0.48 – 0.76
TRS	North	132,183	2,114,928	1,434,848	67.84%	0.99 – 1.80
TRF	North	2160	34,560	30,656	88.70%	1.26 – 2.30
Total	**All**	**482,347**	**7,727,552**	**2,565,548**	**33.27%**	

Figure 9 illustrates the modelled feral pig population in Australia over a 12-month period ranging from 1.4 million in October up to 3.5 million in May. The number of feral pigs is dominated by the heavily populated TRS wildlife region in tropical north Queensland (Figure 5). This is consistent with West et al., (2008), Gentle et al., (2019) and Hone (2020).

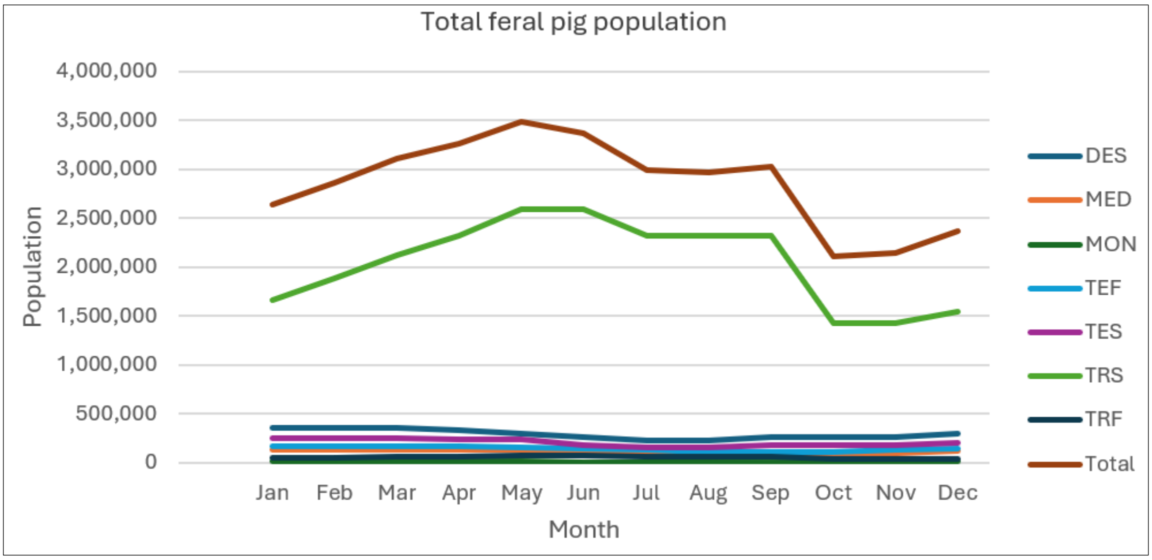


Figure 9. Modelled total feral pig population in Australia by wildlife region by month.

Figure 10 illustrates the modelled average number of feral pigs per cell, per month, by wildlife region (populated cells only). Figure 11 illustrates the 95th percentile number of feral pigs per cell per month, by wildlife region (populated cells only). The modelled population density of up to 4.6 feral pigs per km^2 in northern Qld are consistent with Twigg et al. (2005), Gentle & Pople (2013), Hone (2020) and Gentle et al. (2019). The average feral pig group size ranges from 6 to 37 across Australia, and this is consistent with Choquenot et al. (1996), Twigg et al. (2005) and Cowled et al. (2012).

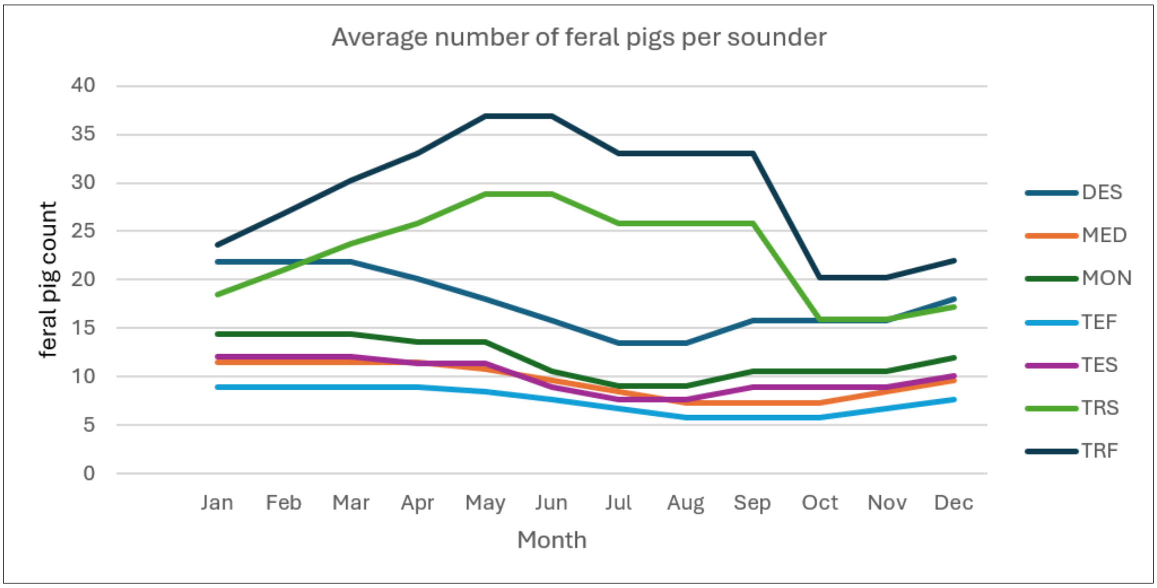


Figure 10. Average number of modelled feral pigs per group per month, by wildlife region.

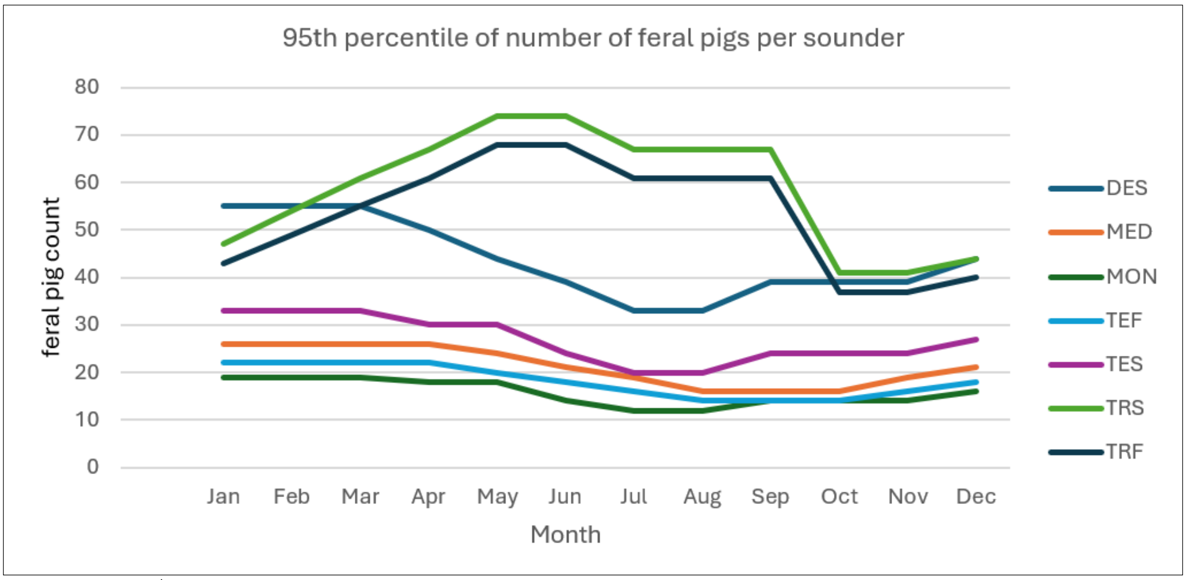


Figure 11. 95th percentile of the number of feral pigs per group per month, by wildlife region.

2.5.3 Feral pig home ranges

GPS collaring studies have demonstrated that feral pig home range geometry varies (Mitchell et al., 2009; Wilson et al., 2023; Miettinen et al., 2023). As the AADIS-FMD-FPF model is national scale, it was necessary to simplify home ranges as circles with a radius that can vary regionally and seasonally. The centre of a home range circle can be configured to be at the centroid of the home cell, or a randomly selected location inside the home cell (Section 2.5.1). The configured values for home range radii were taken from the AADIS-ASF model (Bradhurst et al., 2022) and are provided in Appendix D.

2.5.4 Transmission of FMD in feral pigs

2.5.4.1 Within-group transmission

AADIS considers a feral pig group to be homogeneous and 'well-mixed' from a disease transmission point of view, i.e., all members of a group are deemed biologically equivalent and equally likely to contract a disease (Keeling and Rohani, 2008). When a group becomes infected, it acquires the same SEIRD compartmental EBM as a domestic herd (Section 2.3.1), that predicts the group's infected, infectious and clinical prevalence over time. The parameterisation of the feral pig EBM is provided in Appendix A. Further details on the AADIS within-herd EBM can be found in Bradhurst 2015; Bradhurst et al., 2015 and Bradhurst et al., 2021.

2.5.4.2 Between-group transmission

When the home range of an infectious feral pig group overlaps with the home range of a susceptible feral pig group, there is potential for direct or indirect contact which can lead to the spread of disease. The short-range diffusive spread of FMD between groups of feral pigs is modelled with a contact rate approach where the probability of transmission is based on a daily likelihood of a direct/indirect contact, in conjunction with a probability that the contact was effective. The pathway is aggregative in that it combines direct, indirect and short-range airborne spread mechanisms into a simplified kernel.

The number of daily contacts that a feral pig group has with neighbouring groups is determined by sampling a Poisson distribution of the configured contact rate. The probability that the contact is effective (i.e., results in the transmission of infection), is given by Equation 3.

$$P_d = P_b\, d_i(t)\, p(t)\, d_s(t)\, W_x \qquad \text{Equation 3.}$$

where

p_d = probability of transmission between an infectious group and an exposed group
P_b = average probability that a contact is effective (defined per region)
$d_i(t)$ = normalised population density of the infectious group on day t
$p(t)$ = normalised infectious prevalence (including carcasses) of the infectious group on day t
$d_s(t)$ = normalised population density of the exposed group on day t
W_x = seasonal weight (reflecting how varying environmental conditions influence virus viability, defined per month, per region)

Further details on the pathway can be found in Bradhurst et al., 2022. The parameterisation is provided in Appendix B.

2.5.4.3 Spillover transmission between feral pigs and livestock

The feral pig spillover pathway from the AADIS-ASF model (Bradhurst et al., 2021; 2022) was incorporated into the AADIS-FMD-FP model. The pathway is aggregative in that it combines direct, indirect and short-range airborne spread mechanisms into a simplified kernel. An important improvement was made to this pathway with the introduction of farm risk areas to provide a better spatial representation of the potential overlap with feral pig home ranges (Section 2.2). This improvement to the feral pig spillover pathway was also retrofitted to the AADIS-ASF model.

On-farm biosecurity can play an important role in preventing transmission spillover events. Biosecurity levels are defined per herd, and this influences the likelihood of local, indirect and spillover transmission into a susceptible farm. Details on the AADIS implementation of on-farm biosecurity can be found in Bradhurst et al., 2021 and 2022.

2.5.5 Population management and control difficulty index

Feral pig management is simulated in the AADIS-FMD-FP model as the removal of a proportion of the population inside a radial area. The method of population thinning (ground baiting, ground shooting, aerial baiting, helicopter shooting, etc.) is not specified, just the target area radius, duration, cost and effectiveness. An example configuration is "reduce the feral pig population by 70% within a 5 km control radius of an IP over a period of 21 days at a cost of A$10,000".

The trigger for feral pig population control is configurable and can be due to a detection of FMD in feral pigs or a detection of FMD in livestock. Further details on the implementation of feral pig surveillance and control are available in Bradhurst et al., 2021.

A control difficulty index (CDI) was implemented in the model as a raster layer, in which values range from 0 to 6 (Figure 12), where higher values (red) indicate more challenging conditions for control operations compared to moderate (yellow) and easy (green) conditions (Hoskins and Perry, 2020). This index considers the ability to mobilize resources, conduct ground and aerial control, and remove carcasses. For instance, areas with high CDI values might have dense forests, rugged terrain, and/or limited road access, making it difficult and resource intensive to find and manage feral pigs.

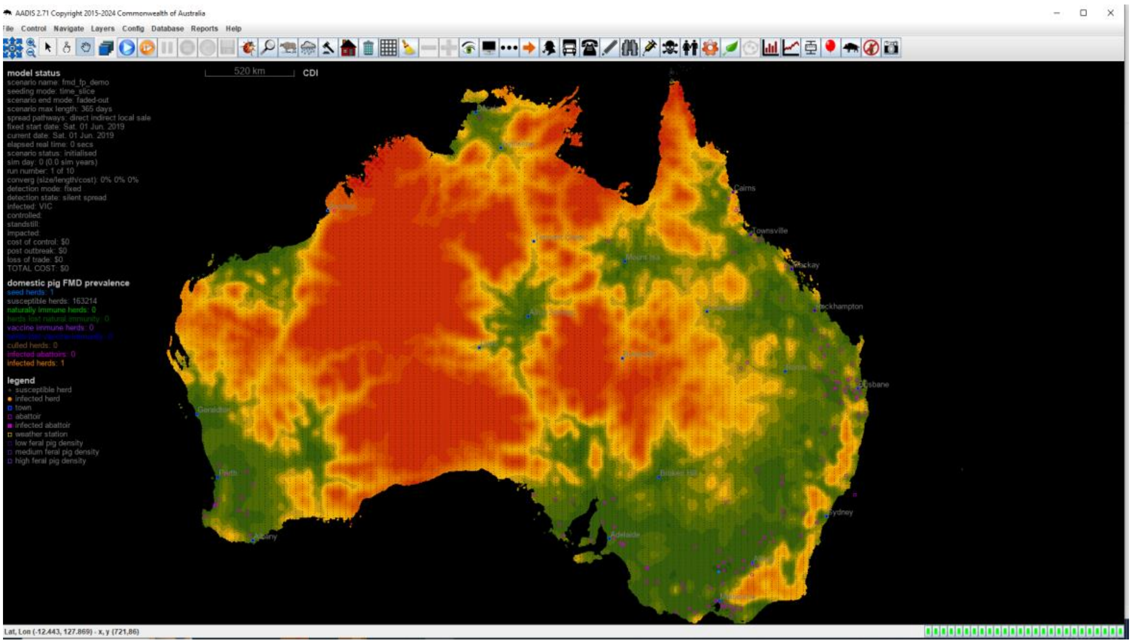


Figure 12. CDI layer used in AADIS-FMD-FP

The CDI can be configured to influence the duration of feral pig population thinning and/or the effectiveness. For example, assuming the configuration in Table 17, if the CDI is configured to influence control duration, then an action that takes 14 days in an easy area will take 21 days in a moderate area, and 28 days in a difficult area. If the CDI is configured to influence control effectiveness, then an action that is configured to thin a population by 80% in an easy area, will only thin the population by 64% in a moderate area, and by 56% in a difficult area. The CDI configuration used for the case studies is provided in Appendix E.

Table 17. Example CDI configuration

CDI	control difficulty	control duration multiplier	control effectiveness multiplier
0.0 ≤ CDI < 2.0	easy	1.0 (baseline)	1.0 (baseline)
2.0 ≤ CDI < 4.0	moderate	1.25	0.8
4.0 ≤ CDI < 6.0	difficult	1.5	0.7

After a feral pig population has been thinned, the model allows the population to recover over time (Bradhurst et al., 2021; 2022). The configuration used in the AADIS-FMD-FP model is provided in Appendix A.

2.6 Verification and validation

Verification is the process of ensuring that a model has been implemented correctly (Dent & Blackie, 1979; Sargent, 2013). It targets the mechanics of the software development process and helps assess whether 'the product has been built right'. Validation, on the other hand, looks at the bigger operational picture and helps assess whether 'the right product has been built' (Siviy et al., 2007), i.e., whether it is fit for purpose.

It is challenging to validate epidemiological models when the subject disease has never been detected in the subject country. The AADIS modelling framework has previously been through extensive verification and comparative validation in the context of FMD (Bradhurst, 2015; Bradhurst, Garner, Hóvári, et al., 2022; Bradhurst et al., 2015; Bradhurst et al., 2016; Capon et al., 2021), ASF (Bradhurst et al., 2021;2022) and *Mycoplasma bovis* (Bradhurst et al., 2022). All AADIS models share the same code baseline, and past verification and validation activities provide confidence in the underlying software processes and broad epidemiological principles of the new AADIS-FMD-FP model.

In the absence of local epidemiological data against which to validate a model, the best option is to gauge model outputs against overseas experience and local expectations. The case studies presented in Section 3 illustrate the utility of the new AADIS-FMD-FP model and provide rudimentary validation on the spread and control of FMD in feral pig populations and between livestock and feral pigs. Validation activities are ongoing via the follow-on project “Models to inform foot-and-mouth disease management in wild host populations in NSW” undertaken by CEBRA in partnership with the NSW Department of Primary Industries.

3 CASE STUDIES

In consultation with jurisdictional and industry stakeholders, five case studies were identified to illustrate how the AADIS-FMD-FP model can help assess the potential for disease transmission between feral pigs and domestic herds in areas where both populations overlap. The case studies explore the seasonal impact on FMD outbreak size and duration, the potential role of feral pigs in transmission, and feral pig control options as part of an FMD response. Figure 13 shows the locations of the five case studies (QLD1, QLD2, NSW1, NSW2, WA1) plus the study area of the Kimberley model comparison (Section 4).

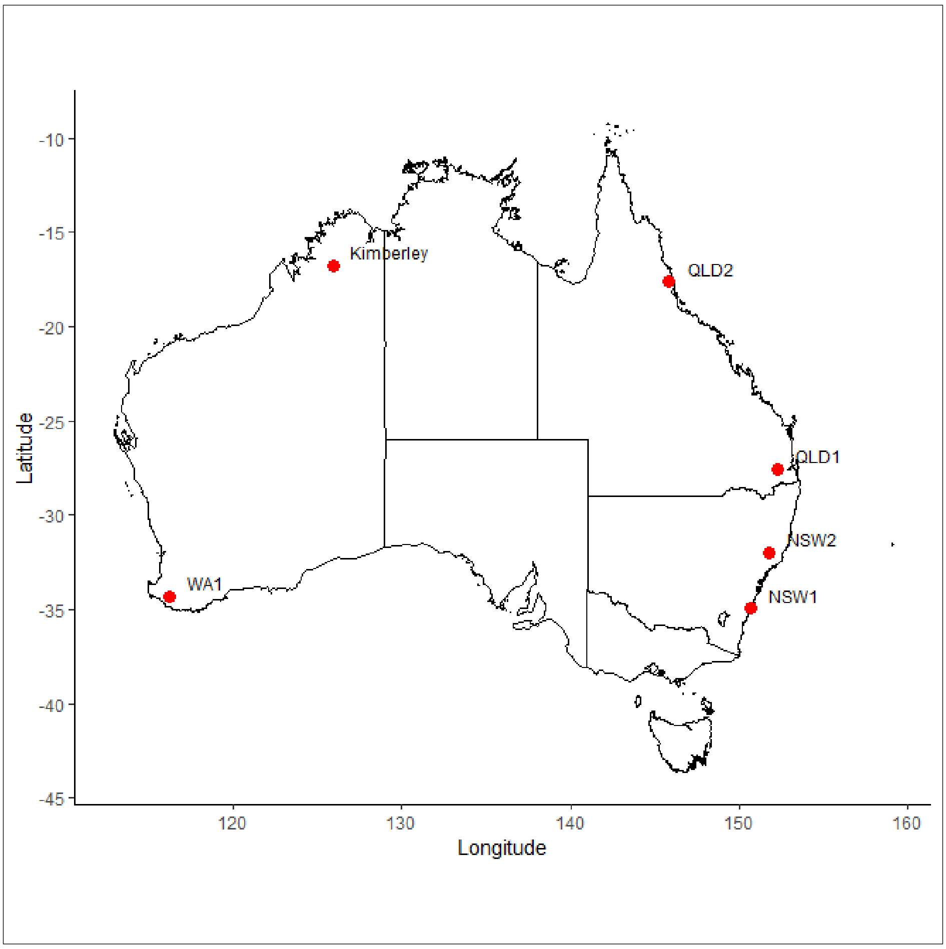


Figure 13. Map of case study locations: QLD1-Placid Hills, QLD2– East Palmerston, NSW1 – Worrigee, NSW2 – Copeland, WA1 – Dingup, Kimberley.

The purpose of the case studies was to illustrate the utility of the new AADIS-FMD-FP model and serve as a rudimentary validation that model outcomes were consistent with overseas experience. The purpose was not to address specific policy questions. This will be done under a follow-on project "Models to inform foot-and-mouth disease management in wild host populations in NSW" undertaken by CEBRA in partnership with the NSW Department of Primary Industries.

