
Epidemiological studies to inform the parameterisation of modelling African swine fever outbreaks in Australia

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Abstract

African swine fever (ASF) is an increasing concern for ASF-free countries such as Australia. The growing number of outbreaks globally, particularly in neighbouring countries, heightens the risk of incursion. As a result, effective preparedness is essential to ensure that any signs of an outbreak can be rapidly addressed and its impact minimised. However, there is currently a lack of Australian-specific data regarding the risk of interaction and disease transmission between feral and domestic pigs. This thesis aimed to address this gap by conducting epidemiological studies to inform the parameterisation of ASF outbreak models for the Australian context.

The research in this thesis explored the potential role of feral pigs in spreading ASF to or from domestic pigs and examined procedures to assess the occurrence and likelihood of such interactions. Chapter 3 involved a survey of authorities responsible for animal health across Asia and the Pacific to evaluate the involvement of wild pigs in recent ASF outbreaks. Findings suggest that the contribution of wild pigs remains poorly understood and may be underestimated, partly due to underreporting to official sources. Recognising the widespread distribution of feral pigs near domestic pig herds in Queensland, Chapter 4 developed a camera trap surveillance protocol to determine whether feral pigs were approaching piggeries, which in turn created an approach that can be adopted by pork producers themselves. The results indicated regular feral pig activity near a piggery, particularly in identified hotspot areas. This data was then used in Chapter 5 to evaluate detection probabilities across different camera coverage levels, with 60% coverage identified as the most efficient for surveillance. Chapter 6 focused on developing a risk assessment tool, informed by expert elicitation, to estimate the likelihood of feral pig encounters at piggeries across various Queensland ecoregions. The assessment also considered seasonal variation and control measures. Results indicated that risk was highest in high habitat suitability areas during winter and the dry season, providing pork producers with information to tailor biosecurity and control measures accordingly. Finally, in chapter 7 the empirical data from Chapter 4 were incorporated into the Australian Animal Disease Spread (AADIS) model to conduct a sensitivity analysis, assessing the impact that feral-domestic pig and inter-sounder contact rates may have on ASF outbreak dynamics. The results from the simulations demonstrated high sensitivity to these parameters, highlighting their influence in an ASF outbreak and signifying the need for further research to improve and strengthen the input data on these aspects. This chapter also demonstrated how collected field data can be prepared and implemented into the AADIS model, to gather insights into potential outbreaks.

Overall, this thesis provides insights and tools to support ASF preparedness in Australia. By gathering local empirical data, establishing surveillance protocols, and developing a risk assessment

framework, the research directly addresses key knowledge gaps around feral and domestic pig interactions. The findings enhance our understanding of the spatial and temporal factors influencing encounter risk, offering practical guidance for producers to improve biosecurity at the farm level. In doing so, this work contributes to national disease preparedness efforts and strengthens the ability of the Australian pork industry to detect, manage, and respond swiftly to potential ASF incursions.

Author Declaration

This is to certify that:

This thesis comprises only of my original work towards my PhD, except where indicated in the preface.

Due acknowledgment has been made in text to all other material used.

This thesis is fewer than 100,000 words in length, exclusive of tables, figures. Bibliography, and appendices.

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Preface

The work described in this thesis was performed by the author at the Melbourne Veterinary School, Faculty of Science, The University of Melbourne between July 2021 and August 2025. The research was conducted under the supervision of A/Prof Simon Firestone, Prof. Mark Stevenson, A/Prof Richard Bradhurst, and A/Prof Victoria Brookes. Research findings of this thesis have been published in peer-reviewed scientific journals or presented in international and domestic conferences as listed below.

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QLD, Australia. <https://feralpigs.com.au/wp-content/uploads/2023/06/National-Feral-Pig-Conference-2023-proceedings-final.pdf>

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Abbreviations

AADIS	: Australian Animal Disease Spread Model
ABARES	: Australian Bureau of Agricultural Resource Economics and Sciences
AHA	: Animal Health Australia
AIC	: Akaike's Information Criterion
APIQ	: Australian Pork Industry Quality Assurance Program
ASF	: African swine fever
ASFV	: African swine fever virus
AUSVETPLAN	: Australia Veterinary emergency Plan
CSF	: Classical swine fever
EAD	: Emergency Animal Disease
EBM	: Equation Based Model
FAO	: Food and Agriculture Organisation of the United Nations
FMD	: Foot and mouth disease
FPC	: Foliage Protection Cover
GF-TADs	: Global Framework for the progressive control of Transboundary Animal Diseases
GPS	: Global Positioning System
HSI	: Habitat Suitability Index
IDEA	: Investigate, Discuss, Estimate and Aggregate protocol
JE	: Japanese Encephalitis
JEV	: Japanese Encephalitis Virus
MCMC	: Monte Carlo Markov Chain
NLIS	: National Livestock Information System
ODE	: Ordinary Differentiated Equations
QLD	: Queensland
SEIR	: Susceptible, Exposed, Infectious, Recovered
WAHIS	: World Animal Health Information System
WOAH	: World Organisation for Animal Health

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1 Introduction

The near global spread of African swine fever (ASF) since its emergence in Georgia in 2007 and subsequent spread to across Europe and Asia has led to the death or destruction of many wild and domestic pigs^{1,2}. Wild pigs (*Sus scrofa*) are commonly categorised as ‘wild boar’ in areas where they are endemic, or ‘feral pigs’ in areas where they are introduced and invasive³, such as in Australia. African swine fever is a highly infectious viral disease that can cause high rates of morbidity and mortality in affected pigs, and has the ability to survive in decomposing carcasses in cool environments for periods up to several months^{4–6}. The highly contagious nature of the disease and the lack of a commercialised, effective vaccine or treatment option available despite ongoing research, makes the spread of ASF difficult to control once it is present^{7–11}. Therefore, strict biosecurity and sanitary measures are essential to reduce the incursion risk and/or limit widespread distribution of ASF¹². Australia is one of the few countries to have remained free from ASF owing to its geographical isolation, strict prohibition of importation of live pigs, as well as preventative and surveillance measures that intercept and test for infected pork products at international borders^{13,14}. Since 2019, Australia’s neighbouring countries (i.e., Indonesia, Papua New Guinea and East Timor) have experienced ASF outbreaks which has heightened Australia’s risk of incursion^{15,16}, making preparation for a potential outbreak essential. There are currently important gaps in information on Australia’s feral pig population, and the risk they pose in spreading ASF to domestic pigs. Previous outbreak simulations using the Australian Animal Disease Spread (AADIS) model produced preliminary findings that ASF has potential to be contained within 6 months of incursion within the domestic pig industry, however feral pigs can possibly increase the size and duration of an outbreak¹⁷. It was also noted that the influence of feral pigs will depend on the region, seasonality, population density and the biosecurity measures imposed, hence further research is required to obtain data specific to the Australian context on feral pig contact rates and transmission between feral pigs and domestic pigs. These investigations highlight that disease transmission within feral pig populations and spill-over to and from domestic pigs is a risk in Australia. Highlighting the necessity for mitigation strategies to be implemented on-farm and at industry-level to reduce the risk of ASF spread into and from farms in the event of an incursion into Australia. Obtaining insight into the role of feral pigs in ASF transmission to domestic pigs in Australia is required.

This research aims to better understand the potential of feral pigs to spread ASF to domestic pigs in the event of an incursion into Australia, with data from field studies intended to inform the Australian pork industry’s biosecurity efforts as well as simulation modelling of the feral-domestic pig interface.

2 Literature Review

2.1 African swine fever overview

2.1.1 African swine fever virus emergence

African Swine Fever (ASF) is caused by a DNA virus, the only member of the *Asfarviridae* family, which is the only known true arbovirus^{18,19}. This means the African swine fever virus (ASFV) replicates within an arthropod vector, particularly soft ticks (*Ornithodoros moubata*)^{18,20}. These soft tick vectors play a crucial role in maintaining the infection within the sylvatic cycle in East Africa, where ASFV has likely originated²¹. In the sylvatic cycle, ASFV is transmitted by infected ticks to wildlife reservoirs such as warthogs (*Phacochoerus africanus*), which remain asymptomatic carriers^{19,22}. These ticks have helped sustain the virus within wild pig populations, allowing ASFV to persist in the environment. The timeline of ASF emergence as a disease is shown in Figure 2.1, which began by ASF being detected in Kenya (then known as British East Africa) affecting domestic pigs belonging to European settlers in 1921^{23,24}. ASF has subsequently spread the world, shown in Figure 2.2. All species from the Suidae family, such as domestic pigs, feral pigs, endemic native pigs and wild boars (*Sus scrofa*) are susceptible to ASFV¹⁸, and humans are not at risk as they cannot be infected with the virus.

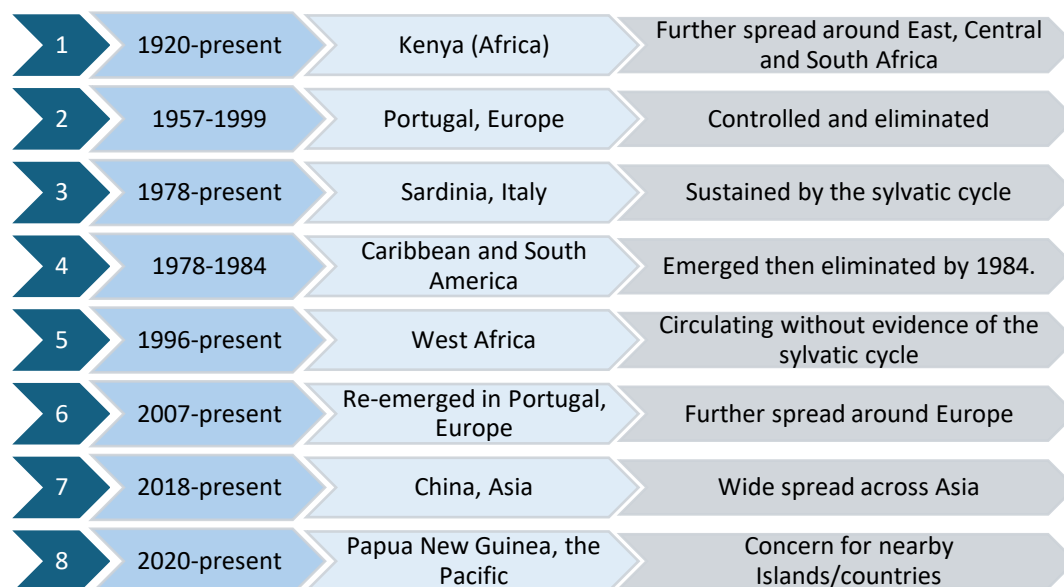


Figure 2.1: The Timeline of ASF emergence in continents around the world.

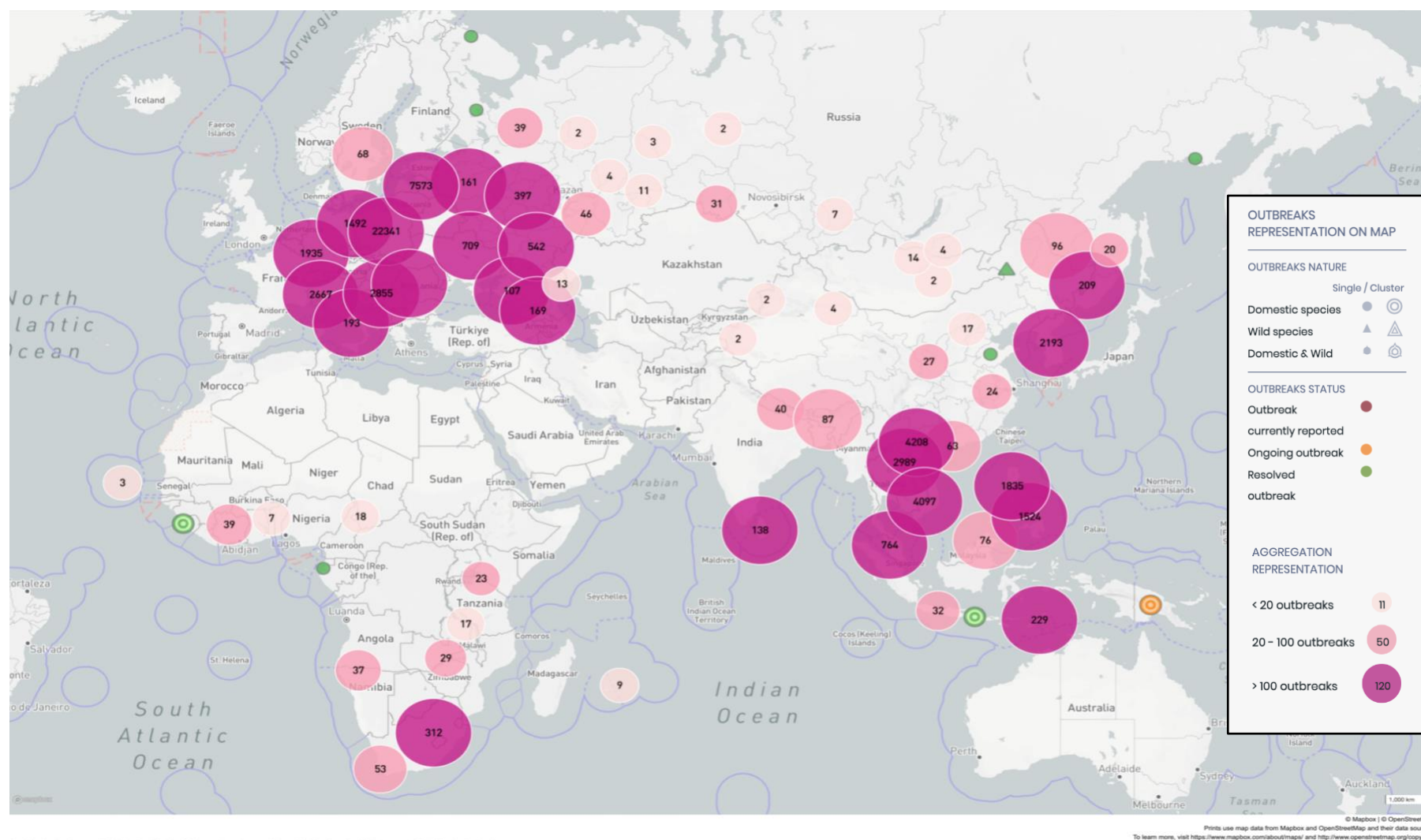


Figure 2.2: Number of reported cases in wild and domestic pigs documented by the WAHIS database (Figure was created using the WAHIS Events Management interface using data from November 2005 – April 2025²⁵).

2.2 Epidemiology of African swine fever

2.2.1 Transmission mechanisms and pathways

The spread and persistence of ASFV heavily relies on the presence of viable hosts and reservoirs. Global experiences have shown that even without competent soft tick vectors, the virus is able to survive and thrive in wild and domestic pig populations²⁶. There are four cycles of transmission: the sylvatic cycle, tick-pig cycle, domestic cycle, and wild pig cycle^{7,27,28}.

The sylvatic cycle is supposedly how the virus emerged and is still maintained within Africa due to contact between the common warthog (*Phacochoerus africanus*) and soft Argasid ticks (*Ornithodoros moubata*)^{19,29}. In this cycle ASFV circulates between the natural reservoirs without causing disease in the vertebrate hosts (i.e. warthogs), whereas during the tick-pig cycle the clinical effects of the disease are present²¹. In the tick-pig cycle, *Ornithodoros* soft ticks (including species of *O. moubata* complex in Africa and *O. erraticus* in Europe) are capable of transmitting ASFV to domestic pigs¹⁹. This cycle does not play a large role in ASF outbreaks in areas where soft ticks are largely absent, such as in Central Europe, the Baltic nations, in comparison to Africa and Madagascar. In these regions, ASF epidemiology is instead characterised by a self-sustaining wild boar cycle, maintained through direct transmission and environmental contamination (e.g. infected carcasses), with relatively infrequent spillover into domestic pig populations³⁰. The domestic cycle of transmission of ASF is between domestic pigs, or from pig products to domestic pigs²¹. In contrast, in parts of Eastern Europe and Asia, where backyard, free-ranging or low-biosecurity pig production systems are common, repeated spillover between wild and domestic pigs has been documented, contributing to more complex transmission dynamics^{28,31}. Accordingly, the wild pig cycle observed in Asia may involve both wild-to-wild transmission and recurrent interactions with domestic pigs, creating heightened concern for domestic pork producers in these contexts²⁸.

Importantly, the relative contribution of transmission across the wild pig–domestic pig interface is context dependent. While spillover between wild and domestic pigs has been documented internationally, a recent review concluded that for ASF there is limited evidence that direct wild-to-domestic (or domestic-to-wild) transmission is a major driver of spread unless domestic pigs are managed in free-ranging or outdoor/backyard systems that enable close contact³². In contained commercial systems, the interface may be more limited and transmission may occur more indirectly (e.g., via contaminated environments, fomites, feed/waste, or breaches at farm boundaries)^{33,34}. This is particularly relevant when interpreting global evidence for Australia, where most commercial production is indoors with higher biosecurity, yet feral pigs are widespread and indirect boundary contact pathways may still pose risk³⁵. Accordingly, findings from Europe and Asia should not be assumed to translate directly to Australia, reinforcing the need for Australian field-based data to characterise plausible feral–domestic contact pathways and rates.

Transmission between wild-to-wild, wild-to-domestic, and domestic-to-domestic pigs can occur via several pathways such as direct or indirect contact . Direct transmission occurs when an infectious animal comes in contact with a susceptible animal, this may occur via nose-to-nose contact or respiratory pathways such as when animals share a paddock, pen or are confined in a truck^{7,17,36}. Indirect disease transmission is more complex as it can occur via several different mechanisms such as via environmental contamination, contaminated fomites, biological vectors, mechanical vectors, contaminated vehicles and swill feeding^{17,33,37}.

Due to ASF's high case fatality rate (lethality) once infection occurs, and the social structure of wild pig populations^{38,39}, spread of disease by wild pigs is often considered to be slow, as observed in Europe where ASF has been measured to spread around 1-5km per month^{3,40,41}. This limits its potential to spread long distances in wild pig populations⁴². In regions with limited exposure, such as wild boar populations in parts of Europe, population-level mortality may be lower despite high lethality, whereas in high-exposure settings (e.g. dense domestic pig systems

in Asia), both lethality and mortality can be high⁴¹. In addition, human-assisted movement of pigs or pork products has been found to be the main cause of long-distance spread, seeding new outbreaks in distant locations⁴⁰.