3.1 Case Study 1 – QLD1 (small commercial piggery)

3.1.1 Method

FMDV was introduced into a small commercial piggery near Placid Hills in the Darling Downs region of Queensland on May 1st and separately on November 1st. The selected piggery is near extensive beef and dairy herds and the feral pig density in the surrounding 150 km^2 is 0.8/km^2. Control of feral pigs (CDI) is relatively easy in the region (Section 2.6.3). The time to detection was configured to occur in livestock on day 21 of the outbreak. Outbreaks were configured to end upon disease control/fade-out with a maximum outbreak length of 540 days (i.e., outbreaks still active on day 540 were terminated). 1,000 simulation runs were conducted for each scenario.

FMD was allowed to spread within the livestock population via the direct, indirect, local, airborne and saleyard spread pathways. Default domestic control measures and resourcing were employed plus emergency vaccination (Section 2.5). Spillover transmission back and forth with the feral pig population was initially disabled to provide a baseline scenario with no feral pig involvement. Scenarios were then run to demonstrate outbreaks with or without control in feral pigs, and outbreaks in summer versus winter.

Outbreaks in livestock were characterised in terms of number of IPs, duration of control, mix of spread pathways responsible for transmission, number of animals culled. Outbreaks in feral pigs were characterised in terms of number of infected groups, number of infected pigs, area of infection (km^2) and outbreak duration. Welch's t-test ($p < 0.01$) was used to assess the influence of feral pig control and seasonal differences on outbreak size & duration.

Seed Herd ID	Herd type	Size	Initial infection	Lat	Long	Livestock Region	Wildlife region	Cell ID	Feral pigs in cell	Local feral pig density	CDI
53693	Small commercial pig	162	6 exposed	152.2340	-27.5558	Tropical NE Coast	TEF	524245	11	0.8/km^2	1.01

Scenario	Start date	Season	Feral pig spillover	Feral pig control
1	1st May	Winter	disabled	N/A
2	1st May	Winter	enabled	disabled
3	1st May	Winter	enabled	enabled
4	1st Nov	Summer	enabled	disabled
5	1st Nov	Summer	enabled	enabled

3.1.2 Results

Table 18. Domestic outbreak size when seeding FMD into a small commercial piggery in the Darling Downs region of Queensland.

Scenario	Season	Feral pig control	Number of IPS median [5th - 95th] convergence[1]	Control duration (days) median [5th - 95th]	Num animals culled median [5th - 95th]
1	winter	N/A	12 [4 – 44]	55 [41 – 92]	16,692 [1357 – 103,378]
2	winter	disabled	24 [6 – 153] 9%	78 [45 – 519]	24,934 [1705 – 259,646]

3	winter	enabled	22 [6 – 86] 6%	72 [46 – 283]	21,610 [1737 – 153,156]
4	summer	disabled	21 [6 – 105] 6%	69 [46 – 519]	21,535 [1676 – 165,174]
5	summer	enabled	25 [7 – 78] 5%	71 [48 – 288]	24,184 [1939 – 139,643]

[1] percentage standard error of the sample mean (95% confidence)

Table 19. Domestic outbreak spread pathway mix (%) when seeding FMD into a small commercial piggery in the Darling Downs region of Queensland.

Scenario	Season	Feral pig control	local	direct	saleyard	indirect	airborne	feral pigs
1	winter	N/A	59.5	8.5	5.5	21.5	5	0
2	winter	disabled	38.3	3.6	3.1	10.4	2.5	42
3	winter	enabled	43.9	5.1	3.7	13.1	2.7	31.5
4	summer	disabled	44.4	4.3	3.1	13.7	3.1	31.3
5	summer	enabled	46.6	4.9	3.5	14.3	3.1	27.6

Table 20. Feral pig outbreak size and duration when seeding FMD into a small commercial piggery in the Darling Downs region of Queensland.

Scenario	Season	Feral pig control	Spillover (livestock to feral pigs)	infected feral pig groups median [5th – 95th]	infected feral pigs median [5th – 95th]	outbreak area (km^2) median [5th – 95th]	outbreak duration (days) median [5th – 95th]
1	winter	N/A	-	-	-	-	-
2	winter	disabled	89%	3 [0 – 27]	30 [0 – 653]	48 [0 – 428]	66 [33 – 540]
3	winter	enabled	85%	2 [0 – 11]	7 [0 - 89]	32 [0 – 175]	53 [35 – 472]
4	summer	disabled	90%	3 [0 – 14]	19 [0 – 274]	47 [0 – 224]	48 [29 – 540]
5	summer	enabled	91%	3 [0 – 9]	8 [0 – 49]	47 [0 – 143]	50 [34 – 473]

Table 21. Sources of transmission into feral pig groups when seeding FMD into a small commercial piggery in the Darling Downs region of Queensland with no control in feral pigs.

Infection source	Proportion of transmissions into feral pig groups (May outbreak)	Proportion of transmissions into feral pig groups (November outbreak)
Other feral pig groups	30%	17%
Domestic herds	70%	83%

Table 22. Infected herd type mix when seeding FMD into a small commercial piggery in the Darling Downs region of Queensland with no control in feral pigs.

Herd type	Proportion of infected herds (May outbreak)	Proportion of infections due to feral pigs (May outbreak)	Proportion of infected herds (Nov outbreak)	Proportion of infections due to feral pigs (Nov outbreak)
Extensive beef	< 1%	0%	< 1%	0%
Intensive beef	60%	79%	59%	81%
Feedlot	9%	4%	10%	4%
Dairy	9%	4%	10%	5%
Very large comm. pig	< 1%	< 1%	1%	< 1%
Medium to large comm. pig	< 1%	1%	< 1%	< 1%

Small commercial pig	< 1%	1%	< 1%	1%
Specialist gene transfer herds	0%	0%	0%	0%
Microscale pig	< 1%	< 1%	< 1%	< 1%
Small ruminant	11%	8%	9%	6%
Smallholder	9%	4%	10%	4%

3.1.3 Observations

Feral pig involvement:

- FMD was likely to spill over from livestock into feral pigs (85-91% of all outbreaks) regardless of whether feral pig control was enabled or disabled.
- Outbreaks in livestock were larger and longer when feral pig spillover was enabled (i.e., compared to outbreaks where feral pig involvement was disabled).
- Despite the occurrence of significantly fewer infected feral pigs when feral pig control was enacted, median outbreaks in the domestic population were similar in size regardless of feral pig control. This was likely because the primary mechanisms for spread of FMD into livestock was local spread (38-47% of transmissions).
- The likelihood of very large/long outbreaks (95th percentile) was significantly reduced with feral pig control.

Seasonal effects:

- Seasonal influences were evident in feral pig outbreaks when no feral pig control was enacted; outbreaks were larger (# infected pigs) and longer with more feral pig to feral pig spread in winter versus summer when control was disabled.
- Seasonal influences were limited in feral pig outbreaks when feral pig control was enacted; feral pig outbreaks were of a similar size (# infected pigs) and duration in summer and winter with control enabled.
- Seasonal influences were limited in the domestic population regardless of feral pig control; domestic outbreak size (# IPs) and duration were similar in summer and winter. However, the likelihood of very large outbreaks (95th percentile for # IPs & # culled) was significantly reduced in summer.

3.2 Case Study 2 – QLD2 (feral pigs)

3.2.1 Method

FMDV was introduced into the feral pig population near East Palmerston in the tropical north region of Queensland on May 1st. The feral pig density in the surrounding 150 km^2 is 3.2/km^2 and there are several intensive beef farms in the area.

Spillover transmission of FMD back and forth with the livestock was enabled. FMD was allowed to spread within the livestock population via the direct, indirect, local, airborne and saleyard spread pathways. The time to detection was configured to occur in livestock on day 30 of the outbreak in the feral pig population. Default domestic control measures and resourcing were employed plus emergency vaccination (Section 2.5). Control of feral pigs (CDI) is relatively difficult in the region, (Section 2.6.3). Outbreaks were configured to end upon disease control/fade-out with a maximum outbreak length of 540 days (i.e., outbreaks still active on day 540 were terminated). 1,000 simulation runs were conducted for each scenario, which demonstrated outbreaks with or without feral pig control enabled. Seasonal influences were not explored due to the tropical location.

Outbreaks in livestock were characterised in terms of number of IPs, duration of control, mix of spread pathways responsible for transmission, number of animals culled, number of animals vaccinated. Outbreaks in feral pigs were characterised in terms of number of infected groups, number of infected pigs, area of infection, and outbreak duration. Welch's t-test ($p < 0.01$) was used to assess the influence of feral pig control and seasonal differences in outbreak size & duration.

Seed group ID	Location	Nearby farms	Feral pigs in group	Initial Infection	Local feral pig density	CDI	Livestock Region	Wildlife region
240854	West of Innisfail, Nth Qld	Intensive beef	56	4 exposed 1 infectious	3.2/km^2	2.31	Tropical NE Coast	TRF

Scenario	Start date	Season	Feral pig spillover	Feral pig control
1	1 May	Dry	enabled	disabled
2	1 May	Dry	enabled	enabled

3.2.2 Results

Table 23. Domestic outbreak size when seeding FMD into feral pigs in the East Palmerston area of tropical north Queensland.

Scenario	Feral pig control	Spillover into livestock	Num IPs median [5th – 95th] convergence[1]	Control duration (days) median [5th - 95th]	Number of culled animals median [5th - 95th]
1	disabled	100%	86 [24 – 300] 7%	510 [383 – 510]	26,481 [3287 – 107,789]
2	enabled	100%	51 [18 – 154] 12%	131 [54 – 454]	15,986 [2390 – 73,130]

[1] percentage standard error of the sample mean (95% confidence)

Table 24. Domestic outbreak spread pathway mix (%) when seeding FMD into feral pigs in the East Palmerston area of tropical north Queensland.

Scenario	Feral pig control	local	direct	saleyard	indirect	airborne	feral pigs
1	disabled	35.5	1.7	3.7	4.3	0.2	54.6
2	enabled	47.8	2.9	6.3	6.5	0.4	36.1

Table 25. Feral pig outbreak size and duration when seeding FMD into feral pigs in the East Palmerston area of tropical north Queensland.

Scenario	Feral pig control	infected feral pig groups median [5th – 95th]	infected feral pigs median [5th – 95th]	outbreak area (km^2) median [5th – 95th]	outbreak duration (days) median [5th – 95th]
1	disabled	17 [2 - 61]	512 [57 – 1727]	289 [34 – 1034]	540 [540 – 540]
2	enabled	6 [1 - 25]	64 [12 – 236]	102 [17 – 423]	182 [54 – 540]

Table 26. Sources of transmission into feral pig groups when seeding FMD into feral pigs in the East Palmerston area of tropical north Queensland.

Infection source	Proportion of transmissions into feral pig groups (no control in feral pigs)	Proportion of transmissions into feral pig groups (control in feral pigs)
Other feral pig groups	48%	27%
Domestic herds	52%	73%

3.2.3 Observations

- FMD was very likely to spill over from feral pigs into livestock (100% of all outbreaks)
- When feral pig control was enabled:
  - Outbreaks in both domestic and feral pig populations were significantly smaller (# IPs, # infected feral pigs, area of feral pig infection) and shorter
  - There was less variability in the size and duration of outbreaks; the likelihood of very large/long outbreaks (95th percentile) was significantly reduced.

3.3 Case Study 3 – NSW1 (microscale piggery)

3.3.1 Method

FMDV was introduced into a microscale piggery near Worrigee on the NSW south coast separately on May 1st and November 1st. The selected piggery is near intensive beef and dairy cattle herds and the feral pig density the surrounding 150 km^2 is 0.4/km^2. Control of feral pigs (CDI) is relatively easy in the region (Section 2.6.3). The time to detection was configured to occur on day 21 of the outbreak. Outbreaks were configured to end upon disease control/fade-out with a maximum outbreak length of 540 days (i.e., outbreaks still active on day 540 were terminated). 1,000 simulation runs were conducted for each scenario.

FMD was allowed to spread in the livestock population via the direct, indirect, local, airborne and saleyard spread pathways. Default domestic control measures and resourcing were employed plus emergency vaccination (Section 2.5). Spillover transmission back and forth with the feral pig population was initially disabled to provide a baseline scenario with no feral pig involvement. Spillover was then enabled for further scenarios to demonstrate outbreaks with or without control in feral pigs, and outbreaks in summer versus winter.

Outbreaks in livestock were characterised in terms of number of IPs, duration of control, mix of spread pathways responsible for transmission, number of animals culled, number of animals vaccinated. Outbreaks in feral pigs were characterised in terms of number of infected groups, number of infected pigs, area of infection and outbreak duration. Welch's t-test ($p < 0.01$) was used to assess the influence of feral pig control and seasonal differences in outbreak size & duration.

Seed Herd ID	Herd type	Size	Initial infection	Lat	Long	Livestock Region	Wildlife region	Cell ID	Feral pigs in cell	Local feral pig density	CDI
54341	microscale pig	110	6 exposed	150.6630	34.9233	Temperate SE Coast	TEF	732837	5	0.4/km^2	1.38

Scenario	Start date	Season	Feral pig spillover	Feral pig control
1	1st May	Winter	disabled	N/A
2	1st May	Winter	enabled	disabled
3	1st May	Winter	enabled	enabled
4	1st Nov	Summer	enabled	disabled
5	1st Nov	Summer	enabled	enabled

3.3.2 Results

Table 27. Domestic outbreak size when seeding FMD into a microscale piggery near Worrigee on the NSW south coast

Scenario	Season	Feral pig control	Number of IPS median [5th - 95th] convergence[1]	Control duration (days) median [5th - 95th]	Number of culled animals median [5th - 95th]
1	winter	N/A	16 [3 – 107] 9%	58 [4 – 100]	7742 [713 – 135,054]
2	winter	disabled	29 [4 – 160] 12%	70 [43 – 497]	15,195 [929 – 146,218]
3	winter	enabled	28 [4 – 143] 8%	69 [42 – 112]	14,427 [891 – 131,167]
4	summer	disabled	18 [3 – 91] 7%	60 [40 – 281]	10,322 [345 – 81,721]
5	summer	enabled	24 [3 – 101] 6%	64 [41 – 96]	13,187 [721 – 95,008]

[1] percentage standard error of the sample mean (95% confidence)

Table 28. Domestic outbreak spread pathway mix (%) when seeding FMD into a microscale piggery near Worrigee on the NSW south coast

Scenario	Season	Feral control	local	direct	saleyard	indirect	airborne	feral pigs
1	winter	N/A	59.7	4.7	11.5	14.4	9.8	0
2	winter	disabled	56.5	3.2	8.8	11.9	6.8	12.7
3	winter	enabled	57.3	4.2	10.4	13.3	6.7	8.1
4	summer	disabled	47.4	6.2	17.2	11.9	2.4	14.9
5	summer	enabled	46.7	6.2	17.5	11.9	2.6	15

Table 29. Feral pig outbreak size and duration when seeding FMD into a microscale piggery near Worrigee on the NSW south coast

Scenario	Season	Feral pig control	Spillover (livestock to feral pigs)	infected feral pig groups median [5th – 95th]	infected feral pigs median [5th – 95th]	outbreak area (km²) median [5th – 95th]	outbreak duration (days) median [5th – 95th]
1	winter	N/A	-	-	-	-	-
2	winter	disabled	77%	2 [0 – 10]	8 [0 – 76]	29 [0 – 147]	47 [23 – 540]
3	winter	enabled	71%	1 [0 – 6]	2 [0 –,20]	15 [0 – 88]	45 [21 – 81]
4	summer	disabled	73%	1 [0 – 6]	4 [0 – 40]	15 [0 – 88]	37 [20 – 540]
5	summer	enabled	80%	2 [0 – 6]	3 [0 – 19]	29 [0 – 88]	40 [21 – 73]

Table 30. Sources of transmission into feral pig groups when seeding FMD into a microscale piggery near Worrigee on the NSW south coast (no control in feral pigs).

Infection source	Proportion of transmissions into feral pig groups (May outbreak)	Proportion of transmissions into feral pig groups (November outbreak)
Other feral pig groups	17%	7%
Domestic herds	83%	93%

Table 31. Infected herd type mix and influence of feral pig spillover when seeding FMD into a microscale piggery near Worrigee on the NSW south coast (no control in feral pigs).

Herd type	Proportion of infected herds (May outbreak)	Proportion of infections due to feral pigs (May outbreak)	Proportion of infected herds (Nov outbreak)	Proportion of infections due to feral pigs (Nov outbreak)
Extensive beef	< 1%	0%	< 1%	0%
Intensive beef	42%	50%	40%	43%
Feedlot	4%	< 1%	5%	< 1%
Dairy	40%	39%	44%	50%
Very large comm. pig	1%	0%	< 1%	0%
Medium to large comm. pig	1%	0%	2%	0%
Small commercial pig	< 1%	0%	< 1%	0%
Specialist gene transfer herds	0%	0%	0%	0%
Microscale pig	< 1%	< 1%	< 1%	< 1%
Small ruminant	9%	11%	5%	7%
Smallholder	4%	< 1%	5%	< 1%

3.3.3 Observations

Feral pig involvement:

- FMD was likely to spill over from livestock into feral pigs (73-77% of all outbreaks) regardless of feral pig control being enabled or disabled.

- This spillover resulted in larger outbreaks in domestic herds than observed in livestock-only outbreaks (where feral pig involvement was disabled).
- Despite the occurrence of significantly fewer infected feral pigs when feral pig control was enacted, median outbreaks in the domestic population were similar in size regardless of feral pig control. This is because the primary mechanism for spread of FMD into livestock was local spread (47-57% of transmissions) followed by direct/saleyard spread (12-24%) and indirect spread (12-13%). There was less contribution from feral pig spillover (8-15%) and airborne spread (2-10%).
- However, feral pig control did reduce the variability of outbreaks, with the likelihood of very large/long outbreaks (95th percentile) significantly reduced.

Seasonal effects:

- In the absence of feral pig control, winter outbreaks in both the livestock and feral pig populations were larger and longer than summer outbreaks, with more feral pig to feral pig transmission occurring.
- When feral pig control was enabled, outbreaks in both the livestock and feral pig populations were similar in summer and winter.

3.4 Case Study 4 – NSW2 (feral pigs)

3.4.1 Method

FMDV was introduced into the feral pig population near Copeland in NSW separately on May 1st and November 1st. The feral pig density in the surrounding 150 km^2 is 0.8/km^2 and there are several intensive beef and dairy farms in the area. Control of feral pigs (CDI) is relatively difficult in the region (Section 2.6.3). The time to detection was configured to occur on day 30 of the outbreak in the feral pig population. Outbreaks were configured to end upon disease control/fade-out with a maximum outbreak length of 540 days (i.e., outbreaks still active on day 540 were terminated). 1,000 simulation runs were conducted for each scenario.

Spillover transmission of FMD back and forth with the livestock was enabled. FMD was allowed to spread in the livestock population via the direct, indirect, local, airborne and saleyard spread pathways. Default domestic control measures and resourcing were employed plus emergency vaccination (Section 2.5). Scenarios were run to demonstrate outbreaks with or without control in feral pigs, and outbreaks in summer versus winter.

Outbreaks in livestock were characterised in terms of number of IPs, duration of control, mix of spread pathways responsible for transmission, number of animals culled, number of animals vaccinated. Outbreaks in feral pigs were characterised in terms of number of infected groups, number of infected pigs, area of infection, and outbreak duration. Welch's t-test ($p < 0.01$) was used to assess the influence of feral pig control and seasonal differences in outbreak size & duration.

Seed Group ID	Location	Nearby farms	Feral pigs in group	Initial Infection	Local feral pig density	CDI	Livestock Region	Wildlife region
649629	Near Gloucester, NSW	Dairy & intensive beef	26	4 exposed 1 infectious	0.8/km^2	2.19	Temperate SE Coast	TEF

Scenario	Start date	Season	Feral pig control
1	1st May	Winter	disabled
2	1st May	Winter	enabled
3	1st Nov	Summer	disabled
4	1st Nov	Summer	enabled

3.4.2 Results

Table 32. Domestic outbreak size when seeding FMD into feral pigs near Copeland, NSW.

Scenario	Season	Feral pig control	Spillover into livestock	Number of IPs median [5th - 95th] convergence[1]	Control duration (days) median [5th - 95th]	Number of culled animals median [5th - 95th]
1	winter	disabled	100%	22 [5 – 198] 9%	466 [65 – 510]	10,644 [929 – 137,527]
2	winter	enabled	99%	15 [1 – 173] 10%	61 (36 – 151]	8006 [317 – 130,318]
3	summer	disabled	98%	20 [1 – 137] 8%	97 [36 – 510]	11,966 [287 – 124,398]
4	summer	enabled	93%	8 [0 – 88] 10%	52 [0 – 104]	2844 [0 – 72,900]

[1] percentage standard error of the sample mean (95% confidence)

Table 33. Domestic outbreak spread pathway mix (%) when seeding FMD into feral pigs near Copeland, NSW.

Scenario	season	Feral pig control	local	direct	saleyard	indirect	airborne	feral pigs
1	winter	disabled	40	4.4	11.6	15.1	0.9	28
2	winter	enabled	46.1	5.2	14.4	17.7	1	15.6
3	summer	disabled	37.2	7.1	18.5	15.8	1.4	20
4	summer	enabled	36.9	7.8	20.1	16.6	1.2	17.4

Table 34. Feral pig outbreak size and duration when seeding FMD into feral pigs near Copeland, NSW.

Scenario	Season	Feral pig control	infected feral pig groups median [5th – 95th]	infected feral pigs median [5th – 95th]	outbreak area (km^2) median [5th – 95th]	outbreak duration (days) median [5th – 95th]
1	winter	disabled	3 [1 – 18]	30 [17 – 261]	46 [15 – 273]	540 [58 – 540]
2	winter	enabled	2 [1 – 9]	16 [4 – 57]	30 [15 – 137]	48 [42 – 182]
3	summer	disabled	2 [1 – 10]	21 [14 – 124]	30 [15 – 153]	84 [34 – 540]
4	summer	enabled	1 [1 – 5]	14 [3 – 34]	15 [15 – 79]	40 [34 – 90]

Table 35. Sources of transmission into feral pig groups when seeding FMD into feral pigs near Copeland, NSW (no control in feral pigs).

Infection source	Proportion of transmissions into feral pig groups (May outbreak)	Proportion of transmissions into feral pig groups (November outbreak)
Other feral pig groups	50%	31%
Domestic herds	50%	69%

Table 36. Infected herd type mix and influence of feral pig spillover when seeding FMD into FMD into feral pigs near Copeland, NSW (no control in feral pigs).

Herd type	Proportion of infected herds (May outbreak)	Proportion of infections due to feral pigs (May outbreak)	Proportion of infected herds (Nov outbreak)	Proportion of infections due to feral pigs (Nov outbreak)
Extensive beef	< 1%	< 1%	< 1%	0%
Intensive beef	62%	78%	55%	74%
Feedlot	5%	< 1%	6%	< 1%
Dairy	20%	11%	23%	16%
Very large comm. pig	< 1%	0%	< 1%	< 1%
Medium to large comm.	1%	< 1%	1%	0%
Small commercial pig	< 1%	< 1%	< 1%	< 1%
Specialist gene transfer	0%	0%	0%	0%
Microscale pig	< 1%	< 1%	< 1%	< 1%
Small ruminant	8%	10%	8%	10%
Smallholder	5%	< 1%	6%	< 1%

3.4.3 Observations

- FMD was very likely to spill over from feral pigs into livestock (93-100% of all outbreaks).
- The primary mechanisms for spread into livestock were local spread (37-46% of transmissions), direct/saleyard spread (16-28%), feral pig spillover (16-28%) and indirect spread (15-18%).
- More feral pig to feral pig transmission occurred in winter than summer.
- In the absence of feral pig control, there was less feral pig to feral pig spread in outbreaks starting in summer versus winter. This resulted in:
  - Smaller and shorter outbreaks in the feral pig population under a summer start.
  - Significantly shorter outbreaks in the domestic population under a summer start, despite similar sized outbreaks in both summer and winter.
- When feral pig control was enacted:

- Outbreaks in both domestic and feral pig populations were significantly smaller and shorter with less variability; the likelihood of very large/long outbreaks (95th percentile) was significantly reduced.

- The impact of control on the duration of feral pig outbreaks was most pronounced for outbreaks starting in winter.

3.5 Case Study 5 – WA1 (feral pigs)

3.5.1 Method

FMDV was introduced into the feral pig population near Pemberton in southwest WA separately on May 1st and November 1st. The feral pig density in the surrounding 150 km^2 is 1.1/km^2 and there are several intensive beef and small ruminant farms in the area. Control of feral pigs (CDI) is relatively easy in the region (Section 2.6.3). The time to detection was configured to occur on day 30 of the outbreak in the feral pig population. Outbreaks were configured to end upon disease control/fade-out with a maximum outbreak length of 540 days (i.e., outbreaks still active on day 540 were terminated). 1,000 simulation runs were conducted for each scenario.

Spillover transmission of FMD back and forth with the livestock was enabled. FMD was allowed to spread in the livestock population via the direct, indirect, local, airborne and saleyard spread pathways. Default domestic control measures and resourcing were employed plus emergency vaccination (Section 2.5). Scenarios were run to demonstrate outbreaks with or without control in feral pigs, and outbreaks in summer versus winter. The feral pig CDI mode was varied between Duration and Effectiveness modes (Section 2.6.3).

Outbreaks in livestock were characterised in terms of number of IPs, duration of control, mix of spread pathways responsible for transmission & number of animals culled. Outbreaks in feral pigs were characterised in terms of number of infected groups, number of infected pigs, area of infection, and outbreak duration.

Seed Group ID	Location	Nearby farms	Feral pigs in group	Initial Infection	Local feral pig density	CDI	Livestock Region	Wildlife region
714634	Near Pemberton, WA	Small ruminant & intensive beef	18	4 exposed 1 infectious	1.1 / km^2	1.07	Southwest WA	MED

Scenario	Start date	Season	Feral pig control
1	1st May	Winter	disabled
2	1st May	Winter	enabled
3	1st Nov	Summer	disabled
4	1st Nov	Summer	enabled

3.5.2 Results

Table 37. Domestic outbreak size when seeding FMD into feral pigs near Pemberton, WA.

Scenario	Season	Feral pig control	Spillover into livestock	Number of IPs median [5th - 95th] convergence[1]	Control duration (days) median [5th - 95th]	Number of culled animals median [5th - 95th]
1	winter	disabled	100%	53 (10 – 270) 8%	245 (51 – 510)	31692 (2982 – 190503)
2	winter	enabled	100%	44 (12 – 202) 9%	80 (53 – 144)	28248 (4450 – 150986)
3	summer	disabled	100%	34 (10 – 176) 7%	73 (50 – 510)	21351 (3233 – 327692)
4	summer	enabled	100%	36 (11 – 131) 7%	72 (50 – 211)	19998 (3218 – 251540)

[1] percentage standard error of the sample mean (95% confidence)

Table 38. Domestic outbreak spread pathway mix (%) when seeding FMD into feral pigs near Pemberton, WA.

Scenario	season	Feral pig control	local	direct	saleyard	indirect	airborne	feral pigs
1	winter	disabled	51.3	1.6	2.6	10.4	1.2	33
2	winter	enabled	58.3	2	2.9	12.7	1.3	22.8
3	summer	disabled	38.5	2.5	5	11.8	1.1	41.2
4	summer	enabled	41.8	2.7	6.1	12	1.3	36

Table 39. Feral pig outbreak size and duration when seeding FMD into feral pigs near Pemberton, WA.

Scenario	Season	Feral pig control	infected feral pig groups median [5th – 95th]	infected feral pigs median [5th – 95th]	outbreak area (km²) median [5th – 95th]	outbreak duration (days) median [5th – 95th]
1	winter	disabled	4 [1 – 22]	48 [15 – 219]	59 [15 – 327]	376 [33 – 540]
2	winter	enabled	3 [1 – 13]	20 [11 – 73]	44 [15 – 193]	64 [32 – 145]
3	summer	disabled	3 [1 – 27]	28 [11 – 277]	44 [15 – 402]	66 [27 – 540]
4	summer	enabled	3 [1 – 20]	16 [5 – 90]	44 [15 – 296]	59 [27 – 299]

Table 40. Sources of transmission into feral pig groups when seeding FMD into feral pigs near Copeland, NSW (no control in feral pigs).

Infection source	Proportion of transmissions into feral pig groups (May outbreak)	Proportion of transmissions into feral pig groups (November outbreak)
Other feral pig groups	31%	18%
Domestic herds	69%	82%

Table 41. Infected herd type mix and influence of feral pig spillover when seeding FMD into FMD into feral pigs near Copeland, NSW (no control in feral pigs).

Herd type	Proportion of infected herds (May outbreak)	Proportion of infections due to feral pigs (May outbreak)	Proportion of infected herds (Nov outbreak)	Proportion of infections due to feral pigs (Nov outbreak)
Extensive beef	< 1%	< 1%	< 1%	0%
Intensive beef	69%	77%	67%	77%

Feedlot	2%	< 1%	3%	< 1%
Dairy	12%	5%	10%	3%
Very large comm. pig	< 1%	< 1%	< 1%	< 1%
Medium to large comm.	< 1%	< 1%	< 1%	< 1%
Small commercial pig	< 1%	< 1%	< 1%	< 1%
Specialist gene transfer	0%	0%	0%	0%
Microscale pig	< 1%	< 1%	1%	< 1%
Small ruminant	14%	18%	15%	20%
Smallholder	2%	< 1%	3%	< 1%

3.5.3 Observations

- FMD was very likely to spill over from feral pigs into livestock (100% of all outbreaks).
- The primary mechanisms for spread into livestock were local spread (39-59% of transmissions) and feral pig spillover (23-41%). There was less spread via indirect spread (10-13%), direct/saleyard spread (4-9%) and airborne spread (1%).
- More feral pig to feral pig transmission occurred in winter than summer.
- In the absence of feral pig control, there was less feral pig to feral pig spread in outbreaks starting in summer versus winter. This resulted significantly smaller and shorter outbreaks in both the feral pig and domestic populations under a summer start.
- When feral pig control was enacted:
    - Outbreaks in feral pigs were significantly smaller and shorter with less variability; the likelihood of very large/long outbreaks (95th percentile) was significantly reduced.
    - These impacts on outbreaks within the feral pig population were most pronounced in winter-start outbreaks.
    - Median outbreaks in the domestic population were only smaller and shorter under winter-starting conditions. However, feral pig control resulted in less variability in the size and duration of outbreaks in both summer and winter starts; the likelihood of very large/long outbreaks (95th percentile) was significantly reduced.

4 MODEL COMPARISION

There have been several modelling studies on the potential spread and control of FMD in Australian livestock, but few have incorporated potential transmission between livestock and feral pigs. An exception was a study was carried out by Ward and colleagues in 2015 on the potential spread of FMD between domestic cattle and feral pigs in the Kimberley region of Western Australia. As a rudimentary model comparison, the AADIS-FMD-FP model was configured to run FMD incursion scenarios like those described by Ward et al., (2015). The location of the study is provided in Section 3.

4.1 Study areas

The Ward et al. study area comprised 10,000 km^2 in the Kimberly region of Western Australia. The domestic cattle and feral pig populations were synthesized based on aerial surveys conducted in 2010 and distributed within the study area according to observed densities, geographical features and land use. The populations are summarised in Table 42.

As the AADIS-FMD-FP model is national-scale, it was not feasible to limit the AADIS study area to 10,000 km^2 in the Kimberley region. As such, the domestic cattle and feral pig populations are considerably larger in the AADIS-FMD-FP model (Sections 2.1 and 2.5) than the Ward model.

The epidemiological units of interest in the Ward et al. model were mobs of domestic cattle (average size 9.65) and groups of feral pigs (average size 4.33). The epidemiological units of interest in the AADIS-FMD-FP model are herds of domestic cattle (average size 1468) and groups of feral pigs (average size 19).

Table 42. Comparison of the domestic cattle and feral pig populations used in the AADIS-FMD-FP and Ward et al. models.

	AADIS-FMD-FP	Ward et al., 2015
Study area	Northern Australia	Kimberly region10,000 km^2
Number of extensive beef cattle farms	1500	10
Number of cattle on ext. beef farms	6,606,897	79,400
Av. number of cattle per ext. beef farm	4405	7940
Average cattle density	3 per km^2 (Derby-West Kimberley LGA)	7 per km^2
Epidemiological unit of interest	herd	mob
Number of epi units	4500 herds (Nth Aust)	8231 mobs
Average number of epi units per farm	3 herds per farm	823 mobs per farm
Average number of cattle per epi unit	1468 cattle per herd	9.64 cattle per mob
Number of feral pig groups	132,183 (TRS in May)	275
Number of feral pigs	2,585,374 (TRS in May)	1190
Average number of feral pigs per group	28 (TRS in May)	4
Average feral pig density	1.75/km^2 (TRS in May)	0.62 – 1.68 per km^2

4.2 Silent spread – feral pigs only

4.2.1 Method

FMD was introduced separately into selected feral pig groups (Table 43) on the 1st of May (dry season) and allowed to spread in the surrounding feral pig population for 180 days with no control. Spillover transmission between livestock and feral pigs was disabled.

Table 43. Seed feral pig groups

Scenario	Feral pig group ID	Number of feral pigs in the seed group	Local feral pig density (surrounding 150 km^2)	Local Government Area (LGA)	Wildlife region
FP3	231664	8	0.5 / km^2	Derby-West Kimberley	TRS
FP2	272739	27	1.2 / km^2	Derby-West Kimberley	TRS
FP1	215467	81	2.4 / km^2	Derby-West Kimberley	TRS
FP4	263019	80	3.7 / km^2	Derby-West Kimberley	TRS

4.2.2 Results

Table 44. Feral pig infections after 180-day silent spread outbreaks in the feral pig population only

Scenario	Local feral pig density (pigs / km^2)	Area of infection (km^2) median [5th – 95th]	Number of feral pig groups infected median [5th – 95th]	Number of feral pigs infected median [5th – 95th]	Secondary spread beyond seed group (% of runs)
FP3	0.5	17 [17 – 17] [a]	1 – 1	6 [6 – 6]	4%
FP2	1.2	17 [17 – 34] [a]	1 – 2	21 [20 – 39]	17%
FP1	2.4	17 [17 – 68] [a]	1 – 4	64 [61 – 126]	48%
FP4	3.7	34 [17 – 85] [a]	1 – 5	64 [61 – 214]	50%
Ward et al.	0.62 – 1.68	0 [0 – 3] [b]	1 – 4	4 [4 – 17] [c]	35%

[a] AADIS-FMD-FP calculates the area of infection by summing the home ranges of infected feral pig groups so applies to outbreaks with any number of infected groups.

[b] The Ward study uses a minimum convex hull to calculate the area of infection, so only applicable when there are 3+ infected feral pig groups in an outbreak.

[c] Estimate only as the Ward paper does not report infections on a per feral pig basis.

4.3 Silent spread – livestock and feral pigs

4.3.1 Method

FMD was introduced on the 1st of May (dry season) into a feral pig group (ID=215467, n=81) located in an area with an average feral pig population density of 2.4 per km^2. FMD was allowed to spread in both the domestic cattle and feral pig populations for 180 days with no control. To align with the Ward et al. study, spread between cattle herds was only possible via the indirect, local and airborne spread pathways (i.e., spread via the anthropogenic movement of live animals between herds was disabled).

4.3.2 Results

Table 45. Infection after 180 days of silent spread in both domestic cattle and feral pig populations.

	AADIS-FMD-FP	Ward et al., 2015
Local feral pig density	2.4 per km^2	0.62 – 1.68 per km^2
Num infected cattle mobs (median [5th - 95th])		2941 [0 – 6000] mobs
Num infected cattle farms (median [5th - 95th])	51 [2 – 70] farms	
Num infected feral pig groups (median [5th - 95th])	31 [5 – 47]	87 [1 – 186)
Num feral pigs in infected groups (median [5th - 95th])	768 [148 – 1205]	376 [4 – 805] [a]
Area of infection (median [5th - 95th])	236,680 [16 – 367,747) km^2	5634 [0 – 9259] km^2
Outbreaks faded out within 6 months	1%	9%

[a] Estimate only as the Ward paper does not report infections on a per feral pig basis

4.4 Control measures in both livestock and feral pigs

4.4.1 Method

FMD was introduced on the 1st of May (dry season) into a feral pig group (ID=215467, n=81) located in an area with an average feral pig population density of 2.4 per km^2. FMD was allowed to spread in both the domestic cattle and feral pig populations (per Section 3.3). The declaration of the index case was fixed to occur on day 30. The following control measures were applied:

- Controlled area radius 10km; Restricted area radius 3km
- Stamping out of infected herds
- Thinning of feral pig population within controlled areas by 80% over 3 weeks

4.4.2 Results

Table 46. Infected cattle and feral pigs for outbreaks with 30 days of silent spread and control measures undertaken in both cattle and feral pig populations.

	AADIS-FMD-FP	Ward et al., 2015
Local feral pig density	2.4 per km^2	0.62 – 1.68 per km^2
Num culled cattle mobs (median [5th - 95th])		329 [71 – 902]
Num culled cattle farms (median [5th - 95th])	1 [1 – 6]	
Num culled cattle (median [5th - 95th])	19,171 [19,163 - 120,233]	3264 [730 – 8529]
Num culled feral pig groups (median [5th - 95th])	0 [0 – 0]	20 [0 – 71]
Num culled feral pigs (median [5th - 95th])	0 [0 – 0]	87 [0 - 307]
Time to eradication (median [5th - 95th])	62 [61 – 150] days	42 [31 – 74] days

Probability of eradication	100%	100%

Table 47. Infected cattle and feral pigs for outbreaks with 30 days of silent spread and control measures undertaken in domestic cattle only.

	AADIS-FMD-FP	Ward et al., 2015
Local feral pig density	2.4 per km^2	0.62 – 1.68 per km^2
Num culled cattle mobs (median [5th - 95th])		349 [83 – 941]
Num culled cattle farms (median [5th - 95th])	2 [1 – 7]	
Num culled cattle (median [5th - 95th])	23,152 [19,162 - 140,952]	3332 [730 – 9986]
Num culled feral pig groups (median [5th - 95th])	43 [22 – 151]	0 [0 – 0]
Num culled feral pigs (median [5th - 95th])	1206 [602 - 4220]	0 [0 – 0]
Time to eradication (median [5th - 95th])	76 [61 – 150] days	49 [31 – 105] days
Probability of eradication	100%	100%

4.5 Observations

There are marked differences in the modelling approaches and study areas of the AADIS-FMD-FP model and the Ward et al., model.

- The AADIS-FMD-FP model is national scale and represents domestic cattle, sheep and pigs and feral pigs across the whole of Australia. The Ward et al. model has a much smaller study area of 10,000 km^2 area of the Kimberley region and only considers domestic cattle and feral pigs. There are far more susceptible cattle and feral pigs in AADIS-FMD-FP than the Ward model (Table 42) and subsequently the silent spread outbreaks generated by AADIS were larger (Tables 43 and 44). The AADIS model also incorporates a much larger feral pig population than the Ward model reflecting more recent estimates (Bradhurst et al., 2022).
- The areas of infection in feral pigs were also larger in the AADIS study than the Ward study. Note, however, that the Ward model calculates area with a minimum convex hull which requires at least three points of infection. As such outbreaks which did not go beyond the seed group have a zero area of infection. In contrast, the AADIS model aggregates feral pig home ranges to calculate areas of infection and this is not limited by a minimum number of infected feral pig groups.
- The epidemiological unit of interest for cattle differs markedly between the two models AADIS represents domestic cattle on a farm as several herds (average size 1500) whereas the Ward model represents domestic cattle as many smaller mobs (average size = 4). These modelling choices influence transmission dynamics in time and space. Although the mob-based approach is well suited to a small-scale study in the Kimberley, it is not practical for a national scale model such as AADIS.

- AADIS has a dynamic within-herd sub-model that predicts within-herd infectious prevalence over time on a per herd basis (Bradhurst et al., 2015) which directly influences the likelihood of between-herd spread. The within-herd model also dynamically estimates a herd's clinical prevalence which, along with herd type, influences the likelihood of detection. In contrast, the Ward et al. model has a very simple within-mob state-based approach. These modelling choices influence transmission dynamics.
- AADIS includes regional and seasonal differences across Australia with respect to livestock density, farming practices, live animal movements, mustering effectiveness and response options. The Ward model is restricted to a single region and does not consider seasonal influences on spread and control.
- Culling in the Ward model is carried out on infected animals only. In the AADIS model, all animals on an IP are culled (per AUSVETPLAN guidelines).
- AADIS control programs are dynamically informed by resource availability, regional and seasonal influences on mustering effectiveness. The Ward et al, model has a simpler duration-based approach, e.g., one day to muster and cull cattle in an infected paddock.

Despite substantial differences in model design and study area, there are several modelling outcomes that were consistent across both the AADIS-FMD-FP and Ward et al. studies:

1) When FMD is seeded into the feral pig population and does not spillover into the domestic cattle population, in the absence of control, outbreaks generally fade-out within 6 months. The likelihood of fadeout within 6 months varies with the density of the feral pig population.
2) When FMD is seeded into the feral pig population and does spillover into the domestic cattle population, outbreaks will be larger, and in the absence of control, will generally persist beyond 6 months.
3) When FMD is seeded in the feral pig population and spills over into the domestic cattle population, provided that FMD is controlled in the domestic population, then it will likely be eradicated. If feral pig culling accompanies the domestic control program, then the time to eradication will be reduced.

In conclusion, the Ward et al. modelling approach was well suited to a regional-scale study, and it provides useful insight into the potential spread and control of FMD in the Kimberley region of Western Australia. The AADIS-FMD-FP model offers a considerable advance in decision support modelling due to its national scale, inclusion of susceptible dairy cattle, small ruminants, pigs and smallholders, and consideration of regional and seasonal influences on FMD spread and response effectiveness.