2.2.2 Clinical signs and symptoms in pigs

The biological properties of ASFV vary around the world, as studies of isolates have established that transmission characteristics and the severity of disease can vary by strain and region^{20,43,44}. Pigs infected with ASF will likely present with severe disease, however some animals with lower virulent strains may act as carriers, or may completely recover⁴⁵. Highly virulent strains can cause acute to peracute disease resulting in 100% mortality within the first 4-10 days of contracting the virus^{46,47}. Moderate and low virulent strains demonstrate mortality risks from 30 to 70%. Observed clinical signs include high fevers, inappetence, haemorrhage, lameness, respiratory and gastrointestinal signs and peracute death (see Table 2.1 for clinical signs by form)⁴⁸.

Table 2.1: Differences between the degree of infection with the characterisation of ASF⁴⁸⁻⁵⁰.

	Peracute form	Acute form	Subacute form	Chronic form
Virulence	<i>High</i>	<i>High/ Moderate</i>	<i>Moderate</i>	<i>Low</i>
Clinical signs	<i>High fever, appetite loss, lethargy, hyperpnoea</i>	<i>High fever, appetite loss, lethargy, gastro-intestinal signs</i>	<i>Same as acute, however less pronounced</i>	<i>Respiratory signs, lameness</i>
Pathology	<i>Erythema (redness of skin)</i>	<i>Erythema, petechial haemorrhages in several organs, lung oedema, abortion, splenomegaly</i>	<i>Erythema, petechial haemorrhages in several organs, haemorrhagic lymph nodes, abortion</i>	<i>Arthritis, necrotic skin, pneumonia, pericarditis, abortion</i>
Mortality	<i>High, 100%</i>	<i>High, 70-100%</i>	<i>Variable, 30-70%</i>	<i>Low, 0-30%</i>

2.2.3 Agent considerations

The spread of ASF is further influenced by characteristics of the virus and the disease it causes, as characterised by key epidemiological parameters including the latent period, incubation period and contagiousness^{41,51}. The latent period is the duration from exposure to onset of infectiousness. High and moderately virulent strains of ASFV (such as Georgia II, Estonia and Malta78)⁵² have varying latent periods, with higher virulent strains having shorter latent periods. However, a study by Guinat et al⁵³ investigated outbreaks from the Russian Federation (RF), and found the latent period of seven different herds varied (mean latent periods between 5.8-9.7 days). This suggests that there is variability in latent period even within the same strain. The duration between the point of exposure to the onset of clinical signs is the incubation period. From the reviewed literature, the incubation period of different ASF strains had a mean of 4 days^{54–56}, although it was observed to be 14 days in one study⁵⁷. Across these studies, the high-moderate virulence strains displaying a shorter incubation period than those of lower virulence. Additionally, the incubation period appeared to be longer for studies investigating animals that were naturally infected rather than being inoculated^{55,57}. The infectious period is the period when the animal can transmit disease to other animals, i.e., the number of days from the onset of infectiousness until the animal either recovers or dies. Infectious periods found from different studies ranged from 2.3 days⁵⁸ to 25.4 days⁵⁹ depending on strains. Similar to the latent and incubation periods, the strains of high-moderate virulence (which impose a peracute or acute form of disease) have shorter infectious period than those associated with subacute or chronic clinical signs. Guinat et al⁶⁰ reported that for a highly virulent strain the mean infectious period within pens was 2.4 days. In contrast, Boinas et al⁴⁴ report the mean infectious period of a non-pathogenic strain to be 8.5 days, after which the animals recovered and were cleared of infection. Several studies involved euthanising the animals before they either died or recovered from ASF due to the severity of clinical signs given animal welfare concerns^{52,54,61,62}. Therefore, this poses a limitation in obtaining accurate estimates of the infectious period and could result in an under-estimation of the parameter.

2.2.4 Global outbreaks and trends

ASF has spread around the world since it was first reported in Kenya, with outbreaks progressing between being detected, controlled, eliminated and sporadically emerging or re-emerging across numerous continents, shown in Figure 2.3. Wild and domestic pigs, as well as infected pork products, illegal trade, swill feeding, contaminated vehicles and human interactions have contributed to the spread of ASF outbreaks^{63,64}. Each outbreak is unique to each location, further detailed in the sections below.

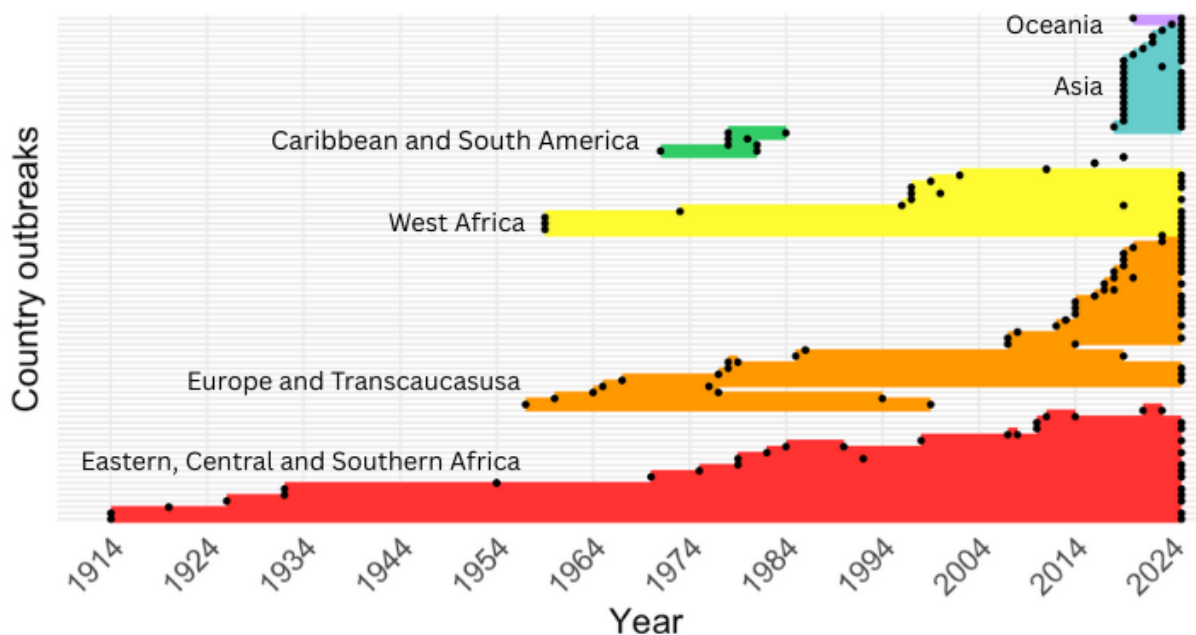


Figure 2.3: Timeline of African swine fever (ASF) outbreaks across countries, grouped by continent created in R studio⁶⁵ using data presented in Penrith et al (2020)⁶⁶, WOAHS ASF situation reports⁶⁷ and FAO ASF situation reports⁶⁸. The horizontal bars represent the duration of each outbreak, with points marking the start and end years, with points in 2025 are outbreaks still present to date.

2.2.4.1 Africa

Since ASF was first reported, it has spread across Eastern and Southern African countries primarily affecting domestic pigs⁶⁹. It is also found in wild pigs and soft ticks (as a reservoir), likely being transmitted via the sylvatic warthog-tick cycle and the domestic tick cycle^{2,70}. In the Western African countries, domestic pigs are the only species thought to be infected as investigations have demonstrated the absence of *O. moubata* complex ticks, and it is suspected that direct and indirect contact between domestic pigs has transmitted the virus^{29,70,71}. Although with the large geographical landscape within west Africa and increasing warmer climate, it might be beneficial to undertake additional research within wild pig populations to assess the possibility of the expansion of the sylvatic cycle²⁹.

2.2.4.2 Europe

ASF first spread beyond Africa in 1957 into Portugal when waste products from airline flights were fed to pigs near Lisbon airport, leading to an outbreak in domestic pigs^{72,73}. This was contained using control programs and for a 3-year period ASF outbreaks were not reported across mainland Europe, including Portugal, Spain, Italy, France, Belgium, and the Netherlands. After this period, Europe was officially considered free of the disease in 1999, apart from Sardinia. To note, Sardinia is where one of the most persistent examples of the sylvatic cycle outside of Africa has been experienced, where ASF was first reported in 1978 and still continues to circulate among wild boar populations and ticks, making it difficult to eliminate despite significant efforts^{73,74}. The genotype I strain of ASFV was the dominant strain circulating across Africa and Europe, however in 2007 a new highly lethal genotype II strain of ASF reappeared in Europe through a port in Poti, Georgia, creating the 'Georgia-07 strain'^{75,76}. This outbreak most likely arrived in Georgia through contaminated pork products discarded from ships, which were presumably accessed by free-ranging pigs^{1,30}. From Georgia, ASF spread across the country into Armenia, then into a village in Azerbaijan, and then underwent transcontinental spread across to Europe⁵⁶, before making its way into the Russian Federation⁷⁷. Wild boar played a crucial role

in maintaining and expanding the epidemic, along with inadequate biosecurity measures in backyard pig farms, facilitating the virus's persistence and spread across the Caucasus region⁷⁸.

These outbreaks have affected both domestic pig and wild boar populations, primarily through the movement of infected animals (via direct contact) and also contaminated pork products⁷⁰. Evidence of ASFV circulation within wild and domestic populations includes repeated spillover events, as persistence of reservoirs of infection are the main concern in the maintenance of ASFV, despite control measures^{1,30,79}. Genomic analyses of ASFV strains have provided valuable insights into transmission pathways, demonstrating the persistence of distinct viral lineages within wild boar populations and their role in seeding new outbreaks in domestic pigs^{75,76}. A risk assessment in Europe found that the highest risk of new ASF outbreaks in domestic pigs was from wild pig movements and legal trade pathways⁸⁰. As of 2024, a total of 28 countries in Europe have been affected by ASF, with the most recent including Italy mainland and Albania, as well as further spread in previously affected regions⁸¹.

2.2.4.3 Asia

In early March 2017, an ASF outbreak was detected on a backyard farm in the Irkutsk region of the Russian Federation (close to the Mongolian border)⁸². From there, additional outbreaks emerged near the Chinese border, which heightened concerns about the virus spreading to other Asian countries. Shortly after, ASF was first detected in China in August 2018⁸³. China is the largest pork producer globally, as a result millions of pigs have been killed due to ASF outbreaks causing large economic consequences⁸⁴. It is estimated the total economic loss in China in 2019 due to the ASF outbreak was US\$111.2 billion⁸⁴. In 2018, China reported a total of 104 outbreaks (according to the WAHIS database, at least 358,000 susceptible animals and 12,700 infected animals were recorded)^{82,85}. However, in 2019 the virus had spread to many other Asian countries, causing widespread impacts in their highly interdependent pork industries⁸³. Between August 2018 and July 2024, ASF was reported in 19 Asia and Pacific countries^{28,86,87}. The majority of outbreaks in Asia have been associated with domestic pigs (98.1% in 2018, 91.1% in 2019

according to WAHIS database)⁸⁸, presumably due to the high abundance of backyard farms, low biosecurity levels and unregulated transport of livestock⁸⁹. However, there are concerns that the role of wild boar spreading ASFV is underestimated due to the high density of wild pigs within the same locations as agricultural and domestic farms^{28,90}. Further surveillance within the wild boar populations is required to gather a better idea of the disease circulating in Asia and apply appropriate control measures.

2.2.4.4 *Pacific and Oceania*

ASF was confirmed in Papua New Guinea in March 2020⁶⁸. Upon confirmation, The National Agricultural Quarantine and Inspection Authority (NAQIA) activated its emergency animal disease response plan⁹¹. This response involved tracing, containing, and eliminating the disease as it was detected. As of 12 April 2024, Papua New Guinea had three different ASF zones: i) infected zone – Hela, Southern Highlands, Western Highlands, Enga and Jiwaka provinces; ii) buffer zone – Eastern Highlands and Simbu provinces; iii) non-infected zone – the rest of the country⁶⁸. There is a lack of information on how ASF spread into Papua New Guinea, or what pig population it first affected, highlighting further research needed to be conducted or made available. The threat of ASF being in Papua New Guinea creates concern for further spread to nearby pacific islands (including the Solomon Islands and Fiji) and countries (such as Australia and New Zealand) that are currently free of the disease. This highlights the importance of applying proper biosecurity, strict border surveillance, and preventive measures to reduce further spread of the disease¹⁴.

2.3 *Control and Prevention Measures*

2.3.1 *Current strategies in domestic pig production systems*

There is currently no safe, widely used, proven effective vaccine or treatment available for ASF, however ongoing research is being conducted to assist in understand the complex genome structure of ASFV^{8,92}. There has been recent progress towards various potential vaccines (natural

live attenuated, recombinant live attenuated, and DNA and virus-vectored vaccine types) which could potentially improve current control and prevention strategies of ASF^{8,10}. However safety issues (such as chronic ASF side effects and fevers being associated with vaccinations) need to be further investigated before they are widely used, and until then there is heavy reliance on prevention and control strategies to protect pig populations against ASFV^{12,92}. The application of appropriate control measures depend on numerous factors, such as the location, type of production system, and movements of animals⁴⁷. The most effective preventative measures for domestic premises are considered to be biosecurity to control the entries into the farm, control of pig feed, and educating farmers and staff of transmission risks⁹³. Additionally, not allowing contact with external wild pigs, appropriate carcass removal, and proper waste disposal are also considered to be important measures. It is essential to maintain up to date records of animal identification and movements, ban swill feeding, and contain pigs to limit contact with wild and other pigs and prevent ASF outbreaks⁸². To contain ASF requires early intervention through early warning systems, early diagnosis, basic biosecurity, and strict hygiene practices^{46,47}.

2.3.2 Challenges in elimination and management in wild and domestic pig populations

Ideally, if detected early and resources permit, the response to an incursion will result in elimination, if not possible, appropriate strategies should be applied to contain the spread to a low manageable level. Presently, the only way to achieve ASF eradication is by stamping out by slaughter and proper disposal of all infected pigs⁹⁴. Elimination of genotype II in wild pigs has been successfully achieved in Sweden, the Czech Republic and Belgium (after localised spread) by applying targeted control measures in the wild boar population, which included the establishment of restriction zoning, targeted fencing, active searches for carcasses, and depopulation measures^{95–97}. The role of infected wild pig carcasses and the duration ASFV can survive in cool environments has contributed to why elimination hasn't been achieved broadly across Europe^{40,74,98}. Eliminating ASF in wild pigs involves significantly reducing their populations, as well as concurrently removing their carcasses to reduce further spread. This requires large

amounts of effort, resources, social acceptance, and unprecedented levels of coordination and management⁹⁵. For example, in Belgium, the elimination consisted of hundreds of people being involved to varying degrees, such as the regional forestry services (77%), the military (11%), hunters (5%), government departments (3%), a dog team (1%), and other stakeholders (3%)⁹⁶. Elimination of ASF within domestic pigs is also a challenging task, even without the involvement of wild pigs, due to movement of domestic pigs between farms, as well as the ability of ASFV to remain infectious in contaminated pork products^{33,93,99}. It is recommended that biosecurity is strictly adhered to for preventing incursions, as well as applying appropriate hunting practices to manage wild pig populations aiming to reduce their population size by 70% knockdown throughout the year to maintain a stable population and prevent further spread of ASF^{95,100}. Understanding wild pig populations in areas of concern, such as surrounding domestic pig farms, would be valuable for assessing and mitigating the risk of disease transmission. Future research should focus on evaluating the movement patterns of wild pigs to better inform risk assessments and elimination strategies.

2.3.3 African swine fever surveillance and monitoring of wild pigs at the wildlife-domestic interface

The fundamentals of managing wild pigs or wildlife in general, stems from understanding their geographic abundance and population trends¹⁰¹. This can be achieved through reliable monitoring techniques to be able to apply the appropriate mitigation strategies. There are numerous ways animals can be tracked and monitored which all vary in costs and practicality, such as using global positioning system (GPS) telemetry collars, ear tags, adhesive transmitters, implants, camera traps, drones or visual signs^{102,103}. Researchers and farm managers are interested in the presence and absence of wild pigs, and the potential risk of interacting with domestic pigs and spreading disease (such as ASF). Wild pigs can occupy large geographic areas, and their presence can be difficult to monitor. As a result, telemetry GPS collars may be useful to understand the movement of wild pigs and their sounder groups (groups of female pigs and offspring) around the vicinity of the property, including their home range, visitation frequency

and habitat use^{101,104}. Collars can be programmed to record geographical coordinates of the precise location of the wild pig in real-time or at predetermined time intervals (i.e., every 30 minutes, 3 hourly, daily, etc.)^{105–107}. Collaring pigs is resource intensive requiring manual labour for trapping, sedating, and releasing the animal to fit the collar, and then locating and retrieving the collar once they are released/come off the animal which can be a difficult exercise if it is in landscapes difficult to access. Wild pigs that are collared may be also hunted and killed, causing the investigation and data collection to end abruptly without notice, and potentially leading to loss of the equipment.

Another technology available to monitor wild pigs around piggeries and their occurrence is camera traps, a non-invasive method for recording continuous data. They are activated by motion triggers using infrared sensors and take a series of photos and either use batteries or solar power¹⁰⁸. The data can be collected via SD cards and downloaded by users, or there are models that use mobile phone connections for real-time access to footage. There are numerous automatic image recognition software available to help with data analysis, such as eVorta¹⁰⁹ and Wildlife Insights¹¹⁰.

The tool/technology ultimately chosen to monitor wild pigs depends on the goal of the research and resources (time, experience of users, property access, etc.). Camera traps have become increasingly popular as they are non-invasive, relatively cost-effective, and a continuous method of surveillance. They can be applied to help monitor a specific area for the presence of wild pigs, and to determine if they are interacting with certain properties such as piggeries^{111–113}.

2.4 Australia's Feral and Domestic Pig Populations

Australia is currently free from ASF which can be accredited to its rigorous biosecurity aimed at preventing incursions¹¹⁴. Between 2019 and 2021, Australia committed AUD \$125.2 million to provide the necessary protection and resources to detect ASF, as well as other exotic wildlife diseases¹⁴.

2.4.1 Overview of the Commercial Pig Industry

It has been estimated that there are approximately 2.5 million domestic pigs in Australia, and in 2024 there were 4,506 registered pig production sites¹¹⁵. Figure 2.4 shows the location of domestic pig herds within Australia based on 2014 agricultural census data and industry reports, specifying a total of 2379 small-scale pig herds (<100 sows and <1000 animals) and 320 large-scale pig herds (≥ 100 sows or ≥ 1000 animals)^{116–119}.