5 DISCUSSION

The case studies show that the size and duration of FMD outbreaks and the degree to which feral pigs contribute to spread will vary regionally and seasonally. Subject to the modelling assumptions (Section 2; Appendices A-E), the following observations were consistent across the case studies:

- In all scenarios, FMD was either likely or certain to spill over into feral pigs from domestic herds and vice versa. When spillover transmission did occur between livestock and feral pigs, outbreaks were generally larger and longer in both populations compared to simulations where spillover transmission was disabled. Areas with higher densities of feral pigs had increased proportion of spillover transmissions compared to other transmission mechanisms.
- For most scenarios, winter outbreaks were larger and longer outbreaks in both domestic and feral pig populations than summer outbreaks. This suggests that increased feral pig activity in winter months contributes to outbreak size.
- Seasonal differences in outbreak size were less noticeable when feral pig control was enabled. Feral pig control resulted in reduced outbreak size and duration for both livestock and feral pigs in winter months only.
- Feral pig control generally reduced the variability of outbreaks and the likelihood a very large outbreak (95th percentile of outbreak size and duration). This was particularly evident in the summer outbreaks.

Australia is a very large country with considerable heterogeneity in farm production types, livestock movement patterns, climates, and feral pig habitats and densities. The case studies are best viewed as exploratory outbreak scenarios of interest that are intended to verify and illustrate the utility of the AADIS-FMD-FP model, rather than providing national-level insights into the potential role of feral pigs in FMD outbreaks.

Outbreaks in domestic herds mainly involved intensive beef and to a lesser extent dairy, small ruminants and feedlots. It is, however, unclear whether this is a trend or simply an artefact of the production systems and farming densities in the specific outbreak scenario locations. Future simulation work could explore the influence of production system and on-farm biosecurity by seeding FMD randomly into broader areas of interest rather than specific farms.

The case studies suggested that outbreaks of FMD in the feral pig population will increase the size and duration of outbreaks in domestic herds. It may be worth expanding the model to include other FMD-susceptible feral populations such as cattle, buffalo, deer and goats.

The case studies suggested that feral pig control may reduce: the size and duration of domestic outbreaks; the number of domestic animals culled; and the likelihood of very large outbreak. The benefits of feral pig control varied regionally and seasonally, and further broader simulations are recommended to better understand this.

There are many heterogeneities and uncertainties when considering the potential role of feral pigs in an FMD outbreak. Decision support tools such as AADIS-FMD-FP can help stakeholders unpack this complex time-space problem and better prepare for incursions of FMD. The model is not intended to predict how any given FMD incursion will unfold in real time. The stochastic nature and incorporation of regional and seasonal variability, means it is best suited generating a range of plausible FMD outbreaks, against which the cost effectiveness of candidate livestock and feral pig control strategies can be assessed.

It is important to note that as AADIS is a data-driven model, modelling results are always dependent on the quality and availability of underlying data. When modelling the potential role of feral pigs in EAD outbreaks, dependent data includes regional and seasonal estimates of feral pig distribution, abundance, home ranges, contact rates between groups, and contact rates with farms. It has previously been shown in the context of ASF that modelling outcomes are sensitive to this data (Bradhurst et al., 2021; 2022). It will be relatively easy to update the AADIS-FMD-FP model with improved feral pig ecological data and parameterisation in step with results from ongoing field studies in Australia on feral pig distribution, abundance, home ranges and contact rates.

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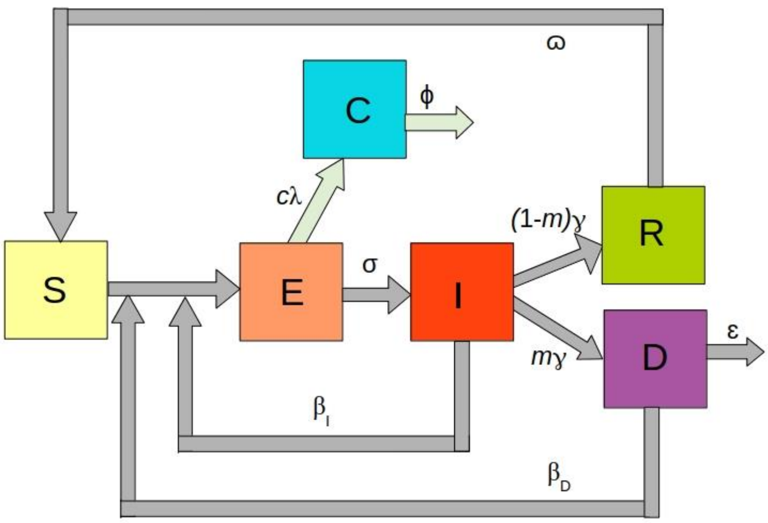
APPENDIX A - Feral pig within-group EBM parameterisation

The spread of FMD within a feral pig group is represented by an equation-based model (EBM) implemented as a system of ordinary differential equations (ODEs). The model estimates the proportion of the group that are susceptible, exposed, infectious, recovered or deceased, over time. This approach assumes homogeneous mixing of pigs within the group.



$$\frac{dS}{dt} = \frac{-\beta_I IS - \beta_D DS}{N} + \omega R$$

$$\frac{dE}{dt} = \frac{\beta_I IS + \beta_D DS}{N} - \sigma E$$

$$\frac{dI}{dt} = \sigma E - \gamma I$$

$$\frac{dR}{dt} = (1-m)\gamma I - \omega R$$

$$\frac{dD}{dt} = m\gamma I - \varepsilon D$$

$$\frac{dC}{dt} = c\lambda E - \phi C$$

Where:

S = number of animals in the group that are susceptible
E = number of latently infected animals in the group
I = number of infectious animals in the group
R = number of recovered animals in the group
N = total number of animals in the group (= S + E + I + R)
D = number of animals in the group that have died from the disease
C = number of animals in the group with clinical signs
β_I = transmission rate (I to S) (average contact rate × transmission probability)
σ = infectiousness progression rate (1/σ = average duration of the latent period)
γ = recovery rate (1/γ = average duration of the infectious period)
m = average probability of FMD-related mortality
ω = loss of immunity rate (1/ω = average duration of the immunity period)
c = proportion of cases showing clinical signs
λ = clinical disease rate (1/λ = average duration of the incubation period)
ϕ = clinical recovery rate (1/ϕ = average duration of the clinical period)
β_D = carcass transmission rate (average contact rate × transmission probability)
ε = carcass decay rate (1/ε = average duration of carcass infectious period)

Table A1. Feral pig within-group EBM parameterisation

EBM parameter	DES	MED	MON	TEF	TES	TRS	TRF	References
transmission rate (β_I)	2.1							Based on domestic pig transmission rate in FMD model (Bradhurst et al., 2015)
latent period ($1/\sigma$)	1 day							(Croft et al., 2019; Stenfeldt et al., 2016)
infectious period ($1/\gamma$)	8 days							
carcass transmission rate (B_D)	0.4							Leivers et al., 2003 Cukor et al., 2019 Probst et al., 2017 (See Note below)
carcass infectious period ($1/\varepsilon$) days								(Guan et al., 2010; Hunnam et al., 2018; Stenfeldt et al., 2020) (See Note 1 below)
summer	2	9	46	10	5	3	5	
autumn	8	18	70	26	14	6	8	
winter	34	46	77	50	46	14	18	
spring	8	26	75	30	14	5	8	
mortality rate (m)	0.05							(Kinsley et al., 2016)
incubation period ($1/\lambda$)	3 days							(Moreno-Torres et al., 2022)
proportion clinical (c)	0.5							(Fukai et al., 2022)
clinical period ($1/\phi$)	14 days							(Moreno-Torres et al., 2022)
natural immunity (days)	min = 90, mode = 120, max = 180							(Doran & Laffan, 2005)
recovery period R_p (days)	365							Bradhurst et al., 2021; 2022
recovery lag R_l (days)	213							
recovery gradient	Summer & Autumn = 1 Winter & Spring = 1.2							

Notes

Emily Sellens, August 2024, updated June 2025.

1) Derivation of carcass infectious period (1/ε)

The infectivity of carcasses is expected to be driven by carcass pH and temperature, which are influenced by several factors including days since humane killing air temperature, rainfall, relative humidity, anatomical site and study location (Schlosberg et al 2025).

For the purposes of this model, we estimated infectivity based on environmental temperature, as this data is available in the existing model and air temperature is predictive of carcass pH and temperature (Schlosberg et al 2025).

The carcass infectious period was determined for each season by wildlife region.

A search of the literature identified virus survival for:

- At least 77 days at 4 °C (Stenfeldt et al., 2020)
- 10 days at 20 °C (Guan et al., 2010)
- Less than 1 day at 30 °C (Hunnam et al., 2018)
- In most tissues, virus will be inactivated within 14 hours in Queensland study sites, where mean air temperatures ranged from 24.1oC–26.9oC (Schlosberg et al., 2025)

Virus survival at different temperatures was extrapolated from these limited data points (Figure A1).

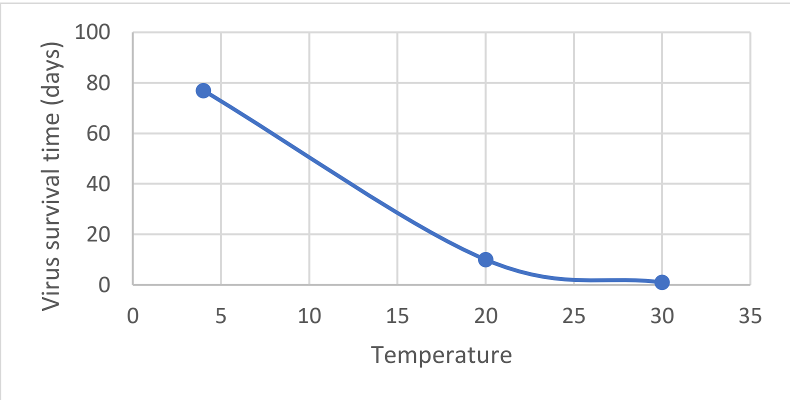


Figure A1. Plot of temperature versus FMD virus survival in carcasses identified in the literature.

The average temperature was calculated for each season from weather station data (Table A2).

Table A2. Average weekly temperature per season and wildlife region.

	Average Weekly Temperature - Wildlife Region						
Season	DES	MED	MON	TEF	TES	TRS	TRF
Summer	28	21	11	20	25	27	25
Autumn	22	18	6	16	19	24	22
Winter	14	11	0	10	11	19	18
Spring	22	16	5	15	19	25	22

The virus survival was then determined for the average temperature by season and wildlife region (Table A3), for application in the AADIS model.

Table A3. Carcass infectious period by season and wildlife region.

	Carcass infectious period - Wildlife Region						
Season	DES	MED	MON	TEF	TES	TRS	TRF
Summer	2	9	46	10	5	3	5
Autumn	8	18	70	26	14	6	8
Winter	34	46	77	50	46	14	18
Spring	8	26	75	30	14	5	8

Literature summary

Hunnam** et al., **2018

- In northern conditions, pH change is enough to inactivate FMD virus in pig carcasses.
- 30 pigs were shot and pH and temperature were assessed every hour for 46 hours for thoracic and skeletal mm temperature and pH.
- Within 16 h post-death, 16 of 18 of pig carcases had central and/or peripheral target pH ≤6.0 (total study period: 20–23 h post-death), but only 2 of 8 pigs were measured with a brain pH ≤6.0
- A target pH ≤ 6.0 at any time and/or a target temperature ≥43°C for ≥7 h or ≥49°C for ≥ 1 h were used as proxies for achievement of FMDV inactivation.
- It is yet unclear if bone marrow/brain will follow the same deactivation as tissues measured in this study
- Alterations of temperature and pH in animal carcasses in warm climatic conditions suggest that FMDV would likely become inactivated within 24 h when ambient temperatures reach 30–35°C
- “Temperature is also a key determinant of FMDV survival. At the optimal pH, there is 90% viral deactivation after 3 s at 61°C, 20 s at 55°C, 1 h at 49°C, 7 h at 43°C and 21 h at 37°C.” cited from a study from 1957

Guan** et al., **2010

- Under <u>compost</u> conditions between 50°C and 70°C, FMDV was inactivated WHEN MEASURED on day 10 on skin and day 21 in organ tissues.
- Among specimens held at ambient temperatures, virus was isolated on day 10 from the skin tissues of C2 but was not isolated from any of the other specimens on days 10 or 21.

Stenfeldt** et al.**, 2020

- Conservative estimate of an infectious duration of 9 days in domestic pigs
- Post-mortem sampling of vesicle epithelium and skeletal muscle was performed on 4 distinct batches of pig carcasses that had been infected with either FMDV A24 Cruzeiro or FMDV O/SKR/2010, following slightly different sampling schedules.
- FMDV virus in MUSCLE was inactivated within 7 days in carcasses stored at 4°C- virus isolation was only positive at 0dpm, 1 dpm (2/4 samples), and 5 dpm (1/4 samples)
- By contrast, all vesicle epithelium samples stored at 4°C obtained from batches 1 through 4 (n = 13) from 0 to 77 dpm were positive both by qRT-PCR and VIRUS ISOLATION; FMDV RNA quantities were substantially higher compared to muscle samples.
- Similarly, RNA was detected in submandibular lns, neck skin and bone marrow at 77dpm. Two bone marrow samples were VI-positive.
- This study used both FMDV A24 and FMDV O/SKR/2010

Schlosberg 2025

- Expanded on prior research by extending the period of carcass monitoring until end-stage decomposition.
- Warra in the Western Downs region of inland southeast Queensland, and Biloela in the Shire of Banana in central Queensland – a summer and an early autumn (wet season) study at each site.
- Trial durations (time to end stage decomposition) ranged between 12.1 and 18.2 days. Mean air temperatures were similar across the four trials (24.1oC–26.9oC).
- The relationship between air temperature and carcass temperature was largely linear.
- Using regression modelling, we identified days since humane killing, air temperature, rainfall, relative humidity, anatomical site and study location as significant predictors of carcass pH and temperature.
- Throughout all trials, the lower (acidic) pH threshold was consistently reached by most sensors in the abdominal cavity, deep muscle, superficial muscle and thoracic cavity. The lower threshold was generally reached in the first 14 hours of the trials.
- Observed carcass pH and temperature suggest foot-and-mouth disease virus (FMDV) was likely to be inactivated in the thoracic cavity, superficial and deep skeletal muscle and abdominal cavity of most carcasses. However, FMDV inactivation thresholds were not reached in bone marrow and brain; carcasses may potentially remain infectious in

situ under the experimental conditions encountered. Though, the absolute viral load present in the environment will be reduced if fewer tissues remain infective.

2) Derivation of carcass transmission rate (B_D)

Contact rate x probability contact is effective

- Direct contact will initially increase over time, b/c pigs are more likely to visit and display more intense contact with carcasses exhibiting some decay.
- Warmer environments – initial contact occurs sooner (b/c decay begins earlier)
- Cooler environments – initial contact occurs later & cannibalism is more likely (b/c 'fresher' for longer)

Based on literature assume:

- Approx a third of carcasses will be visited each day
- 40 – 80% of visits result in direct contact
- Each visit involves 1 – 3 pigs
- Probability of effective contact = 1

Beta is therefore estimated as:

- Minimum = 0.33*0.4*1*1 = 0.13
- Maximum = 0.33*0.8*3*1 = 0.8
- Baseline model = 0.33*0.6*2*1 = **0.4**

Literature Summary:

Texas (Leivers et al., 2023)

- Studied behaviour of wild pigs towards dead conspecifics in hot semiarid climate zone.
- No evidence of cannibalism.
- Recorded live wild pig visitations to only **33% of carcasses** created via aerial shooting before advanced stages of decomposition were reached.
- There was seasonal variation in wild pig visitations to carrion sites, with wild pigs more likely to visit carrion sites in the 'cool' season than the warm season. All instances of investigative behaviour by wild pigs towards dead conspecifics (i.e., scenarios in which diseases could be directly transmitted) occurred during the cool season.
- Carcass decomposition was rapid (2.5 to 3 days), regardless of season.
- Time to the first visitation and investigation of carcasses by live conspecifics was quicker than has been recorded in Europe.

- The mean time taken for wild pigs to first visit a site from the time of euthanasia was 42.3 hours (S.D = 17.1 hours, min = 8.7 hours, max = 66.5 hours) in the cool season and 29.04 hours (S.D = 30.8 hours, min = 7.6 hours, max = 51.2 hours) in the warm season.
- Wild pigs were documented visiting 18 of the 59 carrion sites on a least 1 occasion, for a total of 54 visitation events across seasons (Figure 2).
- Most frequently, only 1 visit per carrion site is recorded (noting that sites may have >1 carcass), and **in only 4 of 54 visitation events (7.4%), were there more than 1 wild pig present in the photograph (max = 3)**.
- The most common behaviour recorded was "investigated," followed by "other" and then "observed." Notably, there were no instances of cannibalism.
- Most visitation events occurred when carcasses were at a decomposition score of 1/5 (fresh). Most investigative (muzzling/direct contact) occurred when decomposition score was 2/5.
- Another factor that likely affects the rate of exposure of live wild pigs to their dead conspecifics is the density of wild pigs on the landscape.
- Active scavenger guilds at our study site, coupled with high temperatures, result in the rapid decomposition of wild pig carcasses, which reduces opportunities for live wild pigs to interact with them when compared to milder climates.
- We suggest additional research investigating the persistence of FMD in hot, arid climates and the interactions between live pigs and the skeletonized remains of conspecifics.

Czech Republic (Cukor et al., 2020)

- 732 records containing wild boars were obtained from all seven study sites
- 146 wild boars came individually (19.9%), other wild boars came in groups.
- The average number of wild boars detected in a video was **2.8 (*SD* 3.1).**
- In 75 out of 87 days (86%), more than one visit to the carcass was recorded.
- In 595 out of 732 cases **(81%), direct contact with the carcass was recorded**. The intensity of direct contacts was observed to be significantly lower when the carcass was not opened or disintegrated, 44% of the wild boar which visited the carcass had direct contact with the carcass (95% conf. interval 35%–53%). Once the opening or disintegration of the carcass began, the intensity of direct contact significantly increased (opened carcass: 92 ± 3%, disintegrated carcass: 89 ± 6% and final fragment: 83 ± 5%).
- The first direct contacts with the carcasses were on average observed after approximately 30 days after each respective carcass had been placed at the site. However, the variability of such results is very high (95% conf. interval; 12–49 days, *SD* 19.72). Earliest was 5 days.
- 70 cases of cannibalism were recorded (9.6% of all visits) - on average after approximately 70 days (95% conf. interval 30–109 days, *SD* 24.76). Earliest at 35 days.

Germany (Probst et al., 2017)

- About one third of the visits of wild boar led to direct contact with dead conspecifics.
- 32 carcasses on 9 study sites.
- A total of 520 wild boar **visits were recorded** in 298 days/nights **(26% of all 1136 camera-nights**), thereof 63 visits (12%) in 55 nights in winter and 457 visits (88%) in 243 days/nights in summer. In most days/nights (191; 64%), only one visit was observed. In 107 days/nights (36%), two or more visits were observed: in 59 days/nights two visits, in 37 days/nights three, in 8 days/nights five, in 2 days/nights six, and in 1 day/night nine.
- No evidence for intra-species scavenging.
- **Direct contact** occurred in a total of 189 visits (**36% of all 520 visits**) in 119 nights, thereof 20 visits in winter (32% of the visits) and 169 visits in summer (37% of the visits).

APPENDIX B – Feral pig between-group spread pathway parameterisation

Table B1. Parameterisation of the feral pig between-group diffusive spread pathway

Parameter	DES	MED	MON	TEF	TES	TRS	TRF	References
contact rate (direct + indirect)								Adapted from:
summer	0.07	0.07	0.07	0.07	0.07	0.07	0.07	Podgorski et al., 2018;
autumn	0.14	0.14	0.14	0.14	0.14	0.07	0.07	Taylor et al., 2020;
winter	0.14	0.14	0.14	0.14	0.14	0.07	0.07	Taylor et al., 2021;
spring	0.07	0.07	0.07	0.07	0.07	0.07	0.07	J. Vicente pers. comms 2021
diffusion mode (Moore, radial)	Radial							Bradhurst et al., 2022
Home range radius (km)								
summer	2.50	3.15	2.50	3.25	3.15	3.20	2.40	Bradhurst et al., 2022
autumn	2.50	2.93	2.50	2.80	2.80	4.00	2.40	
winter	2.50	3.15	2.50	3.58	3.58	3.48	3.94	
spring	2.50	2.65	2.50	3.25	3.25	2.84	3.93	
contact choice (most suitable, most populated, random)	random							N/A
probability of effective contact	0.5							Adapted from: Kinsley et al., 2016 Colenutt et al., 2020
seasonal weight								
summer	0.66	0.66	0.3	1.0	0.66	0.66	0.66	Bradhurst et al., 2022
autumn	0.66	1.0	1.8	1.0	1.0	0.66	0.66	
winter	1.3	1.3	1.8	1.8	1.3	1.0	1.0	
spring	0.66	1.0	1.8	1.0	1.0	0.66	0.33	

Table B2. Overview of studies with available seasonal aggregated feral pigs home range.