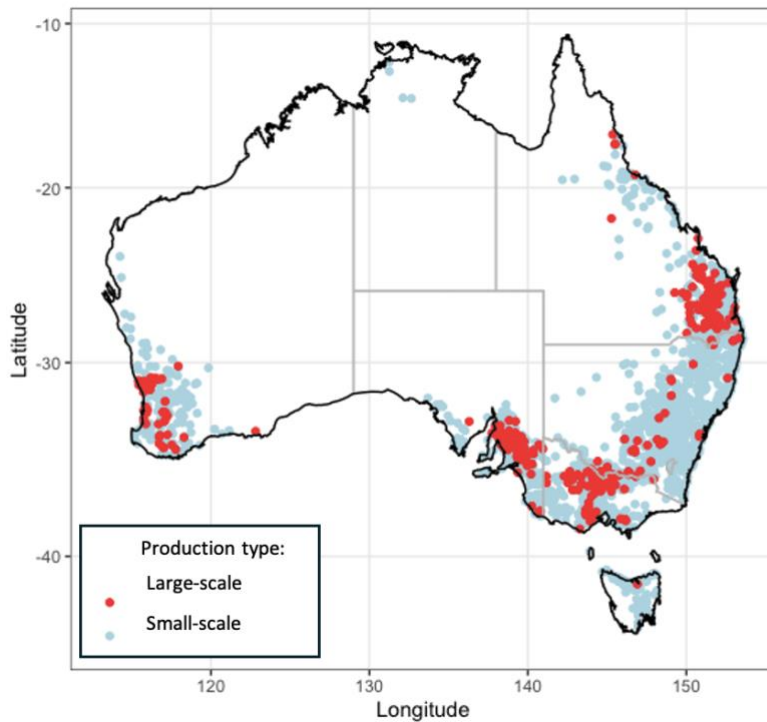


Figure 2.4: Distribution of large-scale and small-scale pig herds around Australia. Produced in Australian Animal Disease Spread model (AADIS) curated for the FMD simulation in Australia¹²⁰.

2.4.2 Production systems

In Australia there are three main types of pig production: indoor, free-range and outdoor³⁵. Indoor pig farming encompasses around 90% of Australia's pig farms due to the ability to manage pigs for optimum health, provide enhanced protection to pigs from extreme environmental elements and disease risk or predators by being inside an enclosed shed structure. Free-ranging and outdoor production systems are less common (5% and 4% of

Australia farms, respectively), as they are more susceptible to disease risk and predators, and are involve higher costs for processes such as pasture monitoring and weed management¹²¹. A more detailed characterisation of Australia's pig herds was undertaken in preparation for modelling with the Australian Animal Disease Spread Model (AADIS) including: very large commercial, medium-large commercial, small commercial, specialist gene transfer (producers that specialise in boar semen and breeding), smallholder, and pig keeper¹⁷. The number of pigs in each of these herds quantities ranges from <50 to >1000 sows incorporating of various housing styles and biosecurity levels.

2.4.3 Biosecurity standards and regulations

Properties that hold domestic pigs pose a level of risk of transmitting ASF either directly or indirectly regardless of the type of production system, which is highly dependent on the biosecurity measures applied. For Australia, if an incursion were to occur, the domestic and wild pig cycles of ASF would be of most concern within and between farms, due to the absence of *Ornithodoros* ticks¹⁸. A review found that transportation-related risk factors for ASF in Australia could be important in an ASF outbreak due to the frequency of trucks travelling between farms, saleyards, and abattoirs, highlighting the need for strict biosecurity and disinfection procedures to be implemented¹³. Thus, the recently adapted AADIS-ASF model incorporated data from the National Livestock Information System (NLIS) to inform the direct spread pathway in the model by representing historical movements of pigs between farms and saleyards¹⁷. Knowing the exact movements of pigs in time and space, allows an accurate representation to be made when modelling the spread of ASF and its potential impacts, as well as trace-back scenarios if an outbreak arose.

Australia has a pork quality assurance program (APIQ) which provides certification that producers are meeting the relevant State and Federal legislations by adhering to high standards of on-farm management, food safety, animal welfare, biosecurity, and traceability¹²². Having

these standards in place helps ensure best practices and that producers are equipped to prevent and manage any potential disease outbreak as best as possible.

2.4.4 Economic significance

Domestic Australian pork production was estimated to contribute AUD \$6 billion¹¹⁵ to the economy in 2023-2024¹²³. In December 2021, there were 1.41 million pigs slaughtered, and 112,094 tonnes of pig meat produced¹²⁴. In 2019, pig meat exports accounted for about 9% of the total production, with a value of about AUD\$130 million¹²⁵. Australia imports the majority of the pork consumed in the country, as during the same period of 2019, imports reached AUD \$895 million.

An ASF outbreak in Australia would cause wide-ranging severe impacts to the domestic pig industry, and it would remove the country's proof of freedom which enables trust and trade security in products free of disease¹²³. As a result, imports would be increased to keep up with the demand within the country.

2.5 Feral pig population monitoring approaches

2.5.1 Population Impacts

Feral pigs were first introduced into Australia in 1788 by European settlers^{126,127}. They became an invasive, pest species in Australia due to their destruction on the environment and economic burden. It is estimated that feral pigs cause at least AUD \$100 million per annum worth of economic damage to the agricultural industry through disturbing water quality, extensive ground rooting, crop and pasture consumption, as well as lamb predation^{128,129}. Globally, feral pigs have caused harm to 600 native species and directly driven 14 species into extinction¹³⁰, with the Australian ground frogs, tree frogs and orchids being mostly impacted in Australia. They additionally pose a biosecurity risk, with studies describing their ability to spread pathogens to not only to other pig populations, but also within the environment, to other animals including livestock, wildlife, domesticated animals and humans, transmitting a range of

diseases other than ASF. These include but are not limited to hepatitis E, tuberculosis, foot and mouth disease (FMD), Japanese Encephalitis (JE), classical swine fever (CSF) and *Brucella suis*^{131–136}. As a result, Australia has a range of control methods available to help manage feral pigs, which include trapping, shooting (aerial or ground), poison baiting, and exclusion fencing¹³⁷. There is no universal management approach, due to the diversity of feral pigs in the environmental, social, behavioural, and demographical considerations of the species¹²⁶. Thus context-specific strategies need to be implemented to account for attributes of each specific location and the level of concern.

2.5.2 Distribution and Abundance

Feral pigs are widely distributed across Australia and inhabit around 45% of the country's landmass (demonstrated in Figure 2.5)¹³⁸. Abundance estimates of feral pig populations within Australia have fluctuated over the past decade, ranging between 4.4, 3.0 and 3.2 million (1980, 1990 and 2000 respectively), with a mean density of about 1.03 pigs/km²¹³⁹. These estimates need to be interpreted with caution as it is difficult to estimate the abundance of pigs across large, diverse geographical areas. An identified weakness in the Australian National Feral Pig Action Plan (2021-2031), was that there is currently low amounts of local/regional knowledge of feral pig population density, as well as their spatial and temporal movement ecology in different habitats and geographical areas¹³⁸.

The lack of recent publications on feral pig abundance in Australia highlights the need for further research needs to be done in this area to gather updated figures and distribution estimates. Specifically feral pig density estimates, group sizes and potential interactions near domestic piggeries is needed to assess overall risk feral pigs pose in Australia for ASF outbreaks. Understanding of feral pig abundance and movement behaviour based on their preferred habitat and access to resources is useful when attempting to plan and execute a management strategy for disease prevention and control.

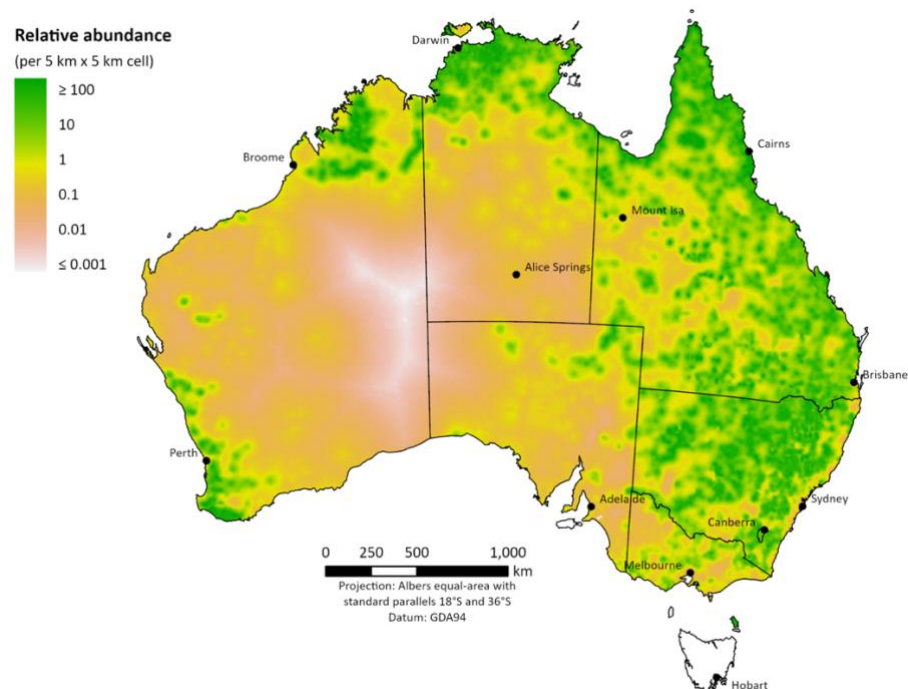


Figure 2.5: Current estimated relative abundance of feral pigs in Australia, created by the Australian Bureau of Agricultural and Resource Economics and Sciences & Commonwealth of Scientific and Industrial Research Organisation¹⁴⁰ under a Creative Commons Attribution 4.0 license.

2.5.3 Ecological impacts

Being its own continent and country, Australia's landmass is large and diverse with 55% of the land being used for agriculture¹⁴¹. The country has a range of ecoregions that differ in climate, topography, geology, seasonality, and vegetation (Figure 2.6)¹⁴². As a result, these numerous factors can be used to help estimate the abundance, density, distribution, and home range of feral pigs and other wildlife species as well. This can be difficult as feral pigs have the ability to adapt to many different landscapes¹⁴³, contributing to widely varying abundance across the country. Knowing their fundamental resource requirements such as food, water, heat refuge and disturbance refuge, can assist in estimating where they can be found regarding habitat suitability^{144,145}. A study evaluated the influence of temperature and distribution of food on feral pig habitat utilisation in a semi-arid environment (in NSW), and it was found that during autumn,

spring and summer feral pigs preferred riverine woodlands, and in winter they favoured shrubland¹⁴⁶. Suggesting that feral pigs limit movement during seasons of high temperatures preferring shady habitats and venture further for food more widely during the cooler months. However, the availability of water is of highest priority for purposes such as drinking and wallowing¹⁴⁶. Another study confirmed that they need to be within 10km of riverine woodlands or around inland river systems, as this allows more efficient foraging and reduces the likelihood of food shortages, as well as thermal refuge¹⁴⁴. A study conducted in the rangelands of eastern Australia, found that management of feral pig control should consider geographical features, such as major rivers in low-rainfall areas and floodplains as feral pigs are likely to migrate to these resources and use them as nature corridors for movement¹⁴⁷. Feral pigs are continuing to expand across Australia due to the vast habitat suitability around the country, highlighted by Cowled et al (2009) in the Kimberley region¹⁴⁸. This study also highlighted considerable uncertainty around feral pig distributions due to large areas of unknown feral pig status that have not been investigated, although utilised habitat modelling to estimate future distributions of feral pigs. The modelling suggested that feral pigs could expand their distribution by realistic natural dispersal in the future (to 61 950 km²), highlighting the importance of pest-management and improved biosecurity against disease transmission from feral pig incursions.

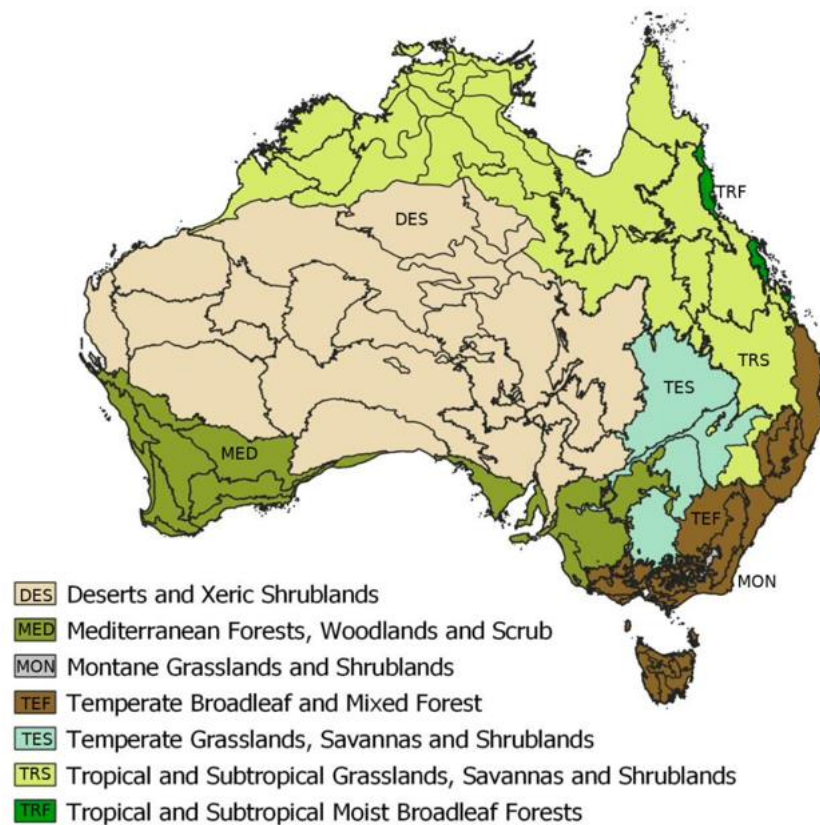


Figure 2.6: Australia's ecoregions¹⁴², produced by ERIN (Environmental Recourses Information Network), and made available under a Creative Commons Attribution 3.0 Australia License.

2.6 Risk of African swine fever spread in Australia

2.6.1 Disease threat and consequences to Australia

An outbreak of ASF within Australia would produce substantial social and economic losses for the pork industry. The loss of trading to export markets for pork and pig products would result in major losses of income and employment in the farm, production, processor, and retail sectors. It is estimated that Australia could face up to AUD \$2.03 billion losses for a large, multi-point impact over five years¹⁴⁹. The disease has the potential to spread rapidly throughout the pig industry, within and between farms, as well as through the feral pig population. Each incursion scenario has large economic costs to attempt to mediate the outbreak (described in Table 2.2). Understanding the potential spread and impact of ASF within Australia allows specific

outbreak preparedness and response policies and control measures to be designed and implemented quickly and effectively to minimise impacts from an outbreak.

Table 2.2: The estimated costs associated with an African swine fever outbreak within feral and domestic pigs in Australia (adapted from Slatyer et al (2023)¹²³.

Disease host	Duration to reach outcome	Cost estimate (\$AUD million)
Feral pigs (small scale outbreak)	5 years for disease eradication	101 – 127
	30 years for dealing with ongoing endemic disease	439 – 2,540
Domestic pigs (small scale outbreak)	5 years for disease eradication	117 – 263

Between 2018 to 2020, Australia intercepted over 43 tonnes of pork products at airports by incoming travelling despite having strict biosecurity import measures in place¹⁴. Australia currently has a range of preventative, control, and elimination policies in place, in preparedness for an incursion of ASF. Animal Health Australia (AHA) has developed the Australian Veterinary Emergency Plan (AUSVETPLAN) which is used nationally by industry, government and stakeholders and entails a policy on the control and elimination of a range of emergency animal diseases (EADs) such as ASF¹⁵⁰. The policy includes strategies on how to apply measures such as biosecurity, quarantine, stamping out, movement, zoning, tracing, active and passive surveillance, compartmentalisation, and movement controls of pigs and pork products to eliminate ASF as soon as possible while also minimising social and financial disruption¹⁵⁰. In 2018, Australia's state and territory governments made it mandatory for all pig movements to be reported to the 'PigPass' database, to ensure there was an efficient tracing tool to determine the source and spread of a disease outbreak¹⁵¹.

2.6.2 Potential ASF spread in Australia

Australia is in a unique position both geographically and in terms of preparedness, which sets it apart from other countries in managing ASF outbreaks. The dynamics and speed of ASF spread would be depend on the context of the incursion including host (domestic or feral pigs), and also environmental factors⁴¹. The risk of disease transmission from feral pigs to domestic pigs is high due to their large population distribution surrounding domestic piggeries, although the pathway and likelihood of this occurring is an under-researched area globally requiring further investigation^{28,152,153}. A study using a deterministic model informed by available literature, found that once ASF is detected in feral pigs, their population may naturally decline sharply by 60-70% due to mortalities from to the disease¹⁵⁴. This was observed in the outbreak in Poland, where the wild boar population decreased by 84% naturally in a non-hunted area within 1 year from the detection of the first wild boar ASF case¹⁵⁵.

The risk of transmission from infected carcasses is another factor to consider. In Northern Australia (where feral pig abundance is the highest) this has been described as low risk, due to the hot climate and rapid decomposition rates in this area^{156,157}. Transmission from infected carcasses may pose a higher risk in the cooler southern ecological zones of the country^{5,158}. Regardless, the risk of feral pig populations infecting domestic pigs is a large concern. From overseas experience disease spill-over from wild to domestic pigs (or vice versa) has been observed, and therefore it is considered a risk in Australia that needs to be investigated. A study found that domestic pigs in free-range and indoor systems in Australia had been exposed to pathogens (*M. hyopneumoniae* and *L. intracellularis*) by feral pigs being in close proximity¹⁵⁹. An additional field study conducted in Southern Queensland in 2010, captured feral pig presence within 5km from domestic piggeries, and three specific feral pigs had potential for direct contact with each other by roaming within 50m of each other in the same time period, over multiple occasions³⁴. Other than these mentioned studies, the presence of feral pigs interacting with domestic piggeries is a relatively unexplored area of research requiring further investigation.

2.6.3 Interaction with domestic pigs

Feral pigs are resourceful and intelligent, with the ability to detect food and escape predators through their refined senses^{129,160,161}. As a result, they can navigate their way to feed, water and preferred habitats with ease. Research into attractants for wild pigs to utilise for control baiting has shown their preference towards food such as wheat, corn, and rotten fruits, as well as sows in oestrus, boar taint, and strawberry scent^{160,162}. Highlighting the risk of feral pig incursions to piggeries.