Study location/country	Habitat/ecoregion	Home Range Size - in km²		Time of the study	Reference
		Female	male		
Texas, USA	arid /humid, grassland and woodland	34	48.3	April to August 2003	(Adkins & Harveson, 2006)
Santa Catalina Island, California USA	Mediterranean/Woodland, Chaparral, coastal, grassland and riparian	0.7	1.4	July 1980-Sep 1981	(Baber & Coblentz, 1986)
Tuscany, Italy	sub-Mediterranean/forest and cultivated fields	4.7	13.4	1984 to 1987, seasonal study	(Boitani et al., 1994)

Douglas Daly district, NT, AUS	Tropical and subtropical grassland, savannas and shrublands	24.1	33.5	1989-1990	(Caley, 1997)
Galapagos Island, Ecuador	tropical and semi-arid/ grassland, forest	0.9	1.6	1983	(Coblentz & Baber, 1987)
Nocoleche Nature Reserve, NSW, AUS	Temperate grasslands, savannas and shrublands	4.9-8.1	8.9-11.6	-	(Dexter, 1999)
Congaree National Park, South Carolina, USA	Humid subtropical/hardwood trees forest	1.9	2.2	April 2005 and November 2006	(Friebel & Jodice, 2009)
Alabama, USA	humid subtropical climate/ hardwoods agricultural fields and pine stands	4	4	February 2005 to March 2006	(Gaston et al., 2008)
Mt. Harte, New Zealand	temperate/ pasture and bracken	0.3--1.2	0.4--2.1	October 1983 to May 1984.	(McIlroy, 1989)
Texas, USA	Semu-arid/Savannah vegetation/ Savannah vegetation	6.5	15.8	1998-1999	(Mersinger & Silvy, 2007)
Sunny Corner, NSW, AUS	Temperate broadleaf and mixed forests	4.9	10.7	August 1986 to July 1987	(Saunders & Kay, 1991)
Kosciusko National Park, NSW, AUS	Temperate broadleaf and mixed forests	11.1	35	Various times from 1985- 1988	(Saunders & Kay, 1996)
Tennessee, USA	temperate/hardwood		3.8--3.9	-	(Singer et al., 1981)
Cardwell, QLD, AUS	Tropical and subtropical moist broadleaf forests	7.2	8.7	-	(Mitchell et al., 2009)
Tyrrhenian coast, Italy	Mediterranean, maquis scrub and pinewood.	0.29	0.29	between March and September 1993	(Russo et al., 1997)
Arcadia Valley, QLD, AUS	Subtropical; Open grassland with woodland	11.8	5.8	2017 to 2021	(Wilson et al., 2023)
Downfall Creek, QLD, AUS	Subtropical; Open grassland or woodland	6.2	8.9	2017 to 2021	(Wilson et al., 2023)
Gebar Island, QLD, AUS	Tropical island, with an equatorial climate.	0.08	0.1	2017 to 2021	(Wilson et al., 2023)
Palerang, NSW, AUS	Temperate; Open grassland interspersed with open eucalypt forests.	0.85	3.78	2017 to 2021	(Wilson et al., 2023)
Florida, USA	Sub-tropical, wetlands and grasslands.	3.56	10.41	Wet and dry season from 2015 to 2017	(Schlichting et al., 2022)

Table B3. Summary home range estimations of feral pigs according to Australia's seven ecoregions

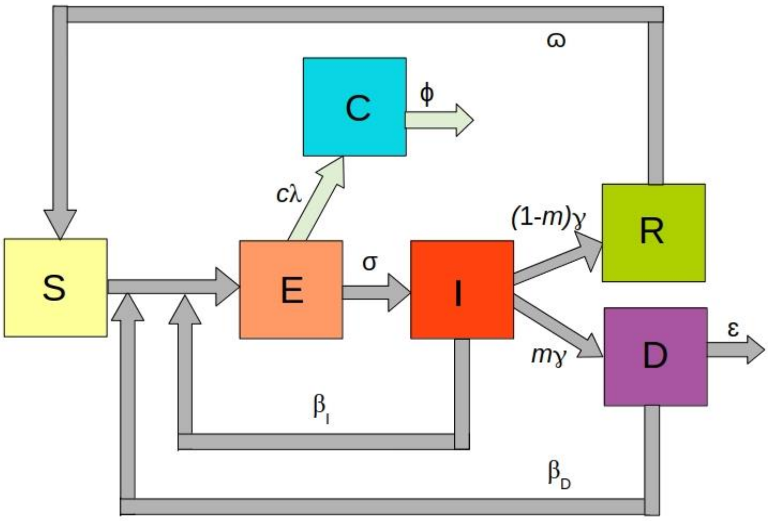
Ecoregion	Name	Home range (km^2)		Reference
		Female	Male	
1	Deserts & xeric shrublands	6.5	15.8	(Mersinger & Silvy, 2007)
2	Mediterranean forests, woodlands & scrub	2.7	7.4	(Boitani et al., 1994)
3	Montane grasslands & shrublands	11.1	35	(Saunders & Kay, 1996)
4	Temperate broadleaf & mixed forest	0.85	3.78	(Wilson et al., 2023)
5	Temperate grasslands, savannas & shrublands	6.5	10.25	(Dexter, 1999)
6	Tropical & subtropical grasslands, savannas & shrublands	11.8	5.8	(Wilson et al., 2023)
7	Tropical & subtropical moist broadleaf forests	7.2	8.7	(Mitchell et al., 2009)

Table B4. Seasonal home range estimations of feral pig groups by wildlife region.

Ecoregion	Name	Seasonal home range (km^2)			
		Summer	Autumn	Winter	Spring
1	Deserts & xeric shrublands	-	-	-	-
2	Mediterranean forests, woodlands & scrub	0.38	-	9.5	0.4
3	Montane grasslands & shrublands	-	6.1	-	-
4	Temperate broadleaf & mixed forest	5.3	3.95	6.4	5.3
5	Temperate grasslands, savannas & shrublands	-	-	-	-
6	Tropical & subtropical grasslands, savannas & shrublands	16.5	12.15	14.55	3.75
7	Tropical & subtropical moist broadleaf forests	3.0	-	-	4.9

APPENDIX C - Livestock within-herd EBM parameterisation

The spread of FMD within a herd is represented by the same EBM as feral pigs (Appendix A) but with different parameterisation. Note that no transmission occurs from carcasses as they are assumed to be removed promptly from the herd.



$$\frac{dS}{dt} = \frac{-\beta_I IS - \beta_D DS}{N} + \varpi R$$
$$\frac{dE}{dt} = \frac{\beta_I IS + \beta_D DS}{N} - \sigma E$$
$$\frac{dI}{dt} = \sigma E - \gamma I$$
$$\frac{dR}{dt} = (1-m)\gamma I - \varpi R$$
$$\frac{dD}{dt} = m\gamma I - \varepsilon D$$
$$\frac{dC}{dt} = c\lambda E - \phi C$$

where

S = number of animals in the herd that are susceptible
E = number of latently infected animals in the herd
I = number of infectious animals in the herd
R = number of recovered animals in the herd
N = total number of animals in the herd (= S + E + I + R)
D = number of animals in the herd that have died from the disease
C = number of animals in the herd with clinical signs
β_I = transmission rate (I to S) (average contact rate × transmission probability)
σ = infectiousness progression rate (1/σ = average duration of the latent period)
γ = recovery rate (1/γ = average duration of the infectious period)
m = average probability of FMD-related mortality
ϖ = loss of immunity rate (1/ϖ = average duration of the immunity period)
c = proportion of cases showing clinical signs
λ = clinical disease rate (1/λ = average duration of the incubation period)
ϕ = clinical recovery rate (1/ϕ = average duration of the clinical period)
β_D = carcass transmission rate (average contact rate × transmission probability) = 0
ε = carcass decay rate (1/ ε = average duration of carcass infectious period) = 0

Table C1. Livestock within-herd EBM parameterisation

EBM parameter	Int beef	Ext. beef	Feed lot	Dairy	VLC pigs	MLC pigs	SC pigs	Boar studs	Micro-pigs	Small-ruminant	Small holder
Transmission rate (β_I)	0.7	1.6	2.5	2.1	2.2	2.2	1.8	0.9	1.2	0.5	1.5
latent period (1/σ) (days)	2	2	2	2	1	1	1	1	1	5	4
infectious period (1/γ)	10	10	10	10	8	8	8	8	8	10	5
mortality rate (m)	0.05	0.05	0.02	0.05	0.1	0.1	0.1	0.1	0.1	0.03	0.04
incubation period (1/λ) (days)	3	3	3	3	3	3	3	3	3	6	4
proportion clinical (c)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.75
clinical period (1/ϕ)	12	12	12	12	14	14	14	14	14	10	12
natural immunity (days) (BetaPERT)	180 280 365	150 220 300	90 120 180	180 280 365	90 120 180	90 120 180	90 120 180	90 120 180	90 120 180	150 200 300	90 180 300

References: Bradhurst, 2015; Bradhurst et al., 2015; Capon et al., 2021

APPENDIX D – Livestock/feral pig spillover spread pathway parameterisation

Table D1. Parameterisation of the livestock/feral pig spillover spread pathway

Parameter	DES	MED	MON	TEF	TES	TRS	TRF	References
farm risk area radius	Varies per farm per region							Section 2.3
Feral pig home radius (km) Summer Autumn Spring Winter	 2.50 2.50 2.50 2.50	 3.15 2.93 3.15 2.65	 2.50 2.50 2.50 2.50	 3.25 2.80 3.58 3.25	 3.15 2.80 3.58 3.25	 3.20 4.00 3.48 2.84	 2.40 2.40 3.94 3.93	Bradhurst et al., 2022
Av. daily prob of transmission feral pig to cattle feral pigs to sheep feral pigs to pigs feral pigs to other cattle to feral pigs sheep to feral pigs pigs to feral pigs other to feral pigs	 0.13 0.13 0.15 0.005 0.01 0.005 0.15 0.005							Adapted from: Ward et al., 2015; Bravo de Rueda et al., 2014; Eble et al., 2006 Notes: The risk of infection is higher from pigs to cattle than from cattle to pigs. Assumption that FMD is 3x more infectious than ASF.
decay mode (linear, exponential, gaussian, Hayama)	Hayama							Hayama et al., 2020
decay alpha	2.81							Adapted from Hayama et al., 2020
decay r0	2.5							Adapted from Hayama et al., 2020

APPENDIX E – Control measures parameterisation

Table E1. Selected parameterisation for domestic control measures

Component	Parameterisation
movement controls	• 3-day national standstill • For each declared IP in mega-region 1: 50km/20km radial CA/RA for two weeks, followed by 25km/10km radial CA/RA • For each declared IP in all other mega-regions: 20km/10km radial CA/RA for two weeks, followed by 10km/3km radial CA/RA • All saleyard movements stopped. • Direct movements: dampened by 98% in RAs, 95% in CAs, and 50% in the OA. • Indirect movements: dampened by 85% in RAs, 50% in CAs, and 25% in the OA. • Declared areas lifted 28 days after all enclosed IP operations have completed.
IP Operations	• Destruction of all susceptible animals on IPs, followed by disposal and decontamination of premises. • No ring destruction or pre-emptive destruction. • NSW: 1 destruction team ramping up to 20 between days 4 and 21 of the response VIC: 2 destruction teams ramping up to 25 between days 3 and 28 of the response QLD: 1 destruction team ramping up to 25 between days 3 and 28 of the response SA: 1 destruction team ramping up to 15 between days 4 and 28 of the response WA: 2 destruction teams ramping up to 24 between days 3 and 40 of the response TAS: 1 destruction team ramping up to 10 between days 4 and 28 of the response NT: 1 destruction team ramping up to 10 between days 3 and 28 of the response • NSW: 1 disposal team ramping up to 20 between days 5 and 21 of the response VIC: 5 disposal teams ramping up to 40 between days 7 and 30 of the response QLD: 4 disposal teams ramping up to 28 between days 7 and 30 of the response SA: 4 disposal teams ramping up to 20 between days 7 and 30 of the response WA: 5 disposal teams ramping up to 28 between days 7 and 40 of the response TAS: 3 disposal teams ramping up to 14 between days 7 and 30 of the response NT: 3 disposal teams ramping up to 16 between days 7 and 30 of the response • NSW: 1 disinfection team ramping up to 100 between days 5 and 21 of the response VIC: 10 disinfection teams ramping up to 100 between days 1 and 25 of the response QLD: 8 disinfection teams ramping up to 100 between days 1 and 25 of the response SA: 7 disinfection teams ramping up to 100 between days 1 and 25 of the response WA: 6 disinfection teams ramping up to 110 between days 1 and 40 of the response

	TAS: 5 disinfection teams ramping up to 100 between days 1 and 25 of the response NT: 5 disinfection teams ramping up to 100 between days 1 and 25 of the response
tracing	• direct and indirect movements onto and off all IPs (14-day tracing window) • Direct tracing effectiveness: cattle 98%, small ruminants 85%, pigs 95%, other 90% • Indirect tracing effectiveness: cattle 80%, small ruminants 70%, pigs 80%, other 90%
surveillance	• investigation of all reported SPs, DCPs and TPs • periodic visits to at-risk premises (ARPs) inside RAs (every 3 days over a 2-week period – subject to resource availability) • lab test required for confirmation of infection • 2 false positive reports of clinical signs for every true positive report • NSW: 5 surveillance teams ramping up to 30 between days 3 and 21 of the response VIC: 3 surveillance teams ramping up to 30 between days 3 and 21 of the response QLD: 5 surveillance teams ramping up to 30 between days 3 and 21 of the response SA: 5 surveillance teams ramping up to 20 between days 4 and 21 of the response WA: 5 surveillance teams ramping up to 25 between days 3 and 30 of the response TAS: 2 surveillance teams ramping up to 10 between days 4 and 21 of the response NT: 2 surveillance teams ramping up to 10 between days 4 and 21 of the response
vaccination	• NSW: 20 vaccination team ramping up to 500 between days 7 and 14 of the response VIC: 12 vaccination teams ramping up to 500 between days 7 and 14 of the response QLD: 20 vaccination teams ramping up to 500 between days 7 and 14 of the response SA: 15 vaccination teams ramping up to 500 between days 7 and 14 of the response WA: 10 vaccination teams ramping up to 500 between days 7 and 14 of the response TAS: 15 vaccination teams ramping up to 500 between days 7 and 14 of the response NT: 5 vaccination teams ramping up to 500 between days 7 and 14 of the response • Commencing on the 7th day of the response • Cattle only • Suppressive vaccination, outside in, within a 3km radius of each IP. • Shared national vaccine back of 500,000 doses • 6-day immunity lag • Vaccine effectiveness: cattle 65%, small ruminants 80%, pigs 87%

References: Animal Health Australia, 2024; estimates based on discussions with stakeholders

Table E2. Parameterisation for durations of domestic control measures

Parameter	Ext beef	Int beef	Feed lot	Dairy	VLC pig	MLC pig	SC pig	SGT pig	Micro pig	Small ruminant	Small holder
surveillance duration (days)	4	1	1.5	0.5	1	1	1	1	0.25	1	0.25
cull duration (days)	1.6	1.4	2.9	1.5	4.2	0.9	0.6	0.6	0.5	1	0.7
disposal duration (days)	2.1	1	2.2	1.6	4.9	0.9	0.6	0.6	0.6	1.4	1
disinfection duration (days)	7	4	7	4	8	1.2	0.6	0.6	0.6	4	1
vaccination duration (days)	7	2	5	1	1.5	1	0.5	0.5	0.3	1	0.3
direct tracing duration (days)	BetaPERT(0, 1, 1)				BetaPERT(1,2,3)					BetaPERT (1,2,3)	BetaPERT (1,2,3)
indirect tracing duration (days)	BetaPERT(1, 2, 2)				BetaPERT(1,3,5)					BetaPERT (1,3,3)	BetaPERT (2,3,5)

Table E3. Parameterisation for feral pig control measures

Parameter	Value
Pre-emptive mode (i.e., auto-culling around IPs)	true
Radius (km)	10
Duration (days)	21
Effectiveness (%)	BetaPERT(80, 80, 80)
CDI mode (refer to Section 2.5.3)	duration
CDI bracket 1 (0.0 to 2.0) duration weight	1.0
CDI bracket 2 (2.0 to 4.0) duration weight	1.25
CDI bracket 2 (2.0 to 4.0) duration weight	1.5

References: Animal Health Australia, 2023; estimates based on discussions with stakeholders

APPENDIX F – Jurisdictions questionnaire and inputs

SEEKING JURISDICTIONAL INPUT – FERAL PIG MANAGEMENT DURING A FOOT-AND-MOUTH DISEASE RESPONSE

BACKGROUND: In collaboration with the Centre of Excellence for Biosecurity Risk Analysis (CEBRA), State and Territory governments, and university and industry partners, DAFF are expanding the AADIS-FMD model to include the potential for spread and control of FMD in feral pig populations. This will allow investigation of the role that feral pigs may play in FMD spread and provide insights into the impact that feral pig population control measures may play in an FMD outbreak response.

Thus, **we are seeking input on potential foot-and-mouth disease (FMD) incursion scenarios involving feral pig populations** to inform case-studies for modelling the spread and control of FMD in Australia.

INSTRUCTIONS: Please provide up to three different scenarios for FMD incursion into either the domestic livestock population AND/OR a feral pig population that is of interest, of concern, or of relevance to your jurisdiction.

Note: The initial disease occurrence or point of infection does not strictly need to involve a feral pig population e.g. 'FMD occurrence due to prohibited matter / swill feeding on a dairy farm with a risk of spread to feral pig populations' is an acceptable scenario.

Please return completed questionnaire to:

Emily Sellens, A/g Senior Veterinary Officer, Epidemiology, Surveillance and Laboratory, DAFF. Emily.Sellens@aff.gov.au

Responses were received from WA only.

SCENARIO	SCENARIO A	SCENARIO B	SCENARIO C
PRIORITY (high, medium, low)			
PATHWAY OF ENTRY (proposed method of entry into animal population)	**Feral pigs accessing waste disposal**	Feral pigs affected by eating dead lambs, following sheep flock infection by movements from primary case (starting with swill fed to pigs on sheep and beef operation)	Feral pigs affected scavenging calves dying from FMD on an extensive beef operation
ENTRY – TIME OF YEAR	**February**	August	May
ENTRY POINT - location	**Pemberton WA**	Peri-urban Perth	Fitzroy crossing
ENTRY POINT – (feral pig population OR livestock enterprise,	**Feral pig population**	Sheep and beef farm (with house pigs)	Swill fed to community pigs by

include number of animals initially infected and type of enterprise)			tourists and spreading to nearby cattle
ENTRY POINT – other info (characteristics of the scenario you may wish to specify/elaborate on)	**Mixed forest and sheep production**	Lots of small blocks	Extensive beef production area
DETECTION POINT First detection may occur at the entry point or at a different location and may occur in a livestock enterprise or feral pig population.	**Hunter report**	Primary case detected Traced to this case	Cattle at muster
SILENT SPREAD PHASE DURATION (time between initial infection at entry point and first detection.	**30 days**	21 days	60 days.

APPENDIX G – Project workshops

CEBRA Project "Assessing the potential role of feral pigs in an outbreak of foot-and-mouth disease in Australia (23F)"

Date:	Wednesday, 13 September 2023
Time:	10:00 am -11:30 am
Location:	Microsoft Teams
Chairperson:	Shumoos Al Riyami

Attendees: Richard Bradhurst, Emily Sellens, Haitham Taha, Sharon Roche, Andrew Bengsen, Narelle Dybing, Claire Harrison, Catherine Kelly, Deane Smith, Cameron Wilson, Matthew Gentle, Nina Kung, Kirsty Richards, Sarah L Hall, Sara Willis, Lyall Grieve, Rachel O'Brien, Amanda Walker, Heather Channon, Andrew Breed, Sally Salmon, Narelle Dybing, Peter Fleming, Rhys Powell, Jens Froese

Agenda

Time	Agenda item	Speaker(s)
10:00-10:05	Welcome and introductions	Shumoos Al Riyami
10:05- 10:10	Project objectives	Dr Emily Sellens
10:10- 10:30	Current modelling capabilities (including demo AADIS-FMD and AADIS-ASF)	Dr Richard Bradhurst
10:30- 11:00	Proposed methodology and approach	Dr Richard Bradhurst
11:00-11:20	Open discussion	All
11:20-11:30	Wrap-up	Shumoos Al Riyami

Australian Government
Department of Agriculture, Fisheries and Forestry

cebra
Centre of Excellence for Biosecurity Risk Analysis

CEBRA Workshop: Representing feral pigs in the national foot and mouth disease simulation model (AADIS-FMD)

Date: Thursday 18th April 2024
Time: 9:00 AM - 3:00 PM
Location: Microsoft teams/Canberra

Attendees: Brendan Cowled (AusVet), Peter Fleming (DPI), Cameron Wilson (QDAF), Deane Smith (DPI), Andrew Bengsen (DPI), Heather Channon (feral pigs), Madalene Oberin (UniMelb), Emily Sellens (DAFF), Haitham Taha (DAFF), Rebekah Burns (DAFF), Shumoos Al Riyami (CEBRA), Richard Bradhurst (CEBRA).
Apologies: Matthew Gentle (QDAF)

Objectives: To consult with feral pig ecologists on (1) the conceptual approach to incorporating feral pig populations into the national foot and mouth disease model (AADIS-FMD), and (2) critical data needs for parameterising feral pig components in the model.

Time	Session details	Facilitator(s)
8:40-8:45 AM	Arrival at DAFF reception for security sign in (in person attendees – please bring photo ID).	Rebekah Burns (DAFF)
9:00 AM - 9:10 AM	Welcome and Introductions	Shumoos Al Riyami (CEBRA)
9:10 AM - 9:20 AM	Project overview	Emily Sellens (DAFF)
9:20 AM - 10:00 AM	Current approaches to representing feral pigs and their interaction with livestock.	Richard Bradhurst (CEBRA)
10:00 AM - 10:20 AM	Coffee break	
10:20 AM - 11:00 AM	Interactive Session 1 **Feral pig distribution & abundance**	Richard Bradhurst (CEBRA)
11:00 AM - 12:00 PM	Interactive Session 2 **Feral pig group dynamics**	Richard Bradhurst (CEBRA)
12:00 PM - 1:00 PM	Lunch break	
1:00 PM - 1:30 PM	Interactive Session 3 **Feral pig group dynamics cont…**	Richard Bradhurst (CEBRA)

1:30 PM - 2:00 PM	Interactive Session 3 Feral pig population control	Richard Bradhurst (CEBRA)
2:00 PM - 2:30 PM	Open discussion and feedback	Richard Bradhurst (CEBRA)
2:30 PM - 3:00 PM	Summary of key points and closing remarks	Shumoos Al Riyami (CEBRA)

Workshop Aims:

CEBRA is undertaking a project to update the existing national foot and mouth disease simulation model (AADIS-FMD) to incorporate feral pig populations. Disease will be able to spread within and between feral pig groups, with possible spillover to and from livestock populations. Thus, understanding the distribution and abundance of feral pigs, their interactions with each other and with livestock, and how these factors vary regionally and seasonally will be crucial for achieving a valid model.

In this workshop, we will present our current approach to representing the feral pig population in the AADIS model and the spread of disease within and between feral pig populations and between feral pigs and livestock. We will be seeking feedback on these approaches and critical input for their further development.

Workshop Minutes:

Session details	Notes
Feral Pig Distribution and Abundance	• Discussed locating groups stochastically inside a cell instead of always at the centroid to more realistically represent feral pig distribution. This in turn would lead to more heterogeneous spread involving feral pigs. • The model currently represents familial groups (sounders). It was suggested to include solitary boars and multiple small groups per cell to enhance realism. Solitary males tend to have larger home ranges and will have greater contact rates. • It would be more realistic to split large groups (e.g., n=80) in northern Australia into several smaller groups that have overlapping home ranges and may hence interact at shared resources.

	• Consistency issues can arise in large-scale aggregative pig density maps due to variations in methods, personnel, and environmental conditions between regional studies. • The model reflects seasonal influences on abundance but does not reflect seasonal changes in distribution. It may be worth considering a future project on the influences of climatic patterns such as El Nino/La Nina cycle and longer-term climate change on resources availability and feral pig distribution. • Estimates of feral pig distribution and abundance density are inherently uncertain, though they remain useful for identifying general trends, rather than making precise conclusions about specific geographic areas.
Group Dynamics	• Feral pigs are generally sedentary and have limited daily movement within their home ranges. Groups might roam 1-2 km per day whilst solitary boars might roam 8-10 km per day. • Distinct groups may have overlapping home ranges and thus may have direct or indirect contact via shared resources. • Consider representing solitary boars (and their potential for longer range movements & increased contact rates compared to sounders) to allow exploration of their transmission potential to other feral pigs and livestock. • Introduction of the concept of circular "splash zones" as an abstraction of feral pig (non-circular) home ranges. The splash zone represents the area within which a group may have direct or indirect contact with other groups or livestock. • Currently, home ranges are defined per region per season. It was suggested to allow these to vary stochastically per model invocation (not per scenario iteration).
Spillover and Farm Type Attractiveness	• Spillover transmission of FMD is possible between feral pigs and livestock and the low biosecurity nature of

	cattle & sheep production systems may be particularly conducive. • The attractiveness of various farm types to feral pigs is unclear and may be influenced by factors such as proximity, biosecurity, land use, and seasonal variability in resource availability and farming practices. A preliminary preference rating is 1) proximity 2) free range piggeries 3) piggeries 4) feedlots 5) sheep/goats 6) other herd types (beef, dairy, mixed, smallholder) • The current AADIS 'sheep' herd type includes goats, so it should be renamed 'small ruminants'. In the future, data permitting, it may be useful to define separate 'sheep' and 'goat' herd types, due to increasing interest in the production of goat meat/milk.
Feral Pig Population Control	• At least a 70% reduction in a feral pig population is required for effective population management, with some experts suggesting aiming for 95% for disease transmission reduction. There will be regional and seasonal variability in the ability to achieve these desired knockdown levels. A key question for the modelling could focus on what knockdown would be required in an FMD outbreak. • The CSIRO feral pig Control Difficulty Index (CDI) layer (Hoskins & Perry, 2020) has been added to the ASF and FMD models but is not yet being used. It was suggested that the normalised CDI scores could be used to extend the duration of control operations proportionally to the level of control difficulty. However, consider that the use of thermal technology (targeted to difficult areas) will increase efficacy and reduce timeframe and thus, reduce the impacts of control difficulty. • It was agreed that it would be appropriate to separately model the resourcing of livestock control actions and feral pig control actions.

	• The model should be able to handle jurisdictional differences in strategies and resourcing for feral pig control.
Feral Pig Population Surveillance	• Passive surveillance only. • Delimiting surveillance in feral populations is not likely to occur in an outbreak.
Feral Pig Recovery (after knockdown)	• Discussion on pig mobility post-control measures and the impact of environmental factors on reproduction rates, influenced by factors like rainfall and climate events. • Propose creating datasets for 'good' and 'bad' seasons to assess impacts on reproduction.

Action items	Assigned to
Group distribution and abundance: • Send out updated data per eco-region on average group sizes, number of groups in a grid, and transition from centroids to random allocation for feedback. • Compare current AADIS distribution and abundance data with jurisdictional information (i.e., NSW) to assess for inconsistencies and inform current data gaps. • Determine regional and seasonal ratio of sounders to solitary males via literature review and expert elicitation.	CEBRA
Home range and contact rate data: • Distribute a review of home range and diffusion contact rate studies per eco-region for feedback. • Expert elicitation activity on contact rates.	CEBRA
Feral pig control: • Need to determine a radius, baseline duration for an easy control area	CEBRA/DAFF

and then maximum duration for difficult area, and scale durations between these - acquire data from jurisdictions to inform this concept.	
Model Adjustments: • Rename the sheep herd type as "small ruminants" to reflect that it represents both sheep and goats. • Currently the model defines a single national strategy for feral pig control. It should be expanded to allow control strategies and resourcing to be defined per jurisdiction. • Allow the location of groups to be anywhere within a cell rather than fixed at the centroid of a cell. • Incorporate solitary males in the model (we will need a rough idea of the regional and seasonal ratio of sounders to solitary males).	CEBRA

APPENDIX H- Visualisation and graphical user interface

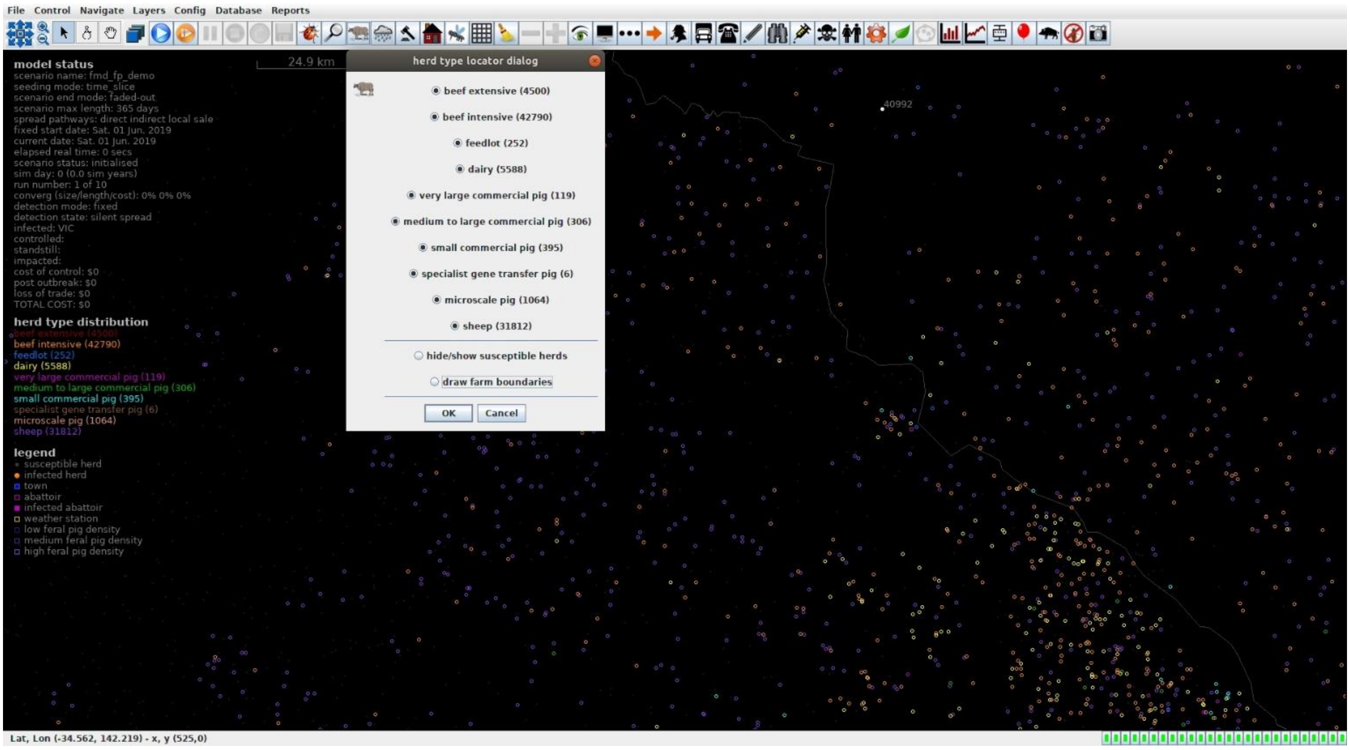


Figure H1. AADIS-FMD-FP herds with the display of farm risk areas disabled.

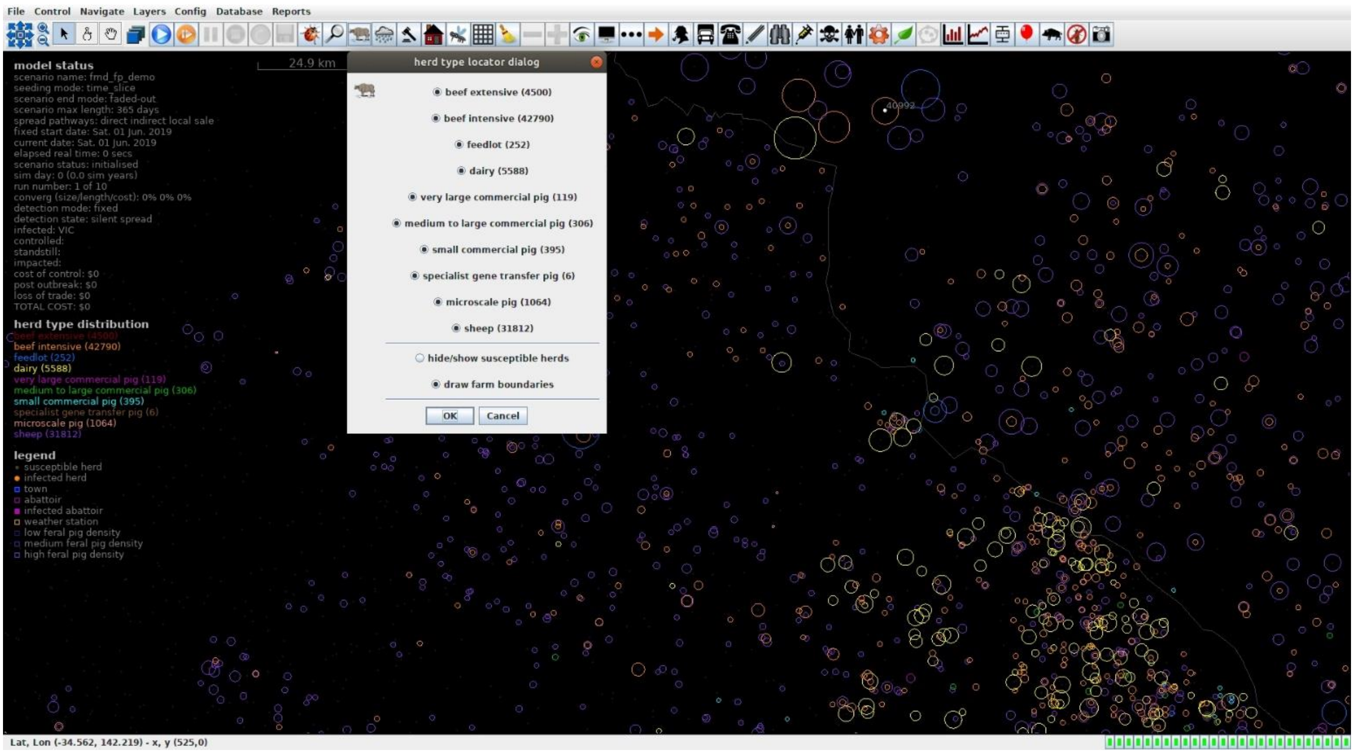


Figure H2. AADIS-FMD-FP with the display of sfarm risk areas enabled.

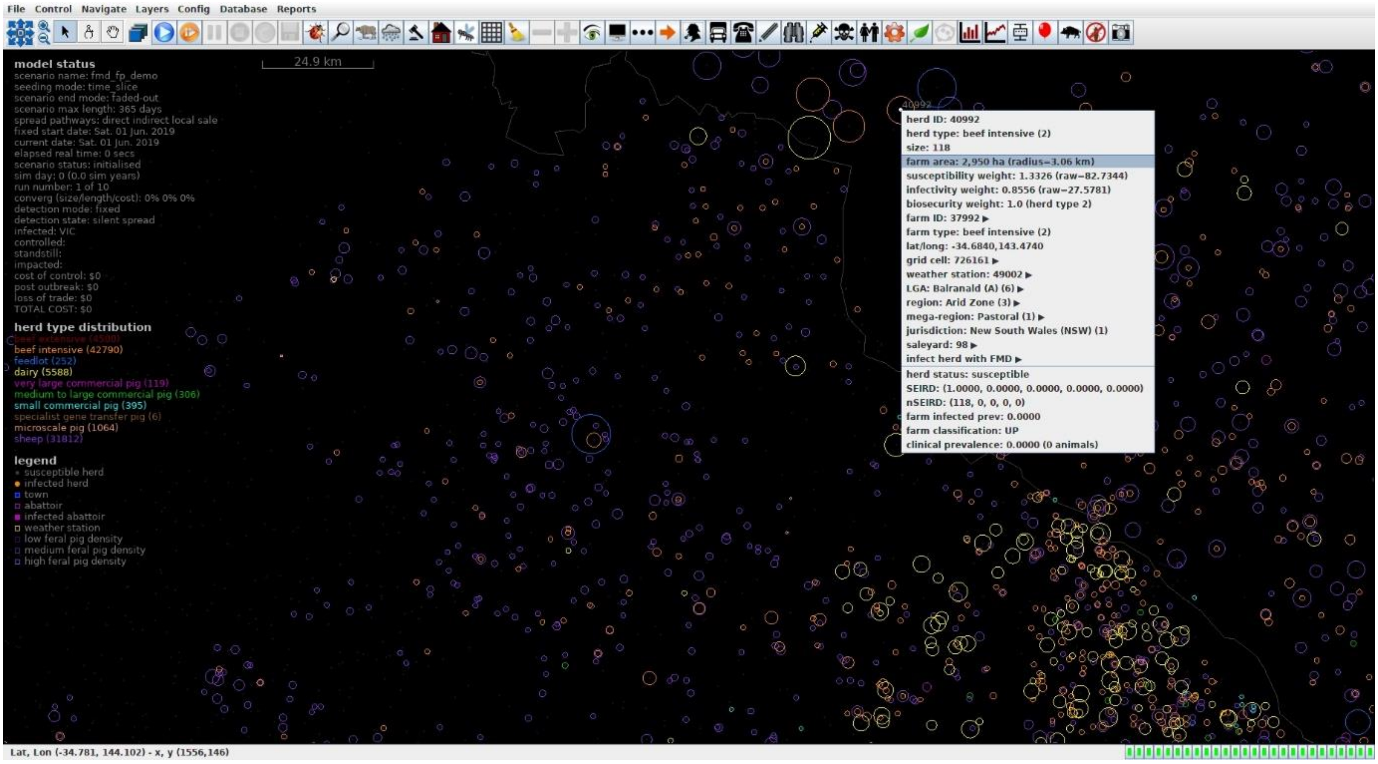


Figure H3. AADIS-FMD-FP herd popup displaying a farm's estimated risk area (both in ha and as a radius in km).

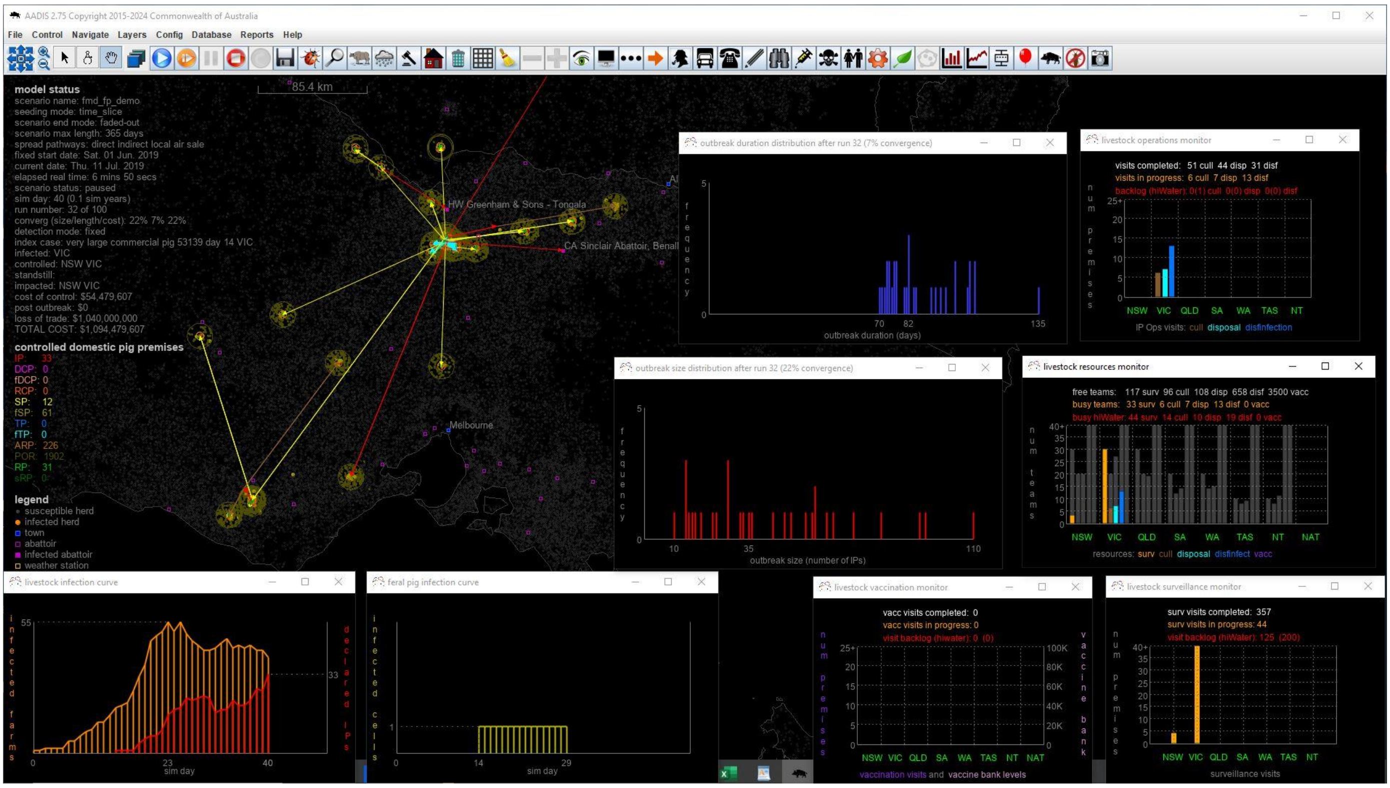


Figure H4. AADIS-FMD-FP outbreak visualisation

APPENDIX I – Literature review

Shumoos Al-Riyami

Introduction

Foot-and-mouth disease (FMD) poses a substantial threat to global livestock industries, with significant economic and agricultural consequences. Known as one of the most contagious diseases affecting cloven-hoofed animals, FMD impacts both domestic and wild species including cattle, water buffalo, deer, sheep, goats, and pigs (Grubman & Baxt, 2004). The disease is caused by the Foot-and-mouth disease Virus (FMDV), which belongs to the genus *Aphthovirus* within the *Picornaviridae* family (Grubman & Baxt, 2004). Clinically, FMD is generally marked by vesicular lesions on the mouth, snout, feet, and teats, and lameness, with severity varying with host species and viral strain (Alexandersen et al., 2002; Jonathan Arzt et al., 2011). An outbreak of FMD in a region like Australia, where important livestock industries rely on FMD-free status for access to export markets, could lead to economic losses exceeding A$80 billion (Buetre, 2013); Department of Agriculture, Fisheries & Forestry, 2022).