Environmental, seasonal and cultivation factors can play a part in attracting feral pigs to the vicinity of piggeries. As such, studies have used environmental predictors according to the most probable risk factors to determine the probability of incursions which have included the distance to water, distance to food sources, and distance to vegetation as a refuge and protection cover^{163,164}. An additional study that used GPS-tracked pigs in Eastern Australia found that feral pigs preferred spending their time in locations with medium woody vegetation (such as acacias, eucalypts trees with a moderately open canopy) and at waterbodies (such as dams), as they both had the longest duration of use (3 and 2.7 hours respectively)¹⁰⁴. In this study this proximity (within 150m) to watercourses, waterbodies, cultivation, open herbaceous vegetation, and medium woody were all negatively correlated with highly revisited sites.

Additionally, feral pigs actively seek protection from elevated temperatures, and as a result in Autumn, Spring and Summer they are mostly attracted to riverine woodland habitats as they provided the most shelter, followed by woodland, shrubland, and shallow ponds (ephemeral swamps)¹⁴⁶. The same study also found that shrubland habitats were preferred in winter as these environments provide higher food availability. In another study based in Spain, the crepuscular/nocturnal nature of wild pigs were captured on a farm via camera traps and were found to be most active between 11pm and 5am, with visits being more frequent during their dry season (July-August, and a second peak during October)¹¹². This could be due to a surge in movement because of the scarcity of natural food and water availability in the environment compared to their wet season and seek for resources on agricultural enterprises.

As a result, there are multiple reasons why feral pigs are attracted to piggeries, however their presence may fluctuate during various times of the day, and on the climatic conditions of the environment as to what motivates them to interact with the property or the animals within. Additional data on feral pig movements toward piggeries in Australia is needed to help the pork industry and farm managers assess the risk of interactions and implement effective control and management strategies.

2.7 Disease Modelling for African swine fever

Epidemiological models are used to simulate the spread of diseases under various scenarios and can estimate the effectiveness of control strategies through mathematical and statistical techniques¹⁶⁵. A recent systematic review found that the main modelling objectives of ASF were to estimate parameters, assess determinants of transmission, examine consequences of hypothetical outbreaks to assess and compare a range of control strategies against each other¹⁶⁶. ASF has been modelled extensively worldwide, with varying objectives and contexts shaped by factors such as the ASFV strain, geographic location, and potential transmission pathways. These models could play a key role in informing strategies for the prevention, management, and mitigation of outbreaks by supporting the evaluation of disease control options, including vaccination strategies, within policy frameworks such as AUSVETPLAN¹⁶⁷.

2.7.1 Application and type of African swine fever modelling

Epidemiological modelling simulates the spread of disease under different scenarios, using mathematical and statistical techniques to evaluate intervention strategies and predict potential outbreaks. This approach enables researchers to explore disease dynamics and assess the likely outcomes of various control measures¹⁶⁶. These models provide a structured framework to integrate empirical data, expert opinion, and probabilistic assumptions to estimate the spread and control of infectious diseases in complex environments. Epidemiological models can broadly be classified into stochastic, deterministic, and hybrid approaches, each with distinct advantages depending on the research question and data availability¹⁶⁸.

Deterministic models use fixed parameters to produce the same outputs when the same inputs and initial conditions are used, making them computationally efficient and useful for capturing broad-scale trends of disease outbreaks^{169,170}. These models are often based on compartmental structures (e.g., susceptible-exposed-infected-recovered (SEIR) models) and are well-suited for large populations where random fluctuations are minimal¹⁷¹. However, deterministic models assume homogeneous mixing, which means all individuals within the model have equal probability of coming into contact with one another, resulting in equal rates of disease-causing contacts^{172,173}. Deterministic models are an oversimplification of reality by overlooking the randomness in disease transmission and host interactions. In contrast, stochastic models incorporate random variation into model processes, such that repeated simulations using the same inputs may produce different outputs, allowing for the variability and uncertainty involved within disease spread^{170,174}. These models can use distributions to represent input parameters to simulate multiple potential outbreak trajectories by accounting for the probabilistic nature of transmission events, host movements, and environmental influences^{169,175}. Stochastic approaches are particularly valuable for studying specific events, such as spillovers from wildlife to domestic animals, and for assessing the probability distributions of outbreak outcomes rather than single-point estimates¹²⁰. Hybrid models combine deterministic and stochastic components within a single modelling framework, integrating deterministic compartmentalisation of disease spread with stochastic diffusion elements to balance computational efficiency with the need for realistic variability^{167,176–178}. For example, a model may use deterministic equations for large-scale disease dynamics while incorporating stochastic components for local transmission or specific population subgroups. Hybrid approaches are utilised in complex epidemiological settings where both large- and small-scale dynamics must be considered, such as in the spread of ASF and FMD across mixed domestic pig production systems or varying biosecurity weights and feral pigs¹⁷⁹.

Disease models can be simulation or inferential based. Inferential models incorporate Bayesian modelling, which involves integrating prior knowledge (based on the literature or

expert opinion) with observed data to produce posterior probability distributions of outcomes (such as the probability of an event to occurring)^{180,181}. Bayesian hierarchical models, for example, can capture spatial and temporal variations in disease spread by considering different levels of uncertainty across regions or populations¹⁸². This is especially relevant for ASF, where outbreaks are influenced by environmental factors, human-mediated transport, and feral pig movements. Where there are situations that the Bayesian approach is not viable to produce a posterior (outcome) probability density function, inferential models such as Markov chain Monte Carlo (MCMC) methods may be used to effectively sample from the posterior distribution without explicitly integrating over the posterior^{180,183,184}. Where the likelihood is difficult or impossible to specify, likelihood-free modelling approaches such as Approximate Bayesian Computation, such as with the Sequential Monte Carlo algorithm, may be implemented to approximately sample from the desired posterior distribution^{185–187}. An example of this is shown in a study that estimated a within-herd transmission rate for ASF in Vietnam, by fitting a SEIR model to the data with transmission coefficients estimated using approximate Bayesian computation¹⁸⁷.

Currently, ASF modelling efforts have largely focused on regions where the disease is endemic, with limited applications for preparedness in disease-free countries such as Australia. Existing models often emphasise transmission within domestic pig populations or rely on expert opinion risk assessments that do not fully capture the role of feral pig populations, which are a key concern for biosecurity in Australia. The Australian Animal Disease Spread (AADIS) model offers a unique opportunity to address these gaps by incorporating feral pig movement, landscape features, and control strategies within a simulation-based framework^{17,179,188}. Incorporating feral pig behaviour, habitat preferences, and seasonal movement patterns into AADIS attempts to ensure that the model reflects the complexities of ASF transmission in Australia's unique environment. Additional data is required for refining existing methodologies and tailoring them to the Australian biosecurity landscape, ultimately enhancing the capacity to predict, prevent, and respond to potential ASF incursions.

2.7.2 *African swine fever models*

The global threat of ASF has led to the development and utilisation of many disease models to examine, estimate and assess current or potential risks of the disease, and how certain control measures can assist (Table 2.3).

Models are adaptable and can account for other diseases and modelling objectives, as such an ASF version of AADIS has recently been developed in 2021, to specifically investigate the how the disease may spread in Australia under a range of policy, resourcing and response options¹⁷. This model can produce sophisticated simulations by seeding outbreaks into specific farms, populations or ecoregions, which can assist with scenario and policy testing associated with the potential of disease incursions and detection, as well as the establishment and spread, with additional features to account for control strategies, effectiveness, and costs, as well as post-outbreak outcomes. A major finding from developing the AADIS-ASF model is that there is no adequate or recent Australian-specific data on contact rates between groups of feral pigs and carcasses, or contacts between feral and domestic pigs. This data would help model the likelihood of disease transmission between the feral and domestic pig populations accounting for regional and seasonal influences¹⁷. A recent (2021) systematic review of current mechanistic simulation models found that almost all models are host specific, focusing on only one of domestic pigs or wild boar/feral pigs, not attempting to model spillover or dynamics between susceptible host species¹⁶⁶. This points to the urgent need for the development of a model that account for feral-to-domestic pig transmission of ASF. The use of epidemiological disease models assists in trialling and observing different control measures in a population, serving particularly helpful in situations where the disease is not present yet such as ASF in Australia. A gap has been identified to incorporate wild animals, vectors, and human factors into these model frameworks as a priority for future work ⁴⁷.

Table 2.3: Summary and description of epidemiological models for African swine fever.

Location	Model output	Model mechanism
Australia ¹⁷	AADIS was developed to simulate FMD and ASF (with capacity to model other animal, plant and pest diseases) spread in Australia	A hybrid simulation based model using both deterministic equation-based model (EBM) containing ordinary differential equations (ODEs) to model livestock diseases within herds (such as FMD and ASF), and also a stochastic, spatially explicit agent-based model (ABM) to model disease spread between-herds and control options ¹²⁰ .
Sardinia, Italy ¹⁸⁹	To estimate the basic and effective reproduction numbers of ASF in wild boar	Stochastic SEIR model using Bayesian (Monte Carlo) simulation. This study used serological data from hunting seasons to gather the required parameters needed in the model.
Lithuania ¹⁹⁰	Temporal trend of prevalence estimates in wild boar	Bayesian space-time model (using surveillance data from hunted animals) to estimate the temporal course for prevalence.
Latvia (representative for Northern and Eastern Europe) ¹⁹¹	(1) if ASF can persist when transmission occurs only through infected wild boars and infected carcasses. (2) if the animals that survive ASF can play a relevant role in increasing ASF persistence chances (3) how hunting pressure can affect the ASF probability to persist.	An evolved version of the SEIR model with the inclusion of a spatially explicit, stochastic, individual-based structure. Each individual could be classified in one of the eight model compartments: susceptible, exposed, infected, convalescent, immune, infectious carcass, non-infectious carcass and hunted. The 'convalescent' compartment included the individuals which survived the acute phase of the disease and were passing through the recovery process.
Estonia and Spain ¹⁹²	To demonstrate key processes that drive ASF spread in wild boar, environmental transmission influence and assess disease control measures and provide suggestions	A deterministic model that includes direct transmission and transmission from infected carcasses and the possibility of survivor individuals, all of which have been implicated in ASF outbreaks and persistence. The model separates wild boar into two age classes: piglets (hosts aged 0 – 10 months on average) and yearlings/adults (known hereafter as adults). This was done to separate the differences in reproduction, natural mortality and mortality due to hunting between these age-classes.
Eurasia ⁹⁸	To compare wild boar hunting and carcass removal as alternative and combined strategies for the elimination of ASF in its endemic state	Spatially explicit SEIRC (infected carcass compartment) individual-based model which incorporated the demography and spatial dynamics of a wild boar population, the spatial epidemiology of ASF in its endemic phase, and a management system acting for the elimination of the disease from the population.
Vietnam ¹⁹³	To develop a disease dynamic model to explain how ASFV spreads in Vietnamese pig populations and suggest a	SIR (removed) compartments. To deal with uncertainty, the within-farm transmission of the ASFV was modelled in four different scenarios.

	protective vaccine coverage level required to prevent future outbreaks.	
Austria ¹⁹⁴	To simulate the chain of infection and compare various control measures and identify potential high risk outbreak locations	A hybrid approach was selected, including discrete-event and agent-based simulation. An extended Susceptible-Exposed-Infectious-Recovered (SEIR) model (within a pig farm) and a standard SEIR model (between pig farms)
France ¹⁹⁵	Simulation of transmission via local routes, movement of animals from infected to susceptible sites, and transit of trucks without physical animal exchange	Stochastic SEIR (removed) transmission model, reaction-diffusion approach for agent-based spread between farms and animal movements, Monte-Carlo algorithm to characterise the occurrence of infection events.
Romania ¹⁹⁶	To assess the spatiotemporal features of the epidemics and their relationships with environmental, human, and agricultural factors	A statistical framework, based on a random forest methodology and ST-DBSCAN clustering algorithm. Random forest is a decision tree-based classification prediction method (combines Bagging algorithm and introduces randomly selected features to establish a set of decision trees for control variables) ¹⁹⁷ . ST-DBSCAN is a type of density-based method, which has the advantage of being able to consider many cases, and to detect irregularly shaped clusters.
Vietnam (data for case study) ¹⁹⁸	A novel architectural framework for simultaneously deploying any epidemic simulation program both on premises and on the cloud to improve performance and scalability	Combined data model standardisation, simulation programs management (mathematical, network-based, or agent-based models) and analysis and visualisation, into modules which form the basis of outbreak simulation programs
South Korea ⁶⁴	To assess the role of vehicle movements and wild boar populations in spreading ASFV to pig farms	Bayesian modelling was used to test the hypothesis that vehicle movements and ASFV-infected wild boars were a main source of infection to pig farms. Parameters were estimated using inferential MCMC method.

2.8 *Future Research Directions*

The current gaps in knowledge surrounding the role of wild pigs in the spread of ASF present several unresolved questions and challenges. A key question is understanding the extent of the contribution of feral pigs to ASF transmission, especially between feral-domestic pig populations. Emerging research areas highlight the need for innovative approaches and strategies to address these gaps. For example, monitoring piggeries for the presence of feral pigs through camera trap surveillance can provide valuable data, allowing farm managers and the pork industry to be proactive by understanding the current intensity of feral pig encounters through surveillance, to then ensure appropriate control measures are implemented. Additionally, integrating ecological and epidemiological data into disease simulation models can help parameterise feral-domestic pig contact rates in models such as AADIS. Local fieldwork, such as using camera traps, collaring, satellite tracking, genomics, pathogen surveillance, and trace elemental studies, is essential for directly informing such parameterisation and the structure and assumptions of these models. Critical questions that remain include determining how often and under what conditions contacts occur between feral and domestic pigs, how these interactions vary across space and time, and the likelihood of different contact types leading to ASF transmission. There is also a need to explore whether ASF can become established in feral pig populations and to identify conditions that could lead to large, uncontrollable outbreaks within Australia. There is evidence that feral pigs could have high potential of spreading ASF to domestic pigs, whether it be directly or indirectly. As a result, there is a need for local field studies to gather empirical data to further inform of the dynamics of the feral pig population (distribution, density, movement, and behaviours) that are near domestic pig herds to determine the probability of experiencing an encounter. With this information, pork producers and industry can implement appropriate biosecurity and control measures depending on their imminent risks, as well as disease models can simulate and assist in preparations for disease incursions in specific situations.

3 The Potential Role of Wild Suids in African Swine Fever

Spread in Asia and the Pacific Region

This chapter has been published in MDPI Journal, Viruses. Supplementary material listed in the manuscript is included in Appendix A. The original publication can be obtained from the following link: <https://www.mdpi.com/1999-4915/15/1/61>

3.1 Introduction

There is an ongoing global panzootic causing high mortality in certain suids as a result of African Swine Fever virus (ASFV) infection. ASFV is a large, double-stranded DNA virus from the *Asfarviridae* family, and is enveloped with genomic DNA of approximately 170–193 kb¹⁹⁹. The current spread involves predominantly the transmission of genotype II strains of the ‘Georgia 2007’ type virus²⁰⁰. Some attenuation has been observed in Estonia, but most strains observed during the current ASF panzootic are highly virulent^{56,201}. There is currently no vaccination available for use in controlling the disease, although there has been an increasing research focus on this area²⁰². ASFV has many transmission routes; these include direct contact with an infected pig or pig carcass, scavenging of infected carcasses or pork products from infected animals, contact with fomites contaminated with blood, faeces, urine or saliva from infected pigs (including bedding, feed, equipment, clothes and footwear, and vehicles), and spread by *Ornithodoros spp.* ticks (particularly *O. moubata*)²⁰³. ASFV is robust to degradation in pork products and in the environment²⁰⁴. There are several forms of ASF disease: acute, which leads to death of up to 100% of infected pigs, typically after 6–13 days; subacute, where mortality rates are lower (30–70%) and clinical signs can be exhibited for long periods of time; and chronic, in which mortality is low and a small number of affected individuals may become virus carriers for life with periodic viraemia^{205–207}. However, some authors contend that there is insufficient evidence of a subclinical carrier state^{208,209}. Eurasian wild boar and feral pigs (both *Sus scrofa*) are highly susceptible to disease, with clinical signs and mortality rates equivalent to those seen in domestic pigs (also *S. scrofa*)²¹⁰. The impacts of ASF outbreaks have had a cascading effect,

threatening domestic populations, the livelihood of farmers (particularly smallholders), the food supply chain and ultimately food security ²¹¹. The panzootic might also put further pressure on the population viability of already threatened endemic wild suid species ^{212,213}.

In terms of the broad geographical progression of the current panzootic, suid populations in the Republic of Georgia and the Russian Federation were first exposed to ASFV in 2007. This probably occurred through improper disposal of contaminated pork meat from a ship at Poti docks ²¹⁴, which led to widespread infections in European domestic pigs and wild boar from 2014 onwards ^{215,216}. During August 2018, ASF was first reported in Asia, China, then spread rapidly across the North-East in domestic pigs; it then spread to the South-East, likely due to local suid movements and ineffective biosecurity ²¹⁷. It has since spread to other areas throughout Asia, and into Papua New Guinea, which has been the only region in the Pacific to have experienced an outbreak. Geographical, ecological, and epidemiological evidence indicates that ASFV transmission is multifaceted and varies across different regions of the world, with differences in the roles that wild and domestic pigs play in virus maintenance and spread ²¹⁸. In many European outbreaks, particularly in western Europe, where outbreaks are mostly occurring in the wild boar population and occasional spillover events occur to domestic pigs, they are dealt with rapidly with whole herd culling ^{205,219–221}. However, in other areas there has been evidence of both wild and domestic pig populations contributing to ASFV spread. For example, in Romania, outbreaks in domestic pigs were associated with proximity to outbreaks in wild boar and wild boar abundance ²²¹. Similarly, in some Mediterranean countries, it was observed that where the disease is actively circulating in domestic pig populations, there were also high densities of wild boar and contact between wild boar and free-ranging pigs, suggesting that wild boar have a role in the spread of the virus ²²⁰. In contrast, in other regions in Eurasia, outbreaks have been initiated within the domestic population cycle, wild boar being of secondary importance to transmission (although regular spillover events and sometimes virus transmission were inferred). For example, in the Russian Federation and Caucasus, ASFV transmission is associated with the movement of live domestic pigs and pork products, or with poor biosecurity in

smallholder pig production ²²². It may be inferred that where wild boar outbreaks have been reported in regions of Asia, the direction of transmission is more commonly domestic pigs to wild boar than vice versa ^{222,223}.

More is known about the epidemiology of ASF in wild suids in Europe than in Asia and the Pacific region, as more surveillance, research and epidemiological analyses have been conducted ^{205,221,222,224}. This knowledge can assist in understanding the epidemiology of ASF and suitable management interventions within Asia and the Pacific contexts, where evidence is still limited. For example, in western Europe, carcasses appear critical to the overwintering of ASFV in a region, whereas this might be less of a concern in particular regions of Asia and the Pacific that have warm tropical climates ^{225,226}. The large geographical region of Asia Pacific is in a unique position, containing twelve species of locally endemic wild suids which are unevenly distributed across the Asian part of this region. These species are generally in population decline, and most have a sub-optimal conservation status such as threatened or endangered ²²⁷. The exception is the common and widespread *S. scrofa*, which occurs as domestic pigs, Eurasian wild boar, or feral pigs. The locally endemic pig species contribute substantially to the diversity of the Suidae family globally, and are an important conservation resource. In contrast, in the Pacific and Australasian regions wild suids are introduced *Sus scrofa* (feral pigs), which although an invasive pest species ^{228,229} can be highly valued as a food and cultural resource. As all Suidae species are believed to be susceptible to ASFV infection ^{213(p11)}, this creates difficulty in balancing ASF management and control scenarios, whilst respecting the diversities of cultures, food security and conservational importance of wild suids ^{220,230}.

The objectives of this paper are to review the role of wild suids in ASF spread across the Asia and Pacific region, including the ecology and distribution of wild *Sus scrofa* and endemic wild suids, ASF reports, transmission pathways, and control measures in place for wild suids. We address these objectives by a review of the literature, an assessment of national surveillance data analysis and an expert opinion survey.

3.2 Materials and method

This paper includes a scoping review of published literature and reports from official databases; and a follow-up survey of World Organisation for Animal Health (WOAH) delegates and representatives in Asia and the Pacific.

3.2.1 World Organisation for Animal Health Wild Suid in the Asia Pacific Region Project

This review was developed following a broader report developed for the WOAH Asia Pacific regional office on the role of wild suids in transmission of the ASF panzootic in the Asia and the Pacific region. The full project report was published by the WOAH ²³¹, and pertinent parts were refocused to produce this paper. The project team worked with a WOAH expert advisory group from the region.

3.2.2 Study Area and Definitions

The study area is defined as the 32 WOAH Member States within the Asia and Pacific region (Table 3.1).

Table 3.1: World Organisation for Animal Health (WOAH) Members within the Asia and the Pacific Regions.

WOAH Members for the Asia and the Pacific Region			
Australia	India	Maldives	Papua New Guinea
Bangladesh	Indonesia	Micronesia (Federated States of)	Philippines
Bhutan	Iran	Mongolia	Singapore
Brunei	Japan	Myanmar	Sri Lanka
Cambodia	Korea (Democratic People's Republic of)	Nepal	Thailand
China (People's Republic of)	Korea (Republic of)	New Caledonia	Timor-Leste
Chinese Taipei	Laos	New Zealand	Vanuatu
Fiji	Malaysia	Pakistan	Vietnam

In this paper, ‘wild suids’ are considered unmanaged suid populations, including wild or feral populations of *Sus scrofa*, other wild suidae and hybrids, whilst domestic pigs refer to managed populations (further defined in Appendix A: Table A1).

3.2.3 Literature Review and Official Reports

For this review, a hybrid qualitative–quantitative approach was used to gather recent and available information on the potential role wild suids may have on the ASF situation in Asia and the Pacific. This was achieved by searching a combination of online literature databases (Web of Science, Medline and PubMed Central), using key terms such as; “African swine fever” OR “African swine fever virus” OR “ASF” OR “ASFV” AND “wild pig” OR “feral pig” OR “wild boar” OR “endemic pig” OR “*Sus scrofa*” OR “*Sus*” OR “*Babyrrousa*” OR “*Porcula*” AND “outbreak” OR “transmission” OR “spread” OR “susceptibility” AND “Asia” OR “Pacific” OR “Oceania”. In addition to searching grey literature and through formal meetings with the Food and Agriculture Organisation of the United Nations (FAO)/WOAH Global Framework for the progressive control of Transboundary Animal Diseases (GF-TADs) standing group of experts on ASF^{232,233}. The World Animal Health Information System (WAHIS), FAO and IUCN databases were used to gather quantitative data on the spread of the disease, reported outbreaks and cases, and the wild suid species distribution and conservation status across the study extent^{234–236}. Specifically, the ‘disease situation,’ ‘qualitative data,’ and ‘control measures’ dashboards were used from WAHIS and data were collected from the online system, with the last search for this paper being conducted on the 7 August 2022^{85,237,238}.

3.2.4 Survey

This study was undertaken following protocols approved by the University of Melbourne Human Ethics Committee (application number 2021-23073-23872-3). The online survey tool Qualtrics²³⁹ was used to design, create and distribute the questionnaire, which comprised mostly closed questions (Appendix A, Questionnaire A1). The survey was distributed in October 2021 by email to WOA Member delegates within Asia and the Pacific via the WOA regional

representative network. It remained open for approximately 6 weeks. In instances in which more than one delegate from a Member provided a response to the survey, where possible their results were amalgamated to represent a single response. If there were contradictory answers provided by multiple respondents from the same Member, the answer was amalgamated with preference given to ‘yes’ answers—for example, if there was an ‘unsure’ or ‘no,’ and a ‘yes’ response for the same question, ‘yes’ was used as the final answer.

Descriptive statistical outputs from the Qualtrics survey tool were examined. The responding Members were categorised as; low, lower middle, upper middle- or high-income status, based on the latest World Bank data ²⁴⁰. Throughout the analysis, *Sus scrofa* was categorized as ‘wild boar’ if it was endemic in the Member State, otherwise as ‘feral pigs’ if introduced and naturalised.

3.3 Results

3.3.1 Ecology and Distribution of Wild *Sus scrofa* in the Region

Sus scrofa is endemic in the Sino-Japanese and Oriental zoogeographic regions of Asia and the Pacific. In contrast, they are introduced in the Oceania and Australian zoogeographic regions, where they inhabit almost all islands, including Australia, New Zealand, and Papua New Guinea. In many of these locations, the populations are a hybrid mix of introduced *Sus scrofa* and domestic pigs ²²⁹.

Broadly, *Sus scrofa* is widely distributed and abundant across Asia and the Pacific ^{213,234,241}. However, specific information on the distribution, density, and ecology of the unmanaged populations of *Sus scrofa* within the Asia and the Pacific region tends to be limited, with few exceptions (e.g., Australia ^{139,242}(1, 2). Recent studies have innovatively used geo-mapping systems parameterised with the estimated climatic and topographic tolerance limits of *Sus scrofa* to broadly assess the distribution of pigs based on available habitats within Eurasia ^{243,244}.

These studies concluded that ecological patterns have a major role on wild suid distribution and density in the Asia and the Pacific region.

Wild *Sus scrofa* are very adaptable and so found in various subalpine, temperate, subtropical, and tropical habitats in the region, including riparian areas, semi-desert areas, rainforests, woodlands, grasslands, and reed jungles ^{229,234,245,246}. They are typically found near thick vegetation, and if the area is warm or dry, then close to a water source ²⁴⁵. This can make wild *Sus scrofa* difficult to observe and survey, and thus also make management and surveillance challenging.

Wild *Sus scrofa* are opportunistic omnivores: their diet varies depending on location and food availability. It is usually predominantly plant material, with some animal components such as carrion (including pig carcasses), small mammals and livestock (e.g., sheep) ^{234,247–249}. As well as cannibalistic scavenging, *Sus scrofa* may show behavioural interest in conspecific carcasses, including investigating the soil next to and under them for invertebrates and thereby making direct contact with the carcass ²⁵⁰. Both of these factors represent a considerable risk in the transmission of ASFV to *Sus scrofa* in some environments, as carcasses can remain infectious for substantial periods of time under favourable (cold) conditions, with experimental conditions confirming ASFV detection ranging from 3 months to over 2 years ^{6,251,252}.

Social behaviour and group size of ‘sounders’—the matrilineal (female) groups in which wild suids live—can also considerably affect disease transmission. *Sus scrofa* is non-territorial and social, with overlapping home ranges and interactions between separate sounders or larger herds of wild suids. Sounders generally comprise up to 50 individuals; however, when water is scarce, and sounders aggregate at available water sources larger groups of up to a hundred pigs have been observed ^{229,253}. Population densities of sounders can be greater than 20 pigs/km², with large home ranges of up to 30 km², depending on available food resources (where food resources are scarce—for example, during colder or drier seasons—home ranges may be relatively increased) ^{161,254–256}. Proximity to water sources is important in hot environments for

thermoregulation²⁴⁵, and wild suid sociability leads to close contact at such aggregation points. Given that *Sus scrofa* infected with ASFV are thought to specifically seek cool, moist, and sheltered environments (including water-related areas) to ease clinical signs ²⁵⁷, there is a high potential for the spread of infections within and between separate groups of pigs at such locations.

In Asia and the Pacific region, domestic pigs may be free-ranging, semi-free ranging or housed, and may be located near wild suid populations. Interaction and contact have been observed globally between free-ranging or housed domestic pigs and wild suids in Europe ^{220,258,259}(3-5) and the Asia and the Pacific region ^{260,261}. These interactions may be an important factor in the spread of ASFV to wild suid populations.

There were 35 responses to the survey, representing 27 different WOAHP Members within Asia and the Pacific; not all Members responded to every question. The most common species present was *Sus scrofa* (wild boar or feral pig) (96%, $n=26/27$ Members). Whilst many Members knew they had wild suids present, many (67%, $n = 18/27$) noted there was no information on the distribution or density of wild suids, or left these sections blank on the survey, suggesting a lack of knowledge.

3.3.2 Ecology of Endemic Wild Suids and Their Potential Role in African Swine Fever Transmission

There are 12 species of endemic wild suid in Asia. These include the abundant *Sus Scrofa*, 10 species endemic to South-east Asia (including seven *Sus* spp. and three *Babirusa* spp.), and *Porcula salvania* (endemic to North-East India). These species contribute substantially to the diversity of Suidae species globally and are an important conservation resource. All these endemic species, except for *Sus scrofa*, are declining in population distribution and abundance (acknowledging a lack of recent data available for many species; Table 3.2). Their conservation status varies from near threatened to critically endangered due to various processes (including habitat loss). Within these wild suid species, some features may contribute to the epidemiology

of ASF. For example, bearded pigs (*S. barbatus*) can migrate vast distances to forage for fruits, which could facilitate the spread of ASFV if pigs are incubating the virus. However, the incubation period and whether there are carrier states for ASFV in bearded pigs is unknown.

Table 3.2: Summary of wild suid species, current African swine fever (ASF) status, distribution, and population size (data mostly collected from the International Union for Conservation of Nature ²¹²) in the Asia Pacific region.

Species	ASF Detected	Distribution	Population Size (Estimate)
Wild boar/Feral pig (<i>Sus Scrofa</i>)	Yes ²¹⁰	Widely distributed across Asian countries in the oriental and Sino-Japanese zoogeographic regions ¹	Abundant throughout the region
Sulawesi babirusa (<i>Babyrousa celebensis</i>)	No	Indonesia	9999 ²⁶²
Hairy babirusa (<i>B. babyrussa</i>)	No	Indonesia	No recent data available ²
Togian Islands babirusa (<i>B. togeanensis</i>)	No	Indonesia	1000 ²⁶³
Bearded pig (<i>Sus barbatus</i>)	Yes ^{264–266}	Indonesia, Brunei, Malaysia ³	No recent data available
Javan warty/Bawean warty pig (<i>S. verrucosus</i>)	No	Indonesia	S. v. blouchi: 172–377 ^{267 4}
Sulawesi warty pig (<i>S. celebensis</i>)	No	Indonesia	No recent data available
Philippine warty pig (<i>S. philippensis</i>)	Yes ²⁶⁸	Philippines	No recent data available
Mindoro (oliver's) warty pig (<i>S. oliveri</i>)	No	Philippines	No recent data available
Palawan bearded pig (<i>S. ahoenobarbus</i>)	No	Philippines	No recent data available
Visayan warty pig (<i>S. cebifrons</i>)	No	Philippines	No recent data available
Pygmy hog (<i>Porcula salvania</i>)	No	India, Bhutan ⁵	100–250 ²⁶⁹

¹ As defined in Holt et al. (2013) ²⁷⁰. ² In 2000, an estimate was made of 4000 individuals ²⁷¹. ³ Extinct in Singapore, possibly extinct in the Philippines ²⁷². ⁴ No recent data are available for the species more broadly.

⁵ Presence in Bhutan is uncertain ²⁶⁹.

3.3.3 African Swine Fever in Wild Suids

African swine fever in wild suids has been primarily documented in the Asian countries of the region (Figure 3.1). Anecdotally, ASFV detections in wild suids have regularly been judged to be secondary to domestic pig outbreaks, having been confirmed several months after domestic pig outbreaks in the same area ^{236,273}. For example, in Vietnam ASFV was confirmed in domestic pigs in February 2019, and then in wild boar in December 2019 ²⁴¹. Meanwhile, Cambodia has yet to report ASFV in wild suids despite confirmation in domestic pigs in March 2019 ²⁴¹. It has been suggested that the spread of ASFV by wild suids is underestimated in Asia ^{219,274}.



Figure 3.1: African Swine Fever cases in wild suids reported to the World Animal Health Information System, red shaded regions representing African swine fever is present and green representing absent [41].

Cases of ASF have been documented in bearded pigs in Borneo ^{264–266} and Philippine warty pigs ²⁶⁸. In the case of Philippine warty pigs, it was specifically noted that the disease appeared similar to that in domestic pigs ²⁶⁸. ASFV was not reported in the other endemic species, which may be attributed to limited surveillance activities within the regions or a lack of transmission to these species (Table 3.2).

The susceptibility of the other wild suid species in which ASF has not yet been reported is poorly understood, though plausible ^{205,213,220,230}. Pigs of the genus *Sus* (bearded pigs and warty pigs) are predicted to be similarly susceptible to infection and disease as other *Sus* species and subspecies; it is not known if susceptibility or ASFV virulence differs in wild suids of other genera (*Babyrusa* spp. and *Porcula salvania*) ²⁷⁵.

The reporting to WAHIS (as of 7 August 2022) of ASF in wild suids is limited ²³⁵. Reports have been submitted by four WOAHA Members in the region—China, the Republic of Korea, Laos, and Malaysia (Table 3.3, Appendix A: Table A2). However, it was found in the literature that 9 Members have had ASF outbreaks in wild suids (Table 3.4, ²³⁶), an increase compared to the WAHIS database.

Table 3.3: Reports of African swine fever in World Animal Health Information System in wild suids in World Organisation for Animal Health Members of Asia and the Pacific.

Member	Year	Species	New Outbreaks	Cases	Killed and Disposed of	Deaths
China (People's Republic of)	2018–2020	Wild boar	4	316	310	304
Laos	2019	Suidae (unidentified)	2	6	0	6
Malaysia	2021	Wild boar	50	115	0	115
		Bearded pigs	2	13	0	13
			2	5	-	5
Korea (the Republic of)	2019–2022	Wild boar	2047	2856	227	2350
	2021	Suidae (unidentified)	4	4	0	4
	2021	-	1	1	0	1

Table 3.4: Reported outbreaks of African swine fever by World Organisation for Animal Health members in Asia-Pacific from 2018 to present (7 August 2022).

Member	Outbreak Start Date, Status	Classification of Infected <i>Sus scrofa</i>	Details of Disease Spread
Bhutan ^{276,277}	6 May 2021 (ongoing)	Wild and domestic	Detected in free-roaming pigs, then to semi-commercial farm.
Cambodia ²⁷⁸	March 2019 (resolved),	Domestic	Detected in backyard pigs, from unregulated importing of pork.
China (People's Rep. of) ^{83,279,280}	1 August 2018 (ongoing)	Domestic and wild	Likely domestic contaminated wild, hypothesised spread due to tick-to-pig transmission.
India ^{278,281}	26 January 2020	Domestic and wild	Detected in domestic pigs then in dead wild boars. Predicted to be from wild boar-habitat cycle.
Indonesia ^{213,278,282,283}	17 December 2019	Domestic and wild	Source is unknown, spread by animal-human-vehicle-animal.
Korea (Dem. People's Rep. of) ²⁸⁴	23 May 2019	Domestic	Detected in Chagang-do (border with China)
Korea (Rep. of) ²⁸⁵	17 September 2019	Domestic and wild	Predicted to spread from domestic to wild boar by Anthropogenic interactions.
Laos ^{241,278}	20 June 2020 (resolved)	Domestic and wild	Spread from domestic to wild boar due to free-ranging farming styles.
Malaysia	8 February 2021 (ongoing)	Wild and domestic	First case in domestic pigs was triggered after wild boar case.
Mongolia ²⁸⁷	10 January 2019 (resolved)	Domestic	Likely spread due to swill feeding.
Myanmar ²⁸⁹	14 August 2019 (ongoing)	Domestic	Detected in a farm due to pigs dying.
Nepal ²⁹⁰	16 May 2022 (ongoing)	Domestic	Likely spread due to swill feeding
Papua New Guinea ²⁹¹	5 March 2020 (ongoing)	Domestic	Unknown/ inconclusive of source or origin, spread by illegal imports of infected pork products and scavenging.
Philippines ^{278,292}	25 July 2019 (ongoing)	Domestic and wild	Suspected to have spread after a resident imported a wild boar.
Thailand ²⁹³	January 2022 (ongoing)	Domestic	Detected in companion pigs and during slaughtering.
Timor-Leste	9 September 2019 (ongoing)	Domestic	Unknown source, likely due to transporting infected pigs.
Vietnam ^{241,278}	1 February 2019 (ongoing)	Domestic and wild	Detected in domestic pigs then wild boar. Spread is likely due to farming method and spillover by domestic pigs

3.3.4 African Swine Fever Transmission Pathways Reported in the Survey

The most reported routes of ASFV transmission between domestic and wild suid populations are direct contact or scavenging of infected carcasses; transmission may also occur through wild suids having access to swill and contact with fomites and effluent from pig production (Table 3.5).

Of the participating WOAHP Members, ASF in wild suids has been detected predominantly in wild boar/feral pigs (*Sus scrofa*) (39%, $n = 9/23$). It has also been detected in bearded pigs (*Sus barbatus*) and Philippine warty pigs (*Sus philippensis*) by two separate members. The question regarding the transmission of ASFV was left unanswered by many respondents possibly due to limited surveillance in wild suids in the area, however the small quantity of answers reported transmission occurring in both directions between wild and domestic pigs (Table 3.5).

Table 3.5: African swine fever virus transmission routes in wild suids reported by 5 Members within regions of Asia and the Pacific.