The spread of FMD occurs primarily through direct contact between infected and susceptible animals, with infected pigs identified as high emitters of virus particles, capable of amplifying FMDV up to 60 times more per day than sheep and cattle (Alexandersen et al., 2003). Pigs' role as efficient spreaders of airborne FMDV highlights the challenges in controlling outbreaks involving mixed-species environments where pigs are present. While direct transmission between livestock plays a central role in outbreaks, wildlife species, particularly wild and feral pigs, significantly complicate disease management due to their mobility, wide distribution, and interactions with livestock. Wild pigs, including feral pigs and wild boar, have been implicated as reservoirs for FMDV, capable of harbouring and transmitting the virus to domestic animals and perpetuating the disease cycle. Studies such as Karniely et al. (2020) confirm the presence of FMDV in wild boars in the Middle East, indicating the capacity of feral pigs to maintain FMDV in the wild. Similarly, research by Fukai et al. (2022) demonstrates that infected Japanese wild boar can spread the virus through both direct contact and environmental contamination.

Australia presents a unique case due to its large, dispersed feral pig population, which overlaps significantly with livestock regions. This overlap poses an additional risk for FMD transmission. Feral pigs in Australia frequently come into contact with livestock through shared water sources and grazing areas, which amplifies the risk of cross-species transmission (Bain & Kinnear, 2015). The ecology and behaviour of feral pigs, combined with often subtle clinical signs of infection, make FMD detection and control challenging in wild populations. The potential for FMD to become endemic in Australia's feral pig population is unclear and if it occurs, would require extensive on-farm biosecurity measures and possibly large-scale culling of feral pigs to suppress transmission. As such, understanding the role of feral pigs in FMD epidemiology is essential for devising effective surveillance and biosecurity measures to mitigate the risk of transmission from wildlife to livestock.

Status of FMD in feral pigs globally

FMD remains endemic in numerous regions across the globe, particularly in Asia, Africa, and parts of South America, with sporadic outbreaks in other areas (Jamal & Belsham, 2013). Feral pigs (*Sus scrofa*)—including wild boar and other hybrids—are identified as significant players in the disease dynamics of FMD due to their ability to harbour and transmit the virus across wildlife and livestock populations (Gortázar et al., 2022). Their resilience and adaptability allow feral pigs to thrive in diverse habitats, facilitating their spread and potential to serve as reservoirs of infection.

In Europe, wild boar is recognized as potential hosts for FMDV, with concerns heightened by their expanding range across the continent. During the 2011 outbreak in Bulgaria, FMDV RNA was detected in wild boar, suggesting their exposure to the virus alongside livestock cases (Sutmoller et al., 2003). This cross-border movement is especially concerning in areas where wild boar populations overlap with livestock farms, presenting transmission risks that require regional FMD management strategies. Surveillance efforts, such as those conducted in Bulgaria and other regions, emphasize the importance of monitoring wild boar populations to prevent spillover events into domestic animals. This outbreak was immediately preceded by the discovery of FMDV in a wild boar with foot lesions located 2 km from the Turkish border (Jonathon Arzt et al., 2011). Another outbreak of FMD was reported at the Paris Zoological Gardens in France, four wild boars were affected after contracting the infection (Urbain et al., 1938).

Asia remains one of the most heavily affected regions, with endemic FMD impacting both livestock and wild pig populations. In Japan, research on wild boar has demonstrated that they can carry and spread FMDV in areas where domestic pigs are prevalent. A study by Fukai et al. (2022) highlighted the transmission risk posed by infected Japanese wild boar populations in FMD-endemic areas, particularly in regions with overlapping livestock operations. Another example involving wild boar in Asia is the 1997 outbreak in Taiwan, where wild boar served as amplifiers of the virus, shedding large amounts of FMDV into the environment (Dunn & Donaldson, 1997). In Sri Lanka, FMD outbreaks frequently occur in areas in close proximity to national parks where there are significant populations of feral water buffalo and wild boar (Roeder, 2011).

In the Middle East, the detection of FMDV in wild boars has been reported, such as in Israel, where outbreaks in wild boar populations raised concerns about potential spillover to livestock. Karniely et al. (2020) documented this transmission risk and emphasized the challenge of implementing control measures in wild boar populations due to their extensive range and mobility.

Whereas domestic pigs infected with FMDV typically exhibit lameness, wild boar MDV have been observed to remain active (Breithaupt et al., 2012; Fukai et al., 2022) and may continue to contact nearby susceptible animals whilst infectious. Modelling studies have suggested that if control actions are not undertaken in infected wild boar populations, there is a risk of spread into adjacent areas and the possibility of persistence (Croft et al., 2019). Efforts to control FMD in South America have involved vaccination campaigns targeting livestock; however, the role of wild pigs as potential reservoirs in remote areas presents ongoing challenges. Studies in the Pantanal wetlands, for example, indicate that wild pigs could act as carriers of FMDV, which may hinder eradication initiatives (Carlos et al., 2023).

Australia, although free from FMD, faces a unique risk due to its substantial feral pig population, which is estimated to inhabit nearly half of the continent (Bain & Kinnear, 2015). The expansive distribution of feral pigs across Australia, particularly in regions with livestock activities, amplifies the potential consequences should FMD be introduced. This risk is heightened in northern and eastern Australia, where livestock and feral pig populations overlap significantly, presenting opportunities for cross-species transmission (Pearson et al., 2014). Although no FMD cases have been recorded in Australian feral pigs, simulations have demonstrated that an outbreak involving feral pigs could lead to prolonged presence of the virus, complicating eradication efforts (Ward et al., 2015).

FMD clinical signs

The clinical signs of FMD in wild swine populations are generally similar to those in domestic pigs but can vary in their specific expression (Jonathon Arzt et al., 2011; Thomson et al., 2003). For instance, during a 2018 FMD outbreak in wild boars in the Middle East, affected animals primarily displayed lameness, which is a common clinical sign of FMD, despite the absence of mouth vesicles or erosions often seen in domestic pigs infected with FMD (Karniely et al., 2020). In contrast, another study found that experimentally infected wild boar exhibited vesicular lesions on their feet, snout, tongue, and lips, though they did not show lameness (Fukai et al., 2022). The average duration of clinical signs in domestic pigs is 14 days (Moreno-Torres et al., 2022) and we assume the same period for feral pigs (Appendix A).

Roh et al. (2021) observed that younger pigs, particularly those under eight weeks, show heightened sensitivity to FMDV and suffer higher mortality rates due to their underdeveloped immune systems. Kinsley et al. 2016 estimated mean disease-induced mortality rates for FMDV, with adults having an average mortality rate of 20.8% and piglets showing a much higher mean mortality rate of 58.3%. We assume an average FMD mortality rate of 5% in feral pigs (Appendix A).

FMDV epidemiology and transmission

The latency and incubation periods of FMDV in feral pigs generally align with those in domestic pigs (Breithaupt et al., 2012; Moreno-Torres et al., 2022), although strain and exposure conditions can lead to variability (Kinsley et al., 2016). For modelling the PanAsia O strain, we assume an average latent period of 1 day and an average incubation period of 3 days, implying on average, a two-day period where feral pigs are infectious yet not showing clinical signs (Appendix A).

The infectious period of FMD in pigs varies with viral strain, exposure conditions, and pig subspecies. The average infectious period for the O strain in domestic pigs is 6 to 10 days (Mardones et al., 2010)Kinsley et al., 2016; Moreno-Torres et al., 2022). The average infectious period for the O strain in feral pigs is 8 to 9 days (Croft et al., 2019), (Fukai et al., 2022). For modelling purposes, we assume an average infectious period of 8 days in both domestic and feral pigs (Appendices A and C).

FMDV transmits readily between feral pigs through direct contact, environmental contamination, and, to a lesser extent, airborne spread. Feral pigs shed high concentrations of FMDV in saliva, nasal secretions, and faeces, contaminating shared water and grazing resources, which can create indirect spread pathways for livestock (Alexandersen et al., 2002). Infected pigs can produce higher quantities of airborne virus particles than other species, underscoring their role as potent spreaders in mixed-species environments (Alexandersen et al., 2003).

Carcass transmission of FMDV depends heavily on environmental conditions, particularly temperature and pH, which influence the rate at which the virus is inactivated after death (Hunnam et al., 2018). Research has shown that under warm conditions, such as those in northern Australia, carcass decomposition can effectively inactivate FMDV, minimizing the risk of infection from carcass remnants. Hunnam et al. (2018) specifically investigated the impact of pH and temperature changes on FMDV survival in pig carcasses. Their study revealed that in northern Australia, pH levels dropped to inactivating thresholds within 16 hours post-mortem for most carcass tissues. For example, when pH reached ≤6.0, a significant viral inactivation effect was observed. At temperatures of 30–35°C, this inactivation typically occurred within 24 hours, suggesting that warm climates naturally limit the virus's persistence in carcasses. However, certain tissues, such as bone marrow and brain, did not always reach this pH level, indicating that these tissues might retain the virus longer than others. Additional studies corroborate these findings. Caridi et al. (2015) reported that FMDV particles tend to destabilize within a pH range of 6.13 to 6.93, leading to viral disassembly and inactivation. In contrast, under cooler conditions, FMDV can persist for extended periods, as Guan et al. (2010) showed in a study of composted pig carcasses. At ambient temperatures around 20°C, FMDV survived in skin tissues for up to 10 days and in organ tissues beyond 21 days. When compost temperatures reached 50–70°C, complete viral inactivation occurred by day 10 for skin and day 21 for internal tissues, suggesting that elevated temperatures from composting can accelerate virus degradation, though this process is slower in moderate temperatures. Stenfeldt et al. (2020) further highlighted the persistence of FMDV in specific tissues under cold storage. They found that while FMDV in muscle tissues was generally inactivated within 7 days at 4°C, the virus in vesicles and some lymph nodes persisted for over 11 weeks. RNA was detectable in these tissues even after 77 days, though the infectious potential of this residual virus remains uncertain. These studies emphasize that while carcass decomposition under warm conditions can rapidly inactivate FMDV, cooler environments significantly slow this process. As a result, carcass management and disposal methods should be adapted based on environmental conditions to prevent extended virus survival and minimize potential transmission risks, especially in regions with cooler climates where virus persistence in carcasses poses a greater threat.

Distribution and abundance of feral pigs in Australia

Feral pigs are widely distributed across Australia, occurring across a reported 38 – 45% of Australia (Choquenot et al., 1996; West, 2008) (Figure I1). As part of the AADIS-ASF model development (Bradhurst et al., 2021;2022), a comprehensive literature review of past national and regional studies on feral pig distribution and abundance was conducted, leading to more granular estimates of feral pig distribution and density per eco-region (Figure I2). This analysis considered various factors, including habitat suitability, availability of permanent water sources, land use, and vegetation data (Cowled B. & A., 2021). It is thought that feral pigs are expanding in distribution (Cowled et al., 2009; Lewis et al., 2017) due to escapes from domestic production, slow natural dispersal (Caley, 1993) and illegal translocations for hunting resources (Spencer & Hampton, 2005). Feral pig populations can expand and contract in response to local environmental conditions, for example, recent rainfall can trigger rapid rates of increase through breeding (Giles, 1980).

In general, feral pigs are constrained by food and thermoregulation over much of Australia. For example, when it is warm, they are found in vegetated areas, especially riparian vegetation, but distribution may be more driven by food availability in cooler areas or seasons (Dexter, 1998). Feral pigs also utilise pasture and crops for food (Dexter, 1998). Thus, in drier or warmer areas or times, feral pigs frequent swamps, floodplains, and large freshwater rivers with riparian vegetation where they reach their highest abundance after adequate rainfall. However, feral pigs are also found in many other habitats such as and subalpine areas, woodlands, and rainforests and even in some peri-urban areas.

Estimates of the number of feral pigs in Australia have been refined over the decades (Hone & Pech, 1990; Tisdell, 2013; Wilson et al., 1992) and most recently by Hone (2019). Hone estimated nationally there are 3.2 million pigs (95% CI: 2.4-4 million) at a density of 1.03 pigs per km2, although densities of up to 20 pigs per km2 have been recorded (Dexter, 1990). This estimate of total feral pigs in Australia is much lower than the previous estimate used by industry (13.5 million (95% CI 3.5-23.5 million) but is more accurate given the large number of studies (142) used to obtain the estimate.

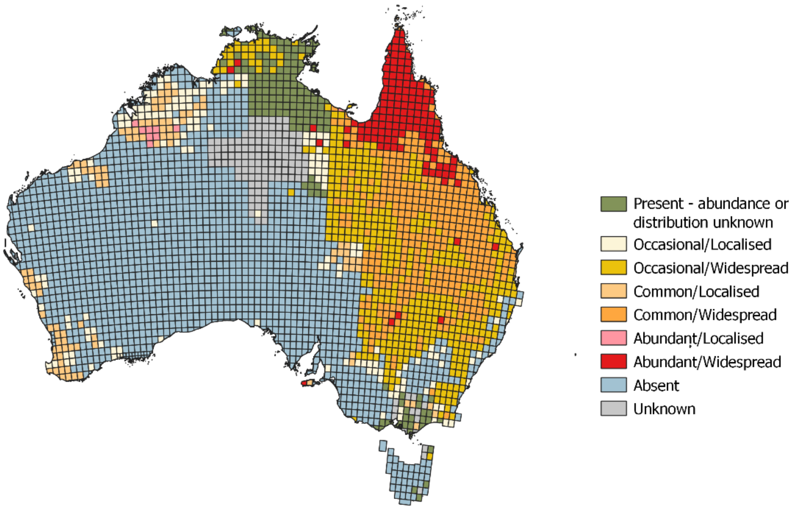


Figure I1. Estimated feral pig distribution and abundance (West, 2008)

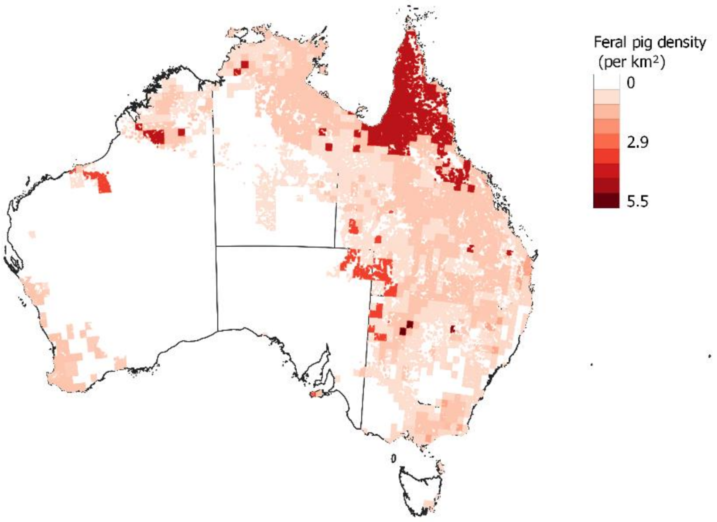


Figure I2. Feral Pig Distributions. Report prepared for CEBRA. Ausvet Pty Ltd. Cowled B and Meyer A. (2021).

Potential role of feral pigs in the spread of FMD

Feral pigs are largely structured across the landscape in female dominated groups of varying sizes, with some solitary males. Many ecological studies suggest that feral pigs are relatively sedentary demonstrating small dispersal distances in general and little tendency to disperse from their home ranges, (Spencer & Hampton, 2005). The size of their home range is influenced by the availability of food and water, population density, and body size (Caley, 1997; Choquenot et al., 1996; Saunders & McLeod, 1999). Some of the larger yearly home ranges have been found to be up to 43 km^2 for males (Giles, 1980) and 24 km^2 for sows (Caley 1997), but most observations of home ranges have been smaller than this

(Choquenot et al., 1996). McIlroy et al. (1989) found that in southeastern mountainous regions, weekly net movements within a larger, fixed home range were around 2.5–3 km (Pech & McIlroy, 1990). Daily movements in the same region ranged from 6.5 to 8.4 km, while mean movements over three-hour intervals in tropical areas were approximately 459 m (Caley, 1993). Daily home ranges observed by Saunders and Kay (1991) and Caley (1993a) were approximately 1 km^2 within a larger home range. When feral pig movements and home ranges have been measured in the past during and after intensive persecution (trapping, monitoring and aerial shooting) they have shown no tendency to change movement patterns or to disperse, with collared pigs remaining in their home ranges (Saunders and Bryant 1988; Dexter 1996). Despite this, rare long-distance movements of feral pigs can occur (Saunders and Bryant 1988; Caley, 1997). For instance, wild pig dispersal during hunting has been associated with the spread of Classical swine fever across European borders and the introduction of infection into new pig populations, (Zanardi et al., 2003).

Feral pigs are highly sociable, and home ranges can overlap, enabling contact and disease transmission between groups of feral pigs. Several authors have found that for wild boar and feral pigs, most intergroup contacts occur over distances of less than 2 km (Pepin et al., 2016; Podgorski et al., 2018) and modelled home ranges of 4 km^2 (Scherer et al., 2020).

There is considerable overlap in Australia between the distribution of feral pigs and livestock production areas. Understanding the contact rates between feral pigs and livestock is important for assessing the potential for disease transmission, particularly for a disease such as FMD that readily spreads through both direct and indirect contacts. Previous Australian studies (Pearson, 2012; Pearson et al., 2014; Pearson et al., 2016) and overseas studies (Wyckoff et al., 2009; Wu et al., 2012; Kukielka et al. 2013; Jori et al. 2017; Hayama et al. 2020) have demonstrated the potential for feral pigs to be close to commercial piggeries. It has been shown that indirect contact between wild pigs and cattle through shared resources and pastures is much more frequent than direct contact (Yang et al., 2021). Feral pigs have also been documented as interacting negatively with sheep, primarily through predation on lambs. The "Australian Feral Pig Report – July 2020" states that lamb predation by feral pigs ranges from 18.7% to 32% of lamb losses in semi-arid rangelands. Beyond direct predation, feral pigs can compete with sheep for feed and graze on pastures, increasing the risk of indirect transmission of disease.

In endemic regions, feral pigs have been linked to the re-emergence of FMD, maintaining viral persistence and acting as long-term reservoirs that can reintroduce the virus to livestock populations. Studies from Asia and Europe highlight that feral pigs can harbor FMDV for extended periods, posing a reintroduction risk even in regions that have eradicated the virus in livestock (Breithaupt et al., 2012; Fukai et al., 2022; Karniely et al., 2020).

Models of FMD transmission in feral pigs

Early work, such as Pech and Hone (1988), focused on the relationship between FMD outbreak dynamics and the structure of feral pig populations, incorporating birth and non-disease-related deaths alongside FMD-induced mortality. A key finding was that the disease transmission coefficient, which drives the rate of spread, remains uncertain due to a lack of specific data on feral pig populations. As a result, the model predicted a wide range for the threshold pig density necessary for FMD to persist, from 2.3 to 14 pigs per square kilometre. This broad estimate highlighted the limitations of modelling disease spread in feral populations without detailed empirical data. Building on this, Pech and McIlroy (1990) used radio-collar data from 24 feral swine to assess home ranges and overlap, finding that the overlapping ranges could facilitate FMD transmission. This work emphasized the importance of spatial interactions in understanding FMD spread.

Dexter (2003) used a stochastic model of feral pig populations coupled with a deterministic FMD model, demonstrating that FMD spread is highly sensitive to pig density. Lower densities facilitated easier disease control, while higher densities posed greater control challenges. Doran and Laffan (2005) advanced FMD modelling in feral pigs by using a compartmental model within a cellular automata framework, allowing a more complex exploration of spatial and seasonal dynamics. They found that the seasonality of an outbreak could greatly influence its persistence and spread, with some areas like Winton showing higher outbreak persistence potential than others like Cape York, where FMD might die out naturally. This study suggested that environmental seasonality and spatial distribution may play as significant a role in FMD dynamics as population density, highlighting a shift from density-focused models to those incorporating ecological factors.

Ward et al. (2007) applied a state transition model within a geographic automata framework to assess FMD transmission from wildlife, specifically feral pigs and deer, to cattle in southern Texas. This study provided a rare instance of modelling cross-species FMD dynamics and found that in some cases, FMD introduced in feral swine did not spread to domestic populations, indicating potential for disease extinction before transmission to livestock. This demonstrated that disease spread could be limited by spatial and behavioural barriers, complicating predictions and requiring nuanced control approaches. Ward et al. (2009) further enhanced model complexity by integrating social and habitat requirements through a geographic-automata model. Their model showed that the fragmented nature of pig herds created unpredictable FMD spread patterns, emphasizing that herd structure and spatial heterogeneity play a significant role in disease dynamics. This complexity highlighted the limitations of prior models that had relied on spatial continuity assumptions, marking a pivotal shift toward more ecologically representative models.

Laffan et al. (2011) focused on how defining neighbourhood boundaries in spatio-temporal models affects FMD simulation accuracy. By examining interactions between home range centroids, the study provided insights into spatial interactions among uncontrolled populations, though it did not fully capture overlapping territories, limiting spatial accuracy. This study illustrated the challenges of representing mobile, territorial animals in disease models, underscoring a need for more refined spatial modelling to improve accuracy.

The integrated model by Ward et al. (2015), which incorporated feral pigs and domestic cattle, marked a further advancement by simulating mixed-species interactions. They showed that multi-species control strategies targeting both pigs and cattle reduced outbreak size and duration more effectively than single-species approaches, pointing to the benefits of coordinated management. This model demonstrated that in mixed ecosystems, controlling FMD requires addressing interactions between wildlife and livestock, a complexity not captured by earlier single-population models.

Croft et al. (2019) introduced an innovative approach by assessing how hunting pressure and spatial factors influence FMD endemicity in wild boar populations. They found that geographic spread, more than population density alone, played a decisive role in disease persistence, with low-density culling proving challenging across large landscapes. Croft et al. proposed fertility control as a non-lethal management alternative, suggesting that sustainable long-term FMD control may require combining lethal and non-lethal strategies. This shift towards integrated control reflects a growing recognition of the limitations of purely density-focused or lethal control measures.

Overall, these studies illustrate a progression from basic density-based models to sophisticated, multi-faceted approaches that account for spatial heterogeneity, seasonality, ecological behaviours, and cross-species interactions. Each model has aimed to address the limitations of its predecessors, yet the absence of real outbreak data continues to introduce uncertainty. The evolution from Pech and Hone's foundational model to Croft et al.'s integrated approach underlines that effective FMD management in feral pig populations requires adaptable strategies that reflect ecological complexity, with an increasing emphasis on sustainable, multi-layered control methods. The progression of FMD models highlights both the steps made in understanding disease dynamics and the persistent challenges posed by data limitations, pointing to the need for empirical outbreak data to refine these models further.

APPENDIX J – Review of Dairy Farm Stocking Rates

Emily Sellens – August 2024

In the FMD model, contact between feral pigs and domestic herds will be conceptualised as overlapping spatial risk zones. The risk zone for feral pigs will be determined by home ranges. The risk zone for farms will be estimated by approximating farm risk areas from the herd size, based on livestock stocking rates defined per livestock region and herd type. Thus, we sought to determine the stocking rates for dairy cattle by livestock region from the available literature.

Table J1. Review of stocking rates

State	Dairy Region	AADIS Beef region	Average Farm size (ha)	Stocking rate cows/ha	Reference
National	-	-	307	1.3	ABARES 2020
Qld	Atherton (Cairns)	5		1.9 (case study)	QLD Gov 2006
	Qld	5 & 6	312 – 491 (south); 249 (north)	Estimate: 0.75 - 1.0 (south); 1.2 (North)	Queensland Dairy Accounting Scheme - 2023
NSW	NSW	6 & 7 (?) 8 & 9	382 (291 north, 461 south)	1.3	Dairy Farm Monitor Project NSW annual report 22/23
			360	1.5	NSW DPI 2020
Victoria	Gippsland	8	205	1.9	Ag Vic Dairy Farm Monitor Project 2022-23 Annual Report
	Northern Victoria (Murray)	9	322	1.5	
	South West Victoria	10	351	1.1	
Tasmania	Tasmania	11		2.6	Dairy Tas Annual Report 22/23
			346	2.5	Dairy Farm Monitor Project Tasmania annual report 22/23
SA	SA	10	510	1.2	Dairy Farm Monitor Project SA annual report 22/23
				Upper limits 2.5 (dryland) and 5.2 (irrigated)	Valentine et al 2009
WA	WA	12	628	0.8	Dairy Farm Monitor Project WA annual report 22/23

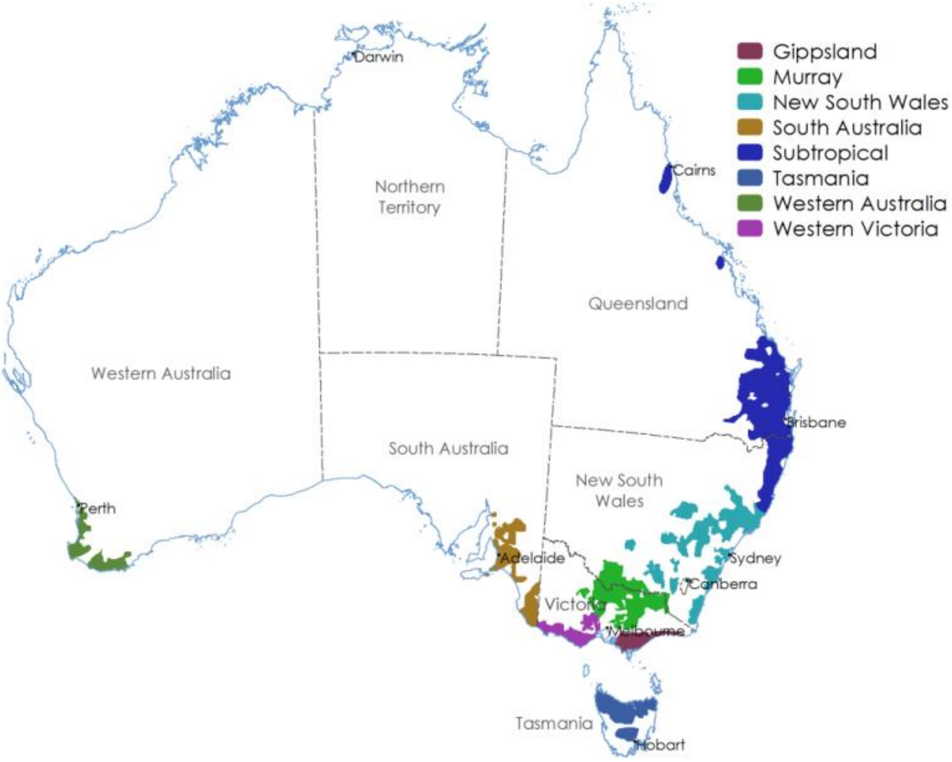


Figure J1. Australia's Dairy Regions – ABARES 2020.

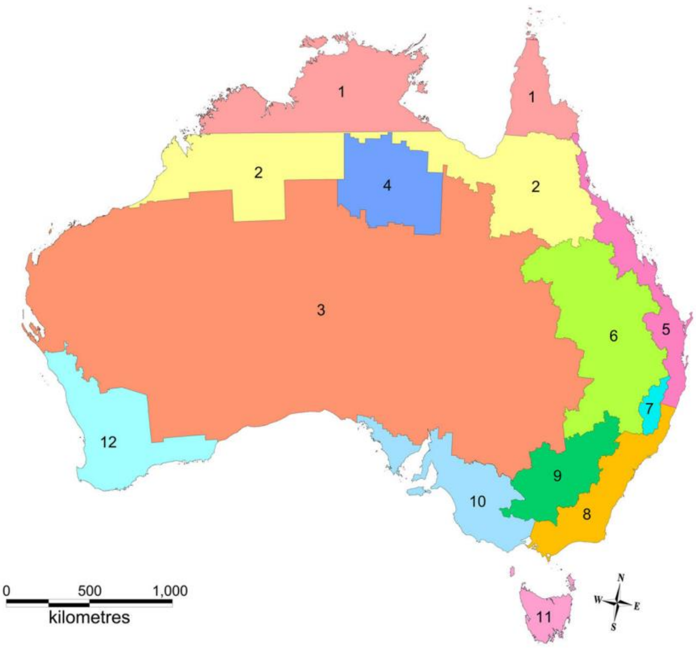


Figure J2. AADIS Livestock Regions

Table J2. Suggested stocking rates for dairy farms by AADIS Beef Region

Region	Region name	Stocking rate (cows/ha)
5	Tropical NE Coast	1.2
6	Central Qld and northern NSW	1.3
7	New England	1.3
8	Temperate SE Coast	1.5
9	Temperate Slopes	1.5
10	Mediterranean	1.1
11	Tasmania	2.5
12	SW WA	0.8

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APPENDIX K – Sensitivity Analyses

Sensitivity analysis is a technique of systematically varying model parameters to estimate their relative influence on scenario outcomes. It is particularly useful for assessing the influence of parameters that are naturally variable, subject to chance, or uncertain due to inadequate data. It is important that modellers and the users of models know how the quality of specific data influences model outcomes. This helps focus into improving the quality of key data, in lieu of data that does not materially impact the model outputs. The identification of parameters that strongly influence scenario outcomes is also useful from an epidemiological perspective, and can then inform planning and preparedness activities, such as a cost benefit analysis of proactive surveillance.

Previous ASF modelling projects (Bradhurst et al., 2021; 2022) have already established the sensitivity of the model to feral pig density, between-group contact rates and spillover contact rates. Sensitivity analyses of farm risk area and feral pig home range are being conducted under the follow-on project “Models to inform foot-and-mouth disease management in wild host populations in NSW” undertaken by CEBRA in partnership with the NSW Department of Primary Industries. The following additional sensitivity analyses were conducted in response to changes made to the livestock EBM.

Domestic pig within-herd transmission rate (β)

As the AADIS-FMD-FP pig herd types were derived from the AADIS-ASF model (and quite different to the legacy AADIS-FMD pig herd types), it was decided to conduct a sensitivity analysis of the within-herd transmission rate β. The goal was to characterise the influence of β on outbreak size and control duration.

6.1.1 Method

FMD outbreaks were randomly seeded into each of the five pig herd types on May 1st. It was decided to compare the baseline β values with 2β and 2.5β (Table 48). Only β values greater than the baseline were assessed as the baseline values (derived from Kinsley et al., 2016) were lower than values reported by Eble et al., (2006).

FMD was allowed to spread in the domestic cattle population via the direct, indirect, local, airborne and saleyard spread pathways. Spillover transmission back and forth with the feral pig population was disabled. The time to detection was configured to occur on day 14 of the outbreak. Default domestic control measures and resourcing were employed (Section 2.5). Outbreaks were configured to end upon disease control/fade-out with a maximum outbreak length of 540 days (i.e., outbreaks still active on day 540 were terminated). 1,000 simulation runs were conducted per herd type, for each β variation.

Table K1. Beta values assessed in the sensitivity analyses.

Herd type	Herd Type ID	Num runs	Baseline β	2x	2.5x
very large commercial pig	5	1000	2.2	4.4	5.5

medium to large commercial pig	6	1000	2.2	4.4	5.5
small commercial pig	7	1000	1.8	3.6	4.5
specialist gene transfer pig	8	1000	0.9	1.8	2.25
microscale pig	9	1000	1.2	2.4	3

6.1.2 Results

When outbreaks were seeded in commercial piggeries (herd types 5 to 7), the likelihood of a very large outbreak was strongly associated with the configured within-herd beta. This is evident by strong increases in the 95th percentile of the number of infected premises and the 95th percentile of the control duration, particularly for medium to very large piggeries (Table K2). The number of IPs and control duration for outbreaks seeded in microscale piggeries and boar studs (herd types 9 and 8) were far less sensitive to the configured beta (Table K2).

The outbreaks generated by the baseline transmission rates were consistent with expectations of FMD outbreaks in Australia (Capon et al., 2021). However, the sensitivity of overall outbreak size to the within-herd transmission beta for outbreaks started in medium to very large piggeries is important to note – particularly given the lack of FMD field data in an Australian context to inform model parameterisation. If beta has been underestimated then there is an increased risk of a very large outbreak.

Table K2. Outbreak size and control duration for different values of beta, by seed herd type.

Beta	mean IP	median IP (p5, p95)	mean control duration (days)	median control duration (days) (p5, p95)	control duration convergence %
		very large commercial pig			
baseline	75	41 (19,125)	83	73 (59, 117)	6
2x	146	54 (23,548)	105	81(60,241)	5
2.5x	148	60 (24,596)	107	83 (60,254)	5
		medium to large commercial pig			
baseline	40	18 (6,104)	71	63 (50, 100)	3
2x	71	21 (7,200)	80	65 (51, 125)	5
2.5x	102	22 (7, 412)	88	64 (50, 187)	6
		small commercial pig			
baseline	16	6 (2,39)	57	52 (36,87)	3
2x	25	7 (2,87)	60	53 (36, 100)	3
2.5x	31	7 (2,97)	63	54 (36, 100)	4
		specialist gene transfer pig			
baseline	4	3 (1,8)	44	43 (31, 59)	1
2x	4	3 (1,9)	44	42 (31, 61)	2
2.5x	4	3 (1,10)	44	42 (31, 61)	2
		microscale pig			
baseline	6	2 (1,24)	45	40 (31,77)	2

2x	14	3 (1, 39)	47	41 (31, 88)	4
2.5x	11	3 (1,42)	47	41 (31, 85)	4

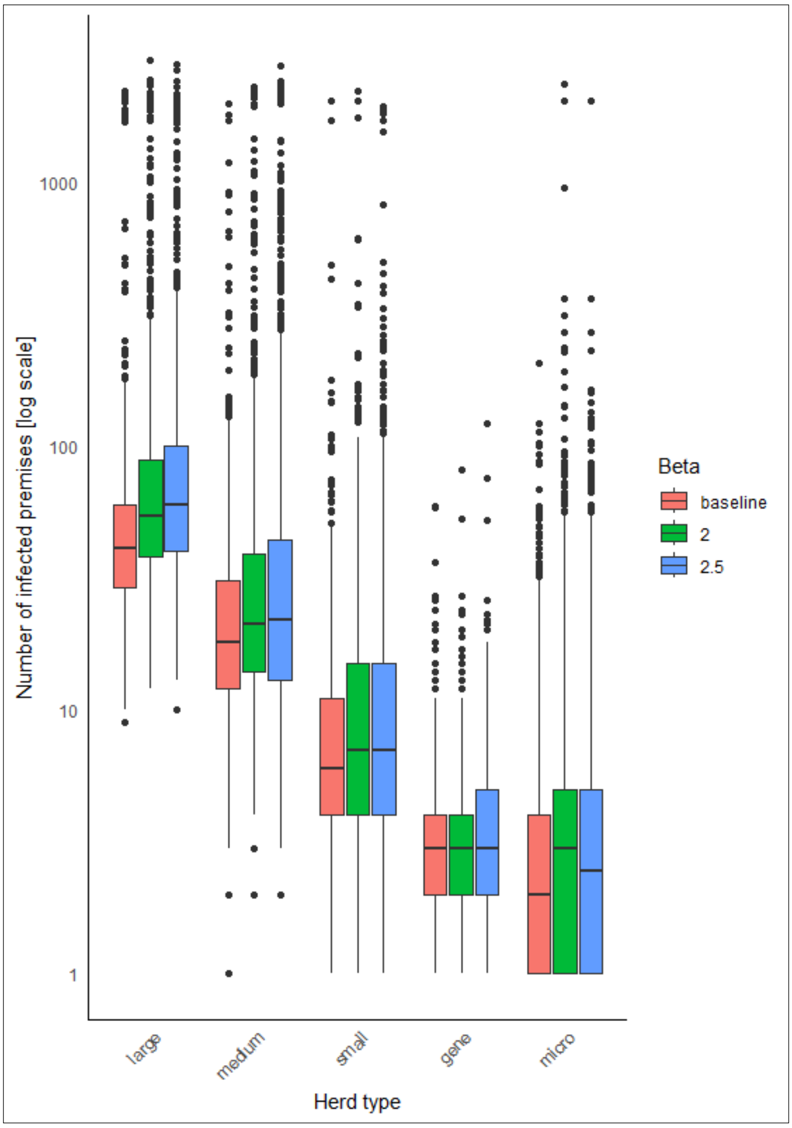

Figure K1. Distributions of outbreak size by beta and seed piggery herd type

Domestic pig within-herd infectious period

6.1.3 Method

The within-herd infectious period for piggeries in the AADIS-FMD-FP model was configured to be 8 days (Appendix C). As this was an increase from the value of 6 days used in the legacy AADIS-FMD model, it was decided to conduct a simple sensitivity analysis on the two values to characterise the influence on outbreak size and control duration

FMD outbreaks were randomly seeded into medium to large commercial piggeries on May 1st. FMD was allowed to spread in the domestic cattle population via the direct, indirect, local, airborne and saleyard spread pathways. Spillover transmission back and forth with the feral pig population was disabled. The time to detection was configured to occur on day 14 of the outbreak. Default domestic control measures and resourcing were employed (Section 2.5). Outbreaks were configured to end upon disease control/fade-out with a maximum outbreak length of 540 days (i.e., outbreaks still active on day 540 were terminated). 1,000 simulation runs were conducted for each infectious period.

6.1.4 Results

The choice of a 6 or 8-day infectious period did not produce statistically significant differences in outbreak size or duration of control (Table K3; Figure K2).

Table K3. Outbreak size and control duration for different infectious periods when seeding FMD into medium to large commercial piggeries

Infectious period	Mean number of IPs	number of IPs median [5th – 95th]	mean control duration (days)	control duration (days) median [5th – 95th]
6 days	43	17 [6 – 104]	72	61 [49 – 103]
8 days	40	18 [6 - 104]	71	63 [50 – 100]

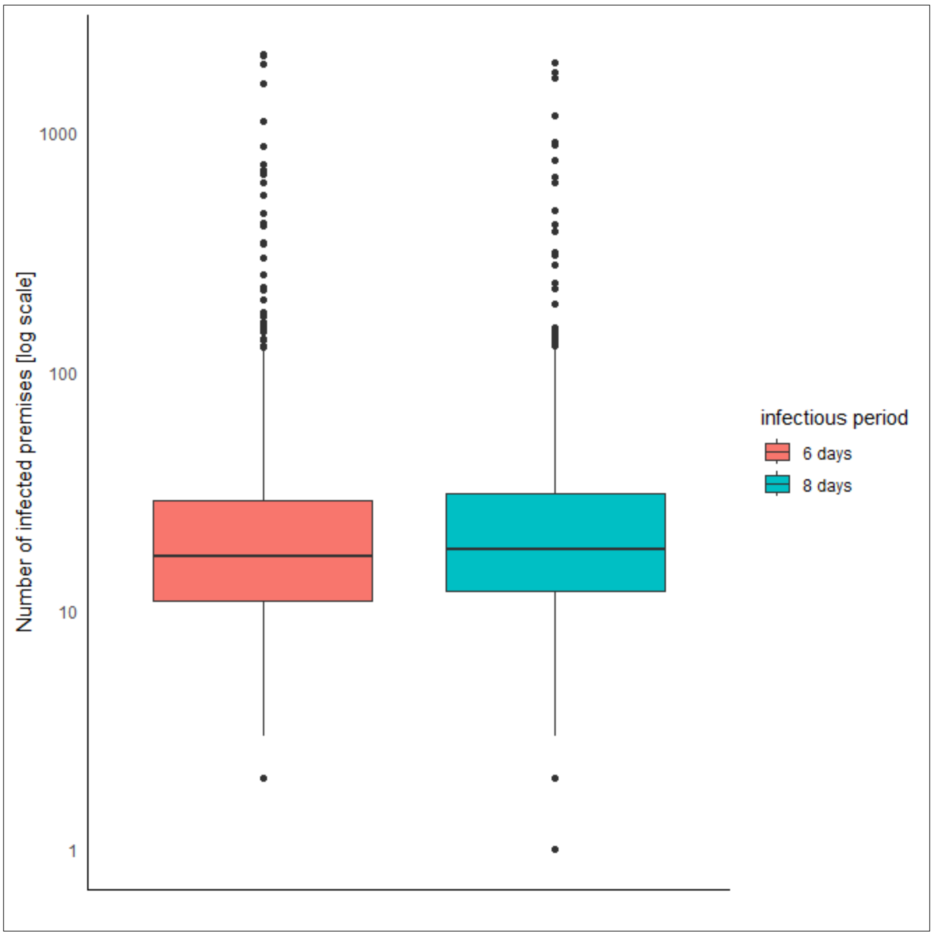

Figure K2. Distributions of outbreak size by infectious period when seeding FMD into medium commercial pig herds.