Direction of transmission nominated in the survey responses	Domestic—Wild (60%, $n = 3/5$) Wild—Wild (60%, $n = 3/5$) Wild—Domestic (60%, $n = 3/5$) Unsure (40%, $n = 2/5$)
Transmission mechanism nominated in the survey responses	Direct contact (pig-to-pig) ($n = 5$) Direct contact with infected dead pig carcass ($n = 3$) Scavenging of food/waste from domestic pig farms ($n = 3$) Indirect contact ($n = 3$) Spread via pig effluent from domestic piggery ($n = 1$) Spread via pig products (i.e., pork) ($n = 1$)

3.3.5 Control Measures in Place for African Swine Fever

There is currently no viable vaccine or treatment available for ASF, placing reliance on prevention and traditional control strategies to protect pig populations¹². The application of appropriate control measures depends on numerous factors, such as the location, type of pig production, movements of animals, and biosecurity strategies in place⁴⁷. Almost all WOAHP Members (30/32) in Asia and the Pacific have reported to WAHIS at least one control measure in place for ASF, with general surveillance and disease notifications being the most common

(Table 3.6). However, in the survey 17/23 (73.9%) Members reported the use of specific control or prevention strategies for ASF in wild suids, which were not represented in the WAHIS data. Overall, a variety of control methods were used, more frequently in high income Members than low-to-middle income Members (Table 3.7). There were fewer responses within the survey ($n = 17$) compared to WAHIS ($n = 30$), with surveillance being one of the most used control measures. Population control/culling tools were reported by 13% ($n = 3/23$) of responding Members. All three used hunting (i.e., shooting on the ground and trapping) as a part of this strategy; one Member also used poison baiting and aerial shooting.

Table 3.6: Control measures reported in place for ASF in wild suids, per WAHIS [40] reporting and FAO [39], in the Asia Pacific region.

Income Status*	Member	General Surveillance	Targeted Surveillance	Disease Notification	Monitoring	Zoning	Control of Wildlife Reservoirs	Control of Vectors
High income	Australia	Yes	Yes	Yes	Yes	-	-	-
	Brunei	Yes	-	Yes	-	-	-	-
	Chinese Taipei	-	-	Yes	-	-	-	-
	Japan	Yes	-	Yes	Yes	-	Yes	-
	Korea (Republic of)	Yes	-	-	-	Yes	Yes	-
	New Caledonia	-	-	Yes	-	-	-	-
	New Zealand	Yes	-	Yes	-	-	-	-
	Singapore	Yes	-	Yes	Yes	-	-	-
Upper middle	China (People's Republic of)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Fiji	Yes	-	Yes	-	-	-	-
	Malaysia	Yes	Yes	Yes	Yes	-	Yes	-
	Maldives	-	-	Yes	-	-	-	-
	Thailand	-	-	Yes	-	-	-	-
Lower middle	Bangladesh	Yes	-	-	-	-	-	-
	Bhutan	Yes	Yes	Yes	-	-	-	-
	Cambodia	-	-	-	-	-	-	-
	India	-	-	Yes	-	-	-	-
	Indonesia	Yes	-	Yes	Yes	-	-	-
	Iran	-	-	-	-	-	-	-
	Lao	Yes	Yes	-	-	Yes	-	-
	Micronesia (Federated States of)	-	-	Yes	-	-	-	-
	Mongolia	Yes	-	-	-	-	-	-
	Myanmar	Yes	-	-	-	-	-	-
	Nepal	Yes	-	-	-	-	-	-

	Pakistan	-	-	-	-	-	-	-
	Papua New Guinea	Yes	-	-	-	Yes	-	-
	Philippines	Yes	-	Yes	-	Yes	-	-
	Sri Lanka	-	-	-	-	-	-	-
	Timor-Leste	-	-	-	-	-	-	-
	Vanuatu	-	-	Yes	-	-	-	-
	Vietnam	Yes	-	-	-	-	-	-
Low	Korea (Democratic People's Republic of)	-	-	Yes	-	-	-	-
	TOTAL	19	5	19	6	5	4	1

* Income status as per the World Data ²⁴⁰.

Table 3.7: Proportion of different control methods for *Sus scrofa* applied throughout Asia and the Pacific reported in the survey.

	Fencing	Zoning	Biosecurity	Surveillance	Carcass Disposal	Vector Control	Culling/Popul ation Control	Border Quarantine
<i>Sus Scrofa</i>	24% (n = 4/17)	18% (n = 3/17)	53% (n = 9/17)	53% (n = 9/17)	29% (n = 5/17)	-	18% (n = 3/17)	35% (n = 6/17)
Proportion implemented in:								
High-income Members	75% (n = 3/4)	100% (n = 3/3)	67% (n = 6/9)	44% (n = 4/9)	80% (n = 4/5)	-	100% (n = 3/3)	83% (n = 5/6)
Upper Middle- income Members	25% (n = 1/4)	-	11% (n = 1/9)	-	-	-	-	17% (n = 1/6)
Lower middle- income Members	-	-	22% (n = 2/9)	56% (n = 5/9)	20% (n = 1/5)	-	-	-
Low-income Members	-	-	-	-	-	-	-	-

3.3.6 Correlation between Survey-Reported Control Measures and the Implementation of Other Prevention Strategies

3.3.6.1 Biosecurity, Pig Production Type and Wild Species Present

Domestic pig farming of *Sus scrofa* with poor biosecurity represents a considerable risk for ASFV transmission, especially where wild suids are in close proximity to domestic pigs. The majority of Asia and Pacific Members conduct domestic pig farming (72%, $n = 18/25$), of which small-scale ($n = 15$) and medium-scale ($n = 14$) production were reported in the survey to be the two most common systems (Appendix A; Table A2). Large-scale production was also reported ($n = 11$). The use of small-scale production systems occurred mostly in developing Members ($n = 11$), and 54.5% ($n = 6$) use free ranging/scavenging systems, of which half also had wild suids present. The control measures implemented by these developing Members were minimal (Table 3.7). For example, the survey found biosecurity was only used in 18% ($n = 2/11$) and fencing was not used by any of the developing Members with free-ranging systems that were reported. Overall, biosecurity practices were implemented in mostly developed Members (78%), and not utilised in any Members where endemic wild suid populations were present.

3.3.6.2 Wild Suid Carcass Disposal and Climatic Conditions

The disposal of dead wild suid carcasses was reported to be used in six different Members, of which four are considered to commonly experience winters below -5°C (and during summer, these four Members rarely experience temperatures above 25°C). The very low temperatures are ideal for carcass preservation in the environment, thus removing dead wild suid carcasses may substantially limit opportunities for transmission of ASFV in these countries. In comparison, the two other Members that reported removing dead pig carcasses rarely experience such extreme cold weather, with temperatures above 30°C common during summer. It was assumed that reporting the carcass disposals of endemic wild suid populations would be too infrequent to include in the survey due to their low population densities.

3.3.6.3 *Border Quarantine and Land Type*

Border quarantine strategies were reported to be in place in six different Members, of which five represent land that is classified as islands. Border quarantine on islands is generally easier to implement, and incursions and imports of wild suids or infected products are easier to manage, than for Members separated by land borders.

3.3.6.4 *Wild Suid Management Strategies and *Sus scrofa* Status*

The majority of responding Members reported managed hunting strategies for wild suids (52%, $n = 12/23$). Reasons for hunting were primarily for food (78%, $n = 7/9$), and game (recreational/sporting) (67%, $n = 6/7$). In eleven of these responding Members, *Sus scrofa* is considered a native species (wild boar); whereas where *Sus scrofa* are an introduced species (feral pigs) managed hunting was reported by 8% ($n = 1/12$) of Members. Thus, native *Sus scrofa* regions are more likely to have a managed hunting system, compared to where *Sus scrofa* is introduced.

3.3.6.5 *Legislation and Regulations*

The regulations or legislation regarding wild suids varied across the different categories (conservation, control of ASF and hunting; Table 3.8). Within these categories, laws about the hunting of wild suids are of the highest concern, with ASF control laws being second.

Table 3.8: The proportion of Members implementing regulations or legislation for conservation, African Swine Fever control and hunting of wild suids.

	Conservation of Wild Suids	For ASF Control	For Hunting Wild Suids
Yes	30% ($n = 6/20$)	44% ($n = 8/18$)	48% ($n = 10/21$)
No	50% ($n = 10/20$)	44% ($n = 8/18$)	33% ($n = 7/21$)
Unsure	20% ($n = 4/20$)	11% ($n = 2/18$)	19% ($n = 4/21$)

n: the number of total counts collected for the respective category.

3.4 Discussion

3.4.1 Occurrence of African Swine Fever in Wild Suids

African swine fever outbreaks have primarily been reported in domestic pig populations in Asia and the Pacific, and the spread of the disease is predicted to continue ^{236,294}. Although generally presumed to be less of a concern compared to other regions of the world, the occurrence and distribution of ASF in wild suids in Asia and the Pacific is uncertain, given the scarcity of current evidence. The absence of or limited official reporting of ASF cases in wild suids cannot be presumed to indicate the absence of infection: many Members have limited active surveillance activities in wild suid populations, or surveillance activities are restricted to general surveillance, which might be insensitive in detection and confirmation of the infection in wild suids ^{219,295}. For example, there might be logistical reasons for an inability to detect ASF in certain ecosystems, or difficulties relating to local authorities and resources ²¹⁹. Given the frequent detections of ASFV in domestic pigs across the region, active surveillance activities targeting wild populations in at-risk regions would be beneficial.

3.4.2 Wild Suids Role in Disease Spread

Inferences as to the role of wild suids spreading ASF in Asia and the Pacific are currently inferred based on observations from other geographic regions of the world where enhanced surveillance, research and analyses have been undertaken ^{205,221,222,224}. This information is regularly used as a substitute for the lack of data within Asia and the Pacific, but such inferences must be made with caution. It is evident that *Sus scrofa* can be found in abundance throughout Asia and the Pacific, and thus have the potential to spread and maintain ASFV in the region. In comparison and irrespective of uncertainties in susceptibility to infection and disease transmission dynamics, the 11 non-*Sus scrofa* endemic pig species are unlikely to have an important role in ASF epidemiology in the region, as their populations are small and have limited distributions.

However, more broadly the distribution of wild suid species and their population densities across the region is uncertain, and this information should be investigated further to assess the role of wild suids in spreading the disease with greater confidence, given the potential implications for ASFV transmission dynamics. Further, ecological attributes may affect the maintenance of infection in wild suid populations, and thus influence the likelihood of transmission from these populations to domestic pigs. For example, geographic locations and times of year in which ambient temperatures are relatively high may influence the likelihood of virus transmission through the relatively rapid decomposition of wild suid carcasses and negative impacts on the virus' viability in the environment.

The risk of transmission of infection from wild suids to domestic pigs is also influenced by farming methods ²⁹⁶. In the Asia and the Pacific region, many Members have a heavy reliance on small-scale production systems that typically involve free ranging/roaming methods.

3.4.3 Potential Improvements on Control/Management Strategies

The impacts of ASF justify proactive strategies in the prevention and management of outbreaks. The suitability of different strategies might vary by epidemiological context across the Asia and the Pacific region. For example, in climates where wild suid carcasses could naturally decompose at a fast rate reducing the potential for ASFV transmission, resources should be targeted at other control measures that are likely to be more effective, such as border quarantine or on-farm biosecurity interventions where transmission risks are elevated. Further research is required to inform strategic approaches that best cater for Members' own situations and specific requirements.

Areas of Asia and the Pacific region that are currently experiencing ASF outbreaks can undertake interventions in wild suid populations to reduce disease transmission (e.g., by decreasing wild *Sus scrofa* population density with control tools if appropriate such as trapping, aerial shooting, poison baiting and intensive hunting) and to prepare for a possible vaccine (through the development of bait delivery strategies, including relevant ecological research).

On-farm biosecurity improvements, such as education about infectious diseases, and establishment of village-level biosecurity practices regarding isolation of moved pigs and confining/penning pigs, might also reduce the risk of transmission between domestic and wild suids²⁹⁶.

For areas of the Asia and Pacific region that have yet to detect ASF, being proactive by implementing prevention, detection and response strategies can assist in remaining free or reducing the impact of an outbreak. For example, prevention via border quarantine (which is especially relevant to islands), reducing time to detection of incursions by improving general surveillance activities in wild and domestic pig populations, and implementing appropriate response frameworks to manage ASFV transmission to, from and within wild suid populations once it is detected.

Importantly, ASF may have catastrophic population-level impacts on the 11 non-*Sus scrofa* endemic wild suid species, threatening populations with local extirpation or extinction. Hence, increased protection through breeding and conservation measures should be considered where these species are endemic. For example, risk assessment with appropriate mitigation strategies to protect important populations of endemic wild suids or captive breeding programs.

3.5 Conclusion

The role of wild suids in the epidemiology of the disease in Asia and the Pacific is poorly understood, though wild *Sus scrofa* has potential to contribute to the spread of disease. Nevertheless, population interventions in wild suid populations may be necessary to control disease outbreaks, and actions to prevent infection in threatened species populations are important considerations. Whether ASFV can survive for long periods in wild suid carcasses in warmer regions of Asia and the Pacific is an information gap requiring research.

Appendix A: Chapter 3 supplementary material

Table A 1: Definitions of suid populations used in this paper

Suid category	Definition	Subcategory	Definition
Wild ¹ suids	Any members of the taxonomic family Suidae that are living freely in the ecosystem without close human management, or that are held in captivity in zoos or breeding programs.	<i>Sus scrofa</i>	Feral pigs and wild boar. In general, wild boar are locally endemic and feral pigs have been introduced to an area.
		Other wild suidae	The eleven species of endemic pigs found locally across the Asia and the Pacific region (<i>Babyrussa celebensis</i> , <i>B. babyrussa</i> , <i>B. togeanensis</i> , <i>Sus barbatus</i> , <i>S. verrucosus</i> , <i>S. celebensis</i> , <i>S. philippensis</i> , <i>S. oliveri</i> , <i>S. ahoenobarbus</i> , <i>S. cebifrons</i> , <i>Porcula salvania</i>).
	There are two main types of wild suids, (i) <i>Sus scrofa</i> and (ii) other wild Suidae.	Hybrids	Wild pigs that are hybrids of wild pig species
Domestic pigs	Any members of the taxonomic family Suidae that are managed by humans, excluding wild pigs held in zoos or breeding programs. Where <i>Sus scrofa</i> are farmed, either intensively or extensively, they are referred to as 'domestic' pigs. 'Domestic pigs' includes farmed wild boar.		

¹ Whilst the term 'wildlife' is used in the WOA definitions to define feral animals, captive wild animals and wild animals, the term 'wild suids' is used for fluency of language.

Table A 2: Analysis of the type of farming methods used in Asia and the Pacific reported by WOA Members

Type of domestic pig production in Member	Proportion of Members reporting	Type of domestic production	Number of Members reporting	Mean proportion of production across all Members (95% CI)	Total number of Members reporting each type of small-scale production	Mean proportion of each small-scale production methods across the reporting Members (95% CI)
Domestic pig production present	72% (18/25)	Large Scale	11	48% (21.7-75.1)	~	~
		Medium scale	14	30% (11.5-47.6)	~	~
		Small scale	15	35% (4.1-65.8)	Free ranging / scavenging (10)	15% (5.81-24.19)
					Semi-intensive (13)	33% (0.3-65.7)
					Intensive (13)	47.5% (20.4-74.6)
No domestic pig production present	28% (7/25)	~	~	NA	Integrated (1)	N/A
					~	~

* Not all Members that specified the type of domestic production system in operation also specified the proportion of the production systems in further detail (percentages). Thus, only those that provided this information were able to be included in this analysis.

Table A 3: Reports to WAHIS of African Swine Fever in wildlife in Asia, as of the 7th of August 2022 ²⁹⁷.

Member	Semester	Administrative division	Species	New outbreaks	Susceptible	Cases	Killed and disposed of	Deaths
China (People's Republic of)	Jul-Dec 2018	Heilongjiang	Wild boar		375	77	298	77
	Jan-Jun 2019	Inner Mongolia	Wild boar	1	222	222	12	210
	Jul-Dec 2018	Jilin	Wild boar			1	0	1
	Jul-Dec 2019	Shaanxi	Wild boar	1		9	0	9
	Jan-Jun 2020	Shennongjia	Wild boar	2		7		7
Laos	Jul-Dec 2019	Huaphanh	Suidae (unidentified)	2		6	0	6

Malaysia	Jan-Jun 2021	Beluran	Wild boar	9	21	43	0	43
	Jan-Jun 2022	Bentong	Wild boar	1		1	-	1
	Jan-Jun 2021	Kinabatangan	Wild boar	6	8	10	0	10
	Jan-Jun 2021	Lahad Datu	Wild boar	10	12	16	0	16
	Jan-Jun 2022	Lipis	Wild boar	1		1	-	1
	Jan-Jun 2021	Nabawan	Wild boar	2	1	2		2
	Jan-Jun 2022	Raub	Wild boar	2		3	-	3
	Jan-Jun 2021	Sandakan	Wild boar	4	7	7	0	7
	Jan-Jun 2021	Sandakan	—	2	5	5		5
	Jul-Dec 2021	Semporna	Wild boar	1	1	1	0	1
	Jul-Dec 2021	Semporna	Bearded pig	0		1	0	1
	Jan-Jun 2021	Tawau	Wild boar	4	2	4	0	4
	Jul-Dec 2021	Temerloh	Wild boar	1		12	0	12
	Jul-Dec 2021	Temerloh	Bearded pig	2		12	0	12
	Jan-Jun 2022	Temerloh	Wild boar	1		1	-	1
	Jan-Jun 2021	Tongod	Wild boar	6	7	14	0	14
Korea (Republic of)	Jan-Jun 2022	Boeun	Wild boar	5		67	4	63
	Jan-Jun 2021	Cheorwon	Wild boar	1		1	0	1
	Jan-Jun 2021	Chuncheon	Wild boar	87		87	0	87
	Jul-Dec 2021	Chuncheon	Wild boar	9		31	0	26
	Jan-Jun 2022	Chuncheon	Wild boar	3		21	0	21
	Jan-Jun 2022	Chungju	Wild boar	4		21	1	20
	Jul-Dec 2021	Danyang	Wild boar	71		71	3	68
	Jan-Jun 2022	Danyang	Wild boar	2		11	0	11
	Jul-Dec 2021	Donghae	Wild boar	1		4	1	3
	Jan-Jun 2022	Donghae	Wild boar	2		4	1	3
	Jan-Jun 2021	Gangneung	Wild boar	72		72	44	28
	Jan-Jun 2022	Gangneung	Wild boar	3		29	15	14
	Jul-Dec 2019	Gangwon-Do	Wild boar			17	2	15
	Jan-Jun 2020	Gangwon-Do	Wild boar	265		269	7	262
	Jul-Dec 2020	Gangwon-Do	Wild boar	182		183	14	169
	Jan-Jun 2021	Gangwon-Do	Wild boar	118		123	4	119
	Jan-Jun 2021	Gapyeong	Wild boar	15		16	0	16
	Jul-Dec 2021	Gapyeong	Wild boar	7		16	1	0
	Jan-Jun 2022	Gapyeong	Wild boar	3		14	0	14
Korea (Republic of)	Jul-Dec 2021	Goseong	Wild boar	7		7	1	6
	Jan-Jun 2022	Goseong	Wild boar	1		1	0	1
	Jul-Dec 2019	Gyeonggi-Do	Wild boar			38	1	37
	Jan-Jun 2020	Gyeonggi-Do	Wild boar	324		332	3	329

Korea (Republic of)	Jul-Dec 2020	Gyeonggi-Do	Wild boar	70		74	10	64
	Jan-Jun 2021	Gyeonggi-Do	Wild boar	54		59	4	55
	Jul-Dec 2021	Hoengseong	Wild boar	44		44		44
	Jan-Jun 2022	Hoengseong	Wild boar	3		12	0	12
	Jan-Jun 2021	Hongcheon	Wild boar	1		1	0	1
	Jul-Dec 2021	Hongcheon	Wild boar	21		45	12	33
	Jan-Jun 2022	Hongcheon	Wild boar	4		15	2	13
	Jan-Jun 2021	Hwacheon	Suidae (unidentified)	2		2	0	2
	Jan-Jun 2021	Hwacheon	Wild boar	57	2	60	0	60
	Jul-Dec 2021	Hwacheon	Wild boar	2		2	1	1
	Jan-Jun 2022	Hwacheon	Wild boar	1		2	0	2
	Jan-Jun 2021	Inje	Suidae (unidentified)	1		1	0	1
	Jan-Jun 2021	Inje	Wild boar	27		27	1	26
	Jul-Dec 2021	Inje	Wild boar	48		68	37	31
	Jan-Jun 2022	Inje	Wild boar	2		3	1	2
	Jul-Dec 2021	Jecheon	Wild boar	44		44	0	44
	Jan-Jun	Jecheon	Wild boar	4		22	0	22
	Jul-Dec 2021	Jeongseon	Wild boar	139		139	11	128
	Jan-Jun 2022	Jeongseon	Wild boar	4		26	0	26
	Jan-Jun 2022	Mungyeong	Wild boar	2		2	1	1
	Jan-Jun 2021	Paju	Wild boar	2		2	0	2
	Jan-Jun 2021	Pocheon	Wild boar	40		41	1	40
	Jan-Jun 2022	Pocheon	Wild boar	1		1	0	1
	Jul-Dec 2021	Pocheon	Wild boar	4		4	2	2
	Jul-Dec 2021	Pyeongchang	Wild boar	15		39	5	34
	Jan-Jun 2022	Pyeongchang	Wild boar	1		1	0	1
	Jul-Dec 2021	Samcheok	Wild boar	1		288	9	19
	Jan-Jun 2022	Samcheok	Wild boar	4		30	5	25
	Jan-Jun 2022	Sangju	Wild boar	4		36	0	36
	Jul-Dec 2021	Sokcho	Wild boar	1		1	0	1
	Jan-Jun 2022	Ulsan	Wild boar	2		10	0	10
	Jul-Dec 2021	Wonju	Wild boar	1		6	0	6
	Jan-Jun 2021	Yanggu	Suidae (unidentified)	1		1	0	1
	Jan-Jun 2021	Yanggu	Wild boar	33		34	0	34
	Jan-Jun 2021	Yanggu	—	1		1	0	1
	Jul-Dec 2021	Yanggu	Wild boar	5		5	1	4

Jan-Jun 2022	Yanggu	Wild boar	2	2	0	2
Jan-Jun 2021	Yangyang	Wild boar	16	26	11	15
Jan-Jun 2022	Yangyang	Wild boar	1	1	0	1
Jan-Jun 2021	Yeoncheon	Wild boar	66	71	0	71
Jul-Dec 2021	Yeoncheon	Wild boar	1	2	0	2
Jul-Dec 2021	Yeongwol	Wild boar	126	126	3	123
Jan-Jun 2022	Yeongwol	Wild boar	4	50	8	42

Questionnaire A 4: Survey questions sent by included Members

Respondent details

The data from this survey may be used in research and published. If you would like your data to remain unpublished, please specify ('No') below and your information reported will not be included in any publications. Otherwise, tick 'Yes':

Yes	No
☐	☐

1. Please write your country / territory name:

2. Contact email and name for follow up questions (if you do not require privacy):

3. Please note your organisation

Wild pigs in your country / territory

4. Please indicate the pig species that are present within your country/territory

⇒ If 'No pigs' are present please end survey here, thank you.

Species	Tick if present:
Wild boar or feral pig (<i>Sus scrofa</i>)	
Sulawesi babirusa (<i>Babyrusa celebensis</i>)	
Hairy babirusa (<i>Babyrusa babyrussa</i>)	
Togian Islands babirusa (<i>Babyrusa togeanensis</i>)	
Bearded pig (<i>Sus barbatus</i>)	
Javan warty pig, Bawean warty pig (<i>Sus verrucosus</i>)	
Sulawesi warty pig (<i>Sus celebensis</i>)	
Philippine warty pig (<i>Sus philippensis</i>)	
Mindoro (Oliver's) warty pig (<i>Sus oliveri</i>)	
Palawan bearded pig (<i>Sus ahoenobarbus</i>)	
Visayan warty pig (<i>Sus cebifrons</i>)	
Pygmy hog (<i>Porcula salvania</i>)	
No pigs	
Other (species not listed – please name)	

5. For the relevant species present in your country / territory, please fill out the corresponding information:

⇒ An example row is presented in the table below for *Sus scrofa* (feral pigs) in Australia for reference. Repeat the information for every species that is present.

Species (complete for the species present within the country)	Has ASF been detected in that species?	Is the species protected for conservation?	Are there conservation breeding efforts?	Minimum density of that species (pigs/square km)	Maximum density of that species (pigs/square km)	Approximate % of country where the species is found
Example row for Wild boar or feral pig (<i>Sus scrofa</i>) in Australia	No	No	No	0.1 pigs/km²	20 pigs/km²	40%
Wild boar or feral pig (<i>Sus scrofa</i>)						
Sulawesi babirusa (<i>Babyrousa celebensis</i>)						
Hairy babirusa (<i>Babyrousa babyrussa</i>)						
Togian Islands babirusa (<i>Babyrousa togeanensis</i>)						
Bearded pig (<i>Sus barbatus</i>)						
Javan warty pig, Bawean warty pig (<i>Sus verrucosus</i>)						
Sulawesi warty pig (<i>Sus celebensis</i>)						
Philippine warty pig (<i>Sus philippensis</i>)						

Mindoro (Oliver's) warty pig (<i>Sus oiveri</i>)						
Palawan bearded pig (<i>Sus ahoenobarbus</i>)						
Visayan warty pig (<i>Sus cebifrons</i>)						
Pygmy hog (<i>Porcula salvania</i>)						
Other (species not listed – please name and complete the table)						

6. Where are wild *Sus scrofa* or other endemic Suidae found in your country / territory?

Locations wild pigs can be found:	Tick if relevant	Species
Natural areas (e.g. National parks)		
Agricultural areas (e.g. farming/crops/livestock)		
Semi-rural (e.g. villages)		
Urbanised areas (e.g main towns/city areas)		
Other instances (specify below):		

If other instances, please specify below:

Farming domestic pigs and harvesting wild pigs

7. Are domestic pigs (*Sus scrofa*) farmed within your country / territory? (If 'No', go to Q8).

Yes	No	Unsure

- (i) If yes, please indicate the type of farming methods conducted within your country / territory:

Farming method	Tick if relevant	Approximate proportion of national production from each category (%)
Large scale production (>500 sows or >4000 fatteners)		
Medium scale production (5-500 sows or 20-4000 fatteners)		
Small scale production (1-2 sows or 1-20 fatteners)		
⇒ Free range/scavenging (unrestrained)		
⇒ Semi-intensive (confined within large area)		
⇒ Intensive (confined to a pig pen)		
⇒ Integrated (with fish farming)		
⇒ Other (specify below)		

If other methods, please explain in further detail:

8. Do parts of the human population in your country / territory use wild pigs for specific purposes (e.g. hunt for cultural or dietary)? (If 'No', go to Q9).

Yes	No	Unsure

- (i) If yes, please indicate the purposes for wild pig use:

Wild pig use	Tick if relevant	Relevant species:
Food (diet / consumption)		
Food (ceremonial occasions)		
Hunting/sport		
Feed for farm animals		
Dowries		
Hierarchy ranking		
Rituals (sacrifice, worship, taboo)		
Payment / monetary reasons		
Other (specify below)		

If other purposes, please explain in further detail:

Transmission of ASF in domestic and wild pigs

9. Has ASF transmitted between wild pigs and domestic pigs in your country / territory? (If 'No', go to Q11).

Yes	No	Unsure

- (i) If yes, has this transmission been between:

<i>Sus scrofa</i>	Tick if relevant	
Domestic pigs to wild pigs		
Wild pigs to wild pigs		
Wild pigs to domestic pigs		
Unsure		
Other wild pigs		Species relevant
Domestic pigs to other wild suidae		
Other wild suidae to other wild suidae		
Other wild suidae to Domestic pigs		
Unsure		

- (ii) If transmission is occurring, how it occurring at the wild pig and domestic interface?

Transmission	Tick if relevant		
	<i>Sus scrofa</i>	Other wild pigs (specify species to the right if relevant)	
Direct contact (pig-to-pig)			
Direct contact with dead pig carcasses			
Scavenging of food/waste from domestic pig farms			

Indirect contact (i.e. via human interactions or fomites)			
Spread via effluent from domestic piggery			
Spread via pig products (e.g. pork)			
Vectors (if present)			
Other (specify below):			

If 'other' transmission pathways present, please explain in further detail below:

10. Do you have any suggestions on how this transmission could be better controlled?

Control of ASF in wild pigs.

11. Are there any control or prevention strategies currently being used for ASF in wild pigs in your country / territory? (If 'No', go to Q12).

Yes	No	Unsure

(i) If yes, please indicate the control measures for ASF that are used in wild pigs, noting if they are successful:

Control / prevention strategy	Tick if relevant	Species	Successful (Y or N)	If unsuccessful, specify why:
Fencing				

Zoning*				
Biosecurity*				
Surveillance				
Carcass disposal				
Vector control				
Culling/population control				
Border quarantine				
Other (specify below)				
* Zoning: identifying geographical areas/boundaries where specific control strategies (i.e., culling within a certain area) are to be carried out. * Biosecurity: implementation of specific strategies within countries to eliminate/reduce the incursion of the disease (i.e., strict import conditions).				

If other strategies used, please explain in further detail below:

- (ii) If culling or population control is conducted, how is this performed and which species are targeted?

Culling method	Y	Species (specify target species)	N
⇒ Shooting on the ground (e.g., hunting)			
⇒ Aerial shooting (e.g., from a helicopter)			
⇒ Trapping			
⇒ Poison baiting			
⇒ Snaring			
⇒ Fertility control			
⇒ Other (please specify):			

- (iii) If surveillance is conducted, please indicate the strategies used:

Surveillance strategy	Y	Species (specify target species)	N
⇒ Pig carcass searching			
⇒ Random / frequent testing of wild pig			
⇒ Looking for signs of pig mortality or morbidity			
⇒ Other (please specify):			

12. Do you have a managed hunting system or season for wild pigs within your country / territory? (If 'No', go to Q13).

Yes	No	Unsure

(i) Please indicate the strategies that are relevant:

Pig management strategies	Yes	No	Unsure
A specific hunting period			
Pigs hunted for game			
Pigs hunted for food			
There is a quota/limit when hunting			
There is a target species or demographic of pig hunted (e.g., females)			
Does illegal hunting occur?			
Other (please specify below)			

Please explain in further detail below any additional information on management strategies:

--

(ii) Please indicate reasons for wild pig management:

Reasons for wild pig management:	Yes	No	Unsure
Prevention of crop damage by wild pigs			
Prevention of potential traffic incidents			
Prevention of invasion to urban areas			
Disease control			
Other (please specify below)			

Please explain in further detail below any additional information on management strategies:

--

Maintenance of ASF in wild pigs in your country / territory (if absent, go to Q17)

13. How long has ASF been in wild *Sus scrofa* populations?

⇒ Write the number of months (e.g. 6 means it has been present in wild pigs for 6 months)

--

14. Do you consider wild *Sus scrofa* to be epidemiologically important in outbreaks in domestic pigs?

Yes	No	Unsure

15. How long has ASF been in other species of wild SUIDAE?

⇒ Write the number of months (e.g. 6 means it has been present in in **other species of wild SUIDAE** for 6 months)

--

16. Do you consider other species of wild SUIDAE to be epidemiologically important in outbreaks in domestic pigs?

Yes	Species	No	Unsure

Regulations / legislations

17. Do you have regulations or legislation to:

- (i) Protect wild pigs for conservation reasons?

Yes (specify below)	No	Unsure

- (ii) Control ASF in wild pigs?

Yes (specify below)	No	Unsure

- (iii) Regulate hunting in wild pigs?

Yes (specify below)	No	Unsure

18. If relevant, please specify any additional laws or regulations associated with wild pigs and/or domestic pigs for ASF prevention:

4 Camera trap surveillance protocol to detect feral pig encounters at commercial piggeries

4.1 Introduction

Feral pigs (*Sus scrofa*) are recognised as an invasive pest species in Australia, which cause destruction to many environmental and agricultural resources around the country ^{126,229,248,298,299}. Being opportunistic omnivores, feral pigs can survive in most climatic settings and adapt to the available resources ^{245,247,300}. Feral pigs occupy around 45% of the land area of Australia and are continuing to expand ³⁰⁰, with their densities and home ranges fluctuating due to abiotic and biotic influences on a seasonal basis ²⁴². Feral pigs are predominantly found throughout Queensland (QLD), due to the level of habitat suitability with water availability, vegetation and cultivation dynamics, and favourable climatic conditions ²⁹⁸. A 2021 Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) survey found that landowners in QLD who experienced problems with feral pigs incurred more crop damage on their property compared to landowners in rest of the country ³⁰¹. As a result, commercial piggeries in Queensland, particularly those in close proximity to feral pig habitats are at increased risk of feral pig – domestic pig encounters and should monitor their presence so that appropriate biosecurity measures can be implemented accordingly.

Feral pigs are hosts to a range of infectious diseases, including several important transboundary animal diseases exotic to Australia, such as African swine fever (ASF) and foot-and-mouth disease (FMD), as well as endemic diseases including porcine brucellosis caused by *Brucella suis* and Q fever/Coxiellosis (*Coxiella burnetii*).^{199,302}. This creates heightened concern for agricultural industries as they pose important disease, welfare, and economic threats. The transmission of swine diseases, particularly ASF, can occur via direct contact or indirect pathways such as contaminated environment, feed stuff, vehicles, equipment, personnel, pork products and infected carcasses ^{64,193,203}. Moreover, the bidirectional risk of disease spreading by feral pigs to domestic pigs or vice versa, is an additional concern ^{162,303–305}. There is currently limited reporting data or evidence that verifies these contacts are occurring ³², and the role of feral pigs spreading disease may be underestimated or underreported ^{28,152,306}.

Monitoring feral pigs in the vicinity of livestock enterprises such as commercial piggeries can help generate a better understanding of the frequency of their presence, contact rates, their daily movement patterns, and identify high-risk locations for feral-domestic pig contact. The data obtained can inform industry producers or piggery managers on how to best conduct feral pig control strategies and best use available resources to prevent feral-domestic pig interactions. In addition, accumulated

data can also be used to parameterise disease simulation models such as the Australian Animal Disease Spread (AADIS) model ¹⁷.

Feral pigs may be attracted to piggeries due to the presence of feed and water, and pheromones produced by sows in oestrus ^{160,303}. Implementing appropriate monitoring systems is essential to: (a) determine if feral pigs are breaching commercial piggery boundaries and having the opportunity to interact with livestock; and (b) inform development of appropriate strategies to prevent disease transmission. Observing feral pig encounters may be difficult as feral pigs are elusive crepuscular animals being most active at night so visual sightings might be limited ^{225,307–309}. Thus, assuming that wild-domestic pig interactions are not occurring without evidence would be naive, and investigations should be conducted using appropriate surveillance methods. For example, GPS collars and camera trap technology are frequently used in wildlife ecology and have been used frequently to investigate disease transmission opportunities ^{112,310–313}. Similarly to how people set up security cameras around their homes to detect burglars breaking in, or if they know there has been break-ins within their area, they equip their houses with alarms or better locks. As a result, cameras around a piggery are essentially doing the same thing.

The aim of this study was to develop a protocol for camera-trap surveillance for feral pig activity and encounters with domestic pigs at properties in Australia. Following confirmation of feral pigs near a piggery, a pilot system was implemented to monitor the frequency and activity patterns at the property to inform risk of encounters of feral pigs with the piggery boundary. This pilot study will inform a feral pig surveillance system for commercial piggeries.

4.2 Methods

4.2.1 Ethics

This research was conducted with the approval of the Animal Ethics Committee of the University of Melbourne (review reference number: 2022-23229-25982-3).

4.2.2 Definitions and terminology

For this study, we use the following definitions for key terms:

Feral pig encounter/s: the instance where a feral pig/s are in the vicinity of a commercial pig farm of interest, with the potential to make direct or indirect contact with domestic pigs present on that farm. The confirmation of an encounter can be made by direct observation (i.e., in real time or via camera traps), or indirectly (i.e., the presence of feral pig footprints, crop damage).

Direct contact: occurs when susceptible animals come in direct physical contact with infectious animals such as when they share a paddock, pen or confined area such as a truck.^{7,17}

Indirect contact: occurs when susceptible animals come in contact with fomites, biological vectors, vehicles, and/or feed that carry the infectious agent of interest^{17,33,37}.

4.2.3 Study area

The study was conducted in The Darling Downs and the Western Downs regions in southeast QLD (Figure 4.1.). This geographic region is classified as having a subtropical climate, with rainfall occurring throughout the year, especially during the summer and autumn months³¹⁴. The average rainfall for 2021 - 2022 was 183% above the annual average mean of 1,936 mm due to the developing La Nina event which peaked in late January 2022. In Australia, QLD is home to around 22% of the total number of commercial pig herds in the country with 56% of QLD's pig herds located in the Darling Downs³¹⁵. The Darling Downs is highly abundant in feral pigs¹⁴⁵.

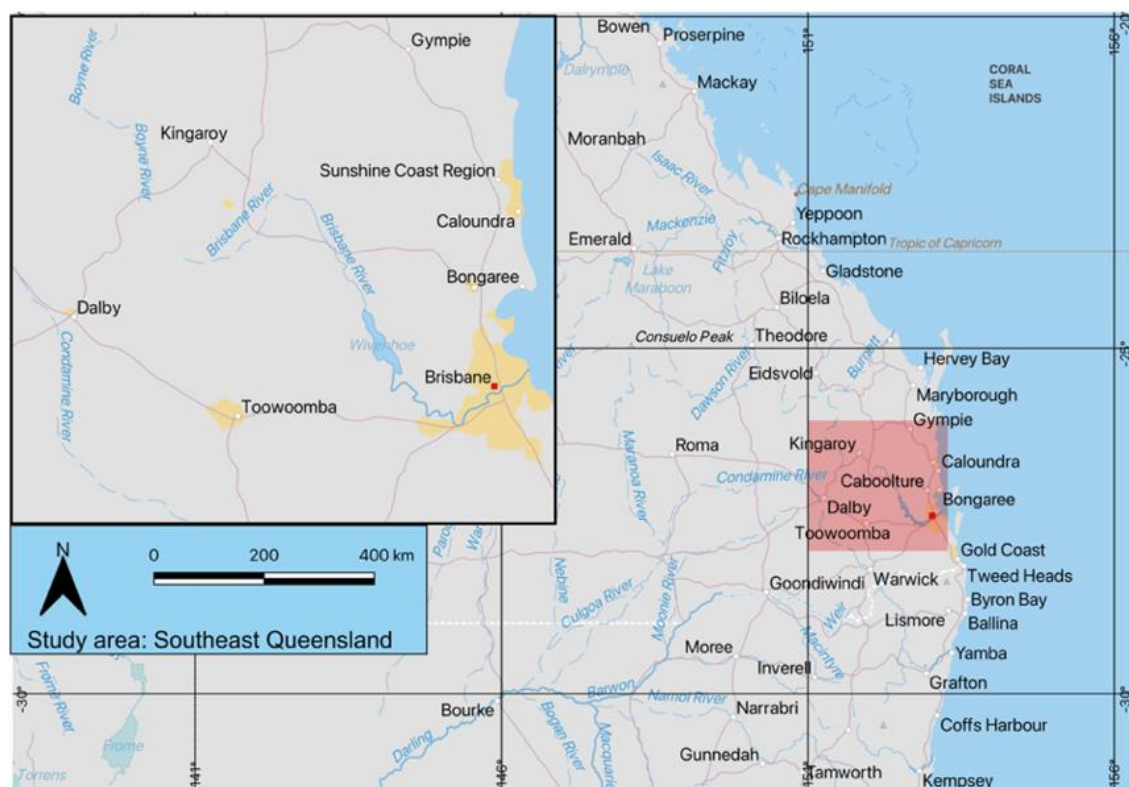


Figure 4.1: Study area in southeast Queensland, Australia (created in QGIS³¹⁶).

4.2.4 Surveillance system set-up

4.2.4.1 Site selection

To assess our proposed camera trap monitoring system in terms of how practical it is to implement and its efficiency, two commercial pig farms with a history of feral pig detections were purposefully selected for this study. Site selection was based on the recommendations of a pork industry veterinarian and proximity to suitable habitats for feral pigs (i.e. near a water source and with sufficient foliage protection cover) ^{145,317}.

4.2.4.2 Camera placement

Cameras were placed around the entire exterior fence of the piggery at 40 m intervals reflecting the estimated camera trap field of view. This spacing provided the highest possible coverage for the property, allowing analysis of subset data to investigate the efficiency of reduced coverage. Additional cameras were also placed in hotspot locations around the piggery, which were deemed likely areas to be visited by feral pigs as assessed by feral pig ecologists and piggery managers at the time of camera deployment.

4.2.4.3 Pilot period

To confirm feral pig presence, a pilot monitoring period was implemented at each site. At Site 1, 44 camera traps were deployed around the boundary fence that surrounded the pig sheds for approximately five months (19 May 2022 to 6 October 2022). At Site 2, eight camera traps deployed for seven weeks (22 November 2022 to 10 January 2023) around nominated hotspot locations. Hotspots included locations near a pig trap on a riverbank, a lagoon, two pre-feed piles of grain, game trails on a riverbank, a location with dense vegetation cover, and the area where pig carcasses are disposed (i.e., carcass pit). All cameras were placed within 600 m of the piggery sheds, with the majority placed less than 250 m to the sheds.

4.2.4.4 Camera traps

Due to this study being conducted in areas with potentially congested vegetation and grassland, Reconyx™ Professional HP2X Hyperfire 2 cameras were used. The cameras were programmed to take a series of three images when triggered, the sensitivity setting was set on 'high,' and picture interval was rapid fire with no delay quiet period. The cameras were mounted to a tree, fence post, or star picket approximately 40 to 50 cm from ground (about knee height). They were oriented at a 23° angle to the presumed pathway that the pigs passed along to intercept the expected passage of a feral pig approaching the fence, and preferably facing south were possible (or south-east or south-west if

necessary) away from direct sunlight to avoid glare at dawn or dusk (Figure 4.2) ³¹⁸. Throughout the 12-month duration of the study, the cameras were serviced with new batteries and Secure Digital (SD) cards were collected every 8 weeks.



Figure 4.2:Demonstration of the camera trap set up description (Image created using Canva generative AI ³¹⁹).

4.2.5 Data analysis

4.2.5.1 Image processing and analysis

Camera images were uploaded to Wildlife Insights ¹¹⁰ which is an automated image recognition software that uses artificial intelligence to identify animal species from digital images. Images where the identity of the animal species was unclear following image recognition were inspected by the first author. Sightings were recorded in Microsoft Excel ³²⁰, including the date, the timestamp, and count of independent pig detections for each day for each camera. Independent pig detections were defined as the presence of a single pig within the image. Due to the morphological similarities of feral pigs, it was difficult to confidently distinguish individual pigs in the images. Therefore, following Bengsen et al (2011) ³²¹, detections were grouped into encounter events using a 10-minute interval window. All pigs visible within a single image were counted as separate individuals for that image. If multiple images were triggered during a continuous period of activity, the encounter-level pig count was taken as the maximum number of pigs observed in any single image during that period, rather than summing

counts across images. A new encounter was only recorded when no pigs were detected for more than 10 minutes or when it was evident that a different group had entered the camera's field of view.

4.2.5.2 Feral pig encounters and activity at piggery

The number of daily, monthly, and seasonal encounters were calculated across all cameras. The number of individual feral pig encounters were calculated per camera per day, and the timestamp of each encounter was recorded to monitor the daily patterns of the pigs over time. The median number of encounters per month was calculated (including minimum and maximum) using Microsoft Excel ³²⁰.

A negative binomial regression model was used to quantify the association of camera location and the presence of feral pigs. This approach was selected after testing multiple model forms (i.e., negative binomial, zero-inflated negative binomial, Poisson and zero-inflated Poisson), as it provided the best fit for the data with the lowest Akaike information criterion (AIC) value ³²², accounting for overdispersion in the count distribution (Appendix B, Table B2). Encounter rates were analysed to determine the relative frequency of feral pig detections between hotspot and fence locations. The regression model adjusted for the number of cameras at each location type to provide a fair comparison of detection rates per camera location. The hourly detections were compared across these two locations, adjusting for camera location to control for any imbalance in the positioning of cameras. Additionally, the temporal patterns in activity were investigated to identify peak periods. A generalised additive model (GAM) was applied to account for diurnal and nocturnal patterns in feral pig activity. To address boundary effects associated with modelling periodic time-of-day data, a cyclic cubic regression spline was applied to ensure continuity at the day boundary (i.e. 0:00 and 24:00). The spline model was fitted using a negative binomial error distribution to account for overdispersion in the count data, with separate smooth functions for hotspot and fence camera locations (by = type). Predicted values and 95% confidence intervals were derived from model-based standard errors on the link scale and back-transformed to the response scale. All analyses were conducted in R (version 4.2.3)⁶⁵, using the contributed MASS package³²³ (for negative binomial regression) and the mgcv package³²⁴ to fit the cyclic spline GAM, alongside the splines package ^{65,325} to fit the non-linear spline for supporting modelling function.

4.3 Results

4.3.1 Pilot period and camera surveillance system

4.3.1.1 Pilot period

Over a period of 5 months, 6,160 camera trap nights ($140 \text{ days} \times 44 \text{ cameras}$) were collected at Site 1, and no evidence of feral pig activity was found, confirming they were not an immediate risk to the piggery at this time. The cameras were therefore removed. At Site 2, feral pig activity was confirmed within the first 7 weeks of monitoring (392 camera trap nights = $49 \text{ days} \times 8 \text{ cameras}$). Their activity was low and intermittent, however their presence within the area indicated their risk of potential interactions with domestic pigs. This triggered the initiation of the full camera surveillance system.

4.3.1.2 Camera surveillance deployment

The full camera surveillance was deployed at Site 2 from 28 March 2023 to 2 April 2024. The camera trap array consisted of 46 fence line cameras positioned around the exterior perimeter of the piggery and an additional 10 hotspot cameras positioned where there was evidence of feral pigs such as trot markings or disturbed tracks (Figure 4.3). The positioning of the cameras was guided systematically by production of a regular hexagonal grid, ensuring one camera was positioned in each adjoining cell 40 m apart, within a 15 m buffer of the cell centroid, where possible (Figure 4.3).

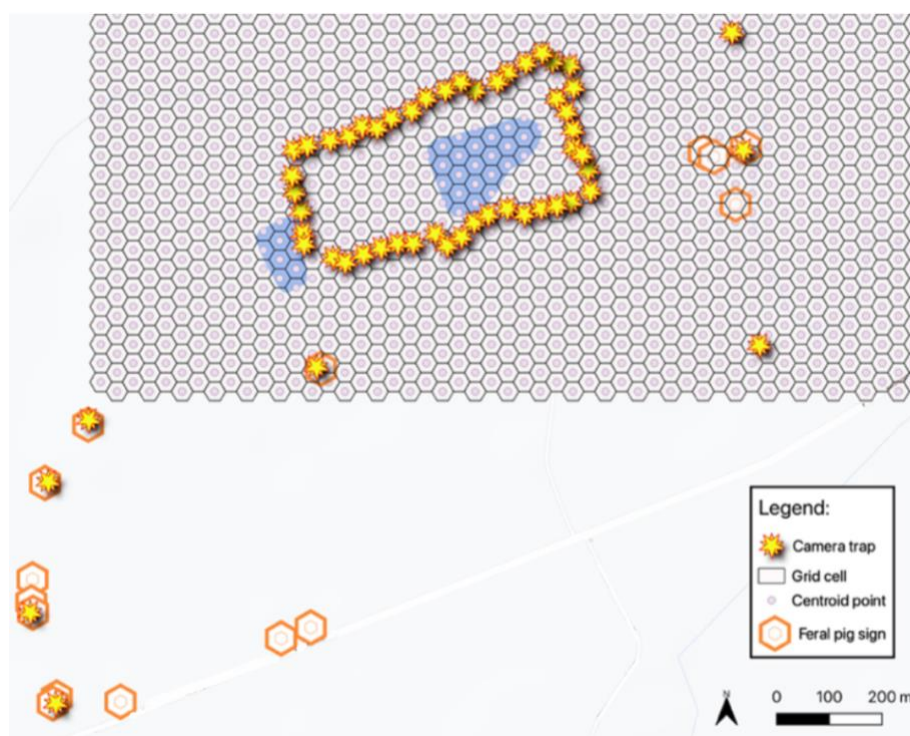


Figure 4.3: Camera trap surveillance system around Site 2.

4.3.2 Description and analysis of results

At Site 2, cameras were deployed for a total of 12 months capturing 20,292 camera trap nights (365 days × 56 cameras). For the duration of the study a total of 3,145,766 images were collected. During the study period the fence was repaired and extended (26 May 2022), which involved two additional sections being added to the perimeter perpendicularly from the piggery to the adjacent river, shown in Figure 4.3. Additionally, a sorghum crop on the property outside the piggery boundary fence was harvested around the 19 April 2022. Throughout the entire study period, cattle were freely roaming on numerous occasions to graze on the exterior of piggery perimeter fence but within the outermost boundary property.

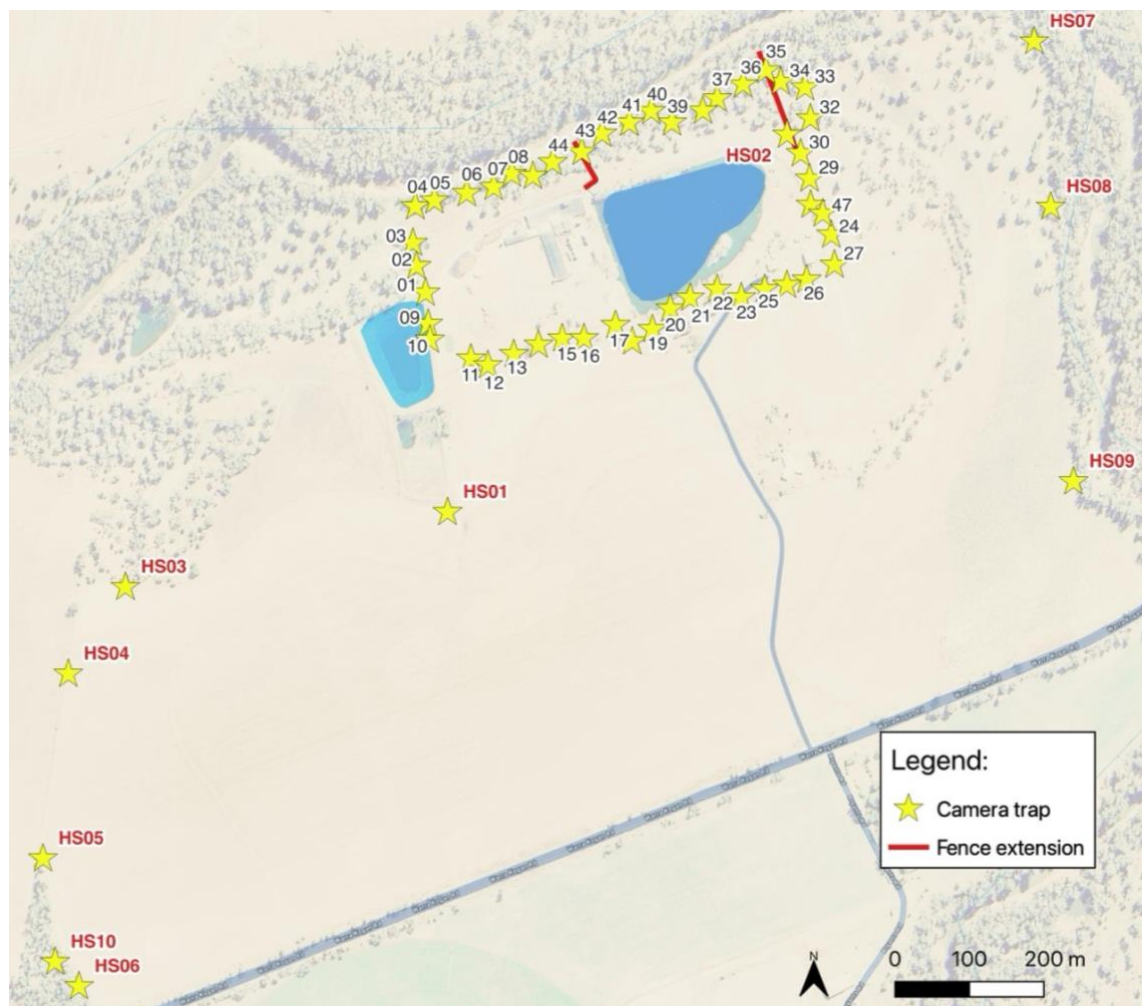


Figure 4.4: Fence cameras 01-47 and hotspot cameras 01-10 labelled around the piggery (please note that camera 31 was skipped unintentionally, total fence cameras was 46.) The fence was extended in two sections on the northern perimeter of the boundary fence shown.

4.3.3 Feral pig encounters

Feral pig encounters were highest in autumn (54%, $n = 1481/2691$ collectively 2023 and 2024 data), peaking in April with a median of 22 feral pig encounters/day (Table 4.1). The lowest number of feral pig encounters were recorded in summer (10%, $n = 274/2746$), with the lowest overall encounters occurring in December 2024 (1.5%, $n = 41$). The total count of feral pigs detected by fence and hotspot cameras throughout the study period is shown in Figure 4.5. Examples of the images collected are shown in Figure 4.6.

Table 4.1: Count of feral pig encounters per month

<i>Period</i>	<i>Total count of feral pig encounters</i>	<i>Median feral pig encounters/day (min, max)</i>			<i>Season</i>
		All cameras	Fence cameras	Hotspot cameras	
<i>April 2023</i>	1022	22 (0, 175)	4 (0, 138)	9.5 (0, 71)	Autumn ($n = 1281$)
<i>May 2023</i>	259	7 (0, 42)	0 (0, 6)	5 (0, 41)	
<i>June 2023</i>	418	14 (0, 63)	0 (0, 7)	11 (0, 63)	
<i>July 2023</i>	192	1 (0, 36)	0 (0, 4)	0 (0, 36)	Winter ($n = 653$)
<i>August 2023</i>	43	0 (0, 16)	0 (0, 0)	0 (0, 16)	
<i>September 2023</i>	65	0 (0, 31)	0 (0, 0)	0 (0, 31)	
<i>October 2023</i>	123	0 (0,0)	0 (0,0)	0 (0, 36)	Spring ($n = 337$)
<i>November 2023</i>	149	0 (0,0)	0 (0,0)	0 (0, 18)	
<i>December 2023</i>	41	0 (0,0)	0 (0,0)	0 (0, 19)	
<i>January 2024</i>	80	0 (0, 26)	0 (0,0)	0 (0, 16)	Summer ($n = 274$)
<i>February 2024</i>	153	2 (0, 21)	0 (0,0)	2 (0, 21)	
<i>March 2024</i>	200	3 (0, 30)	0 (0,0)	3 (0,30)	
<i>Total</i>	2746				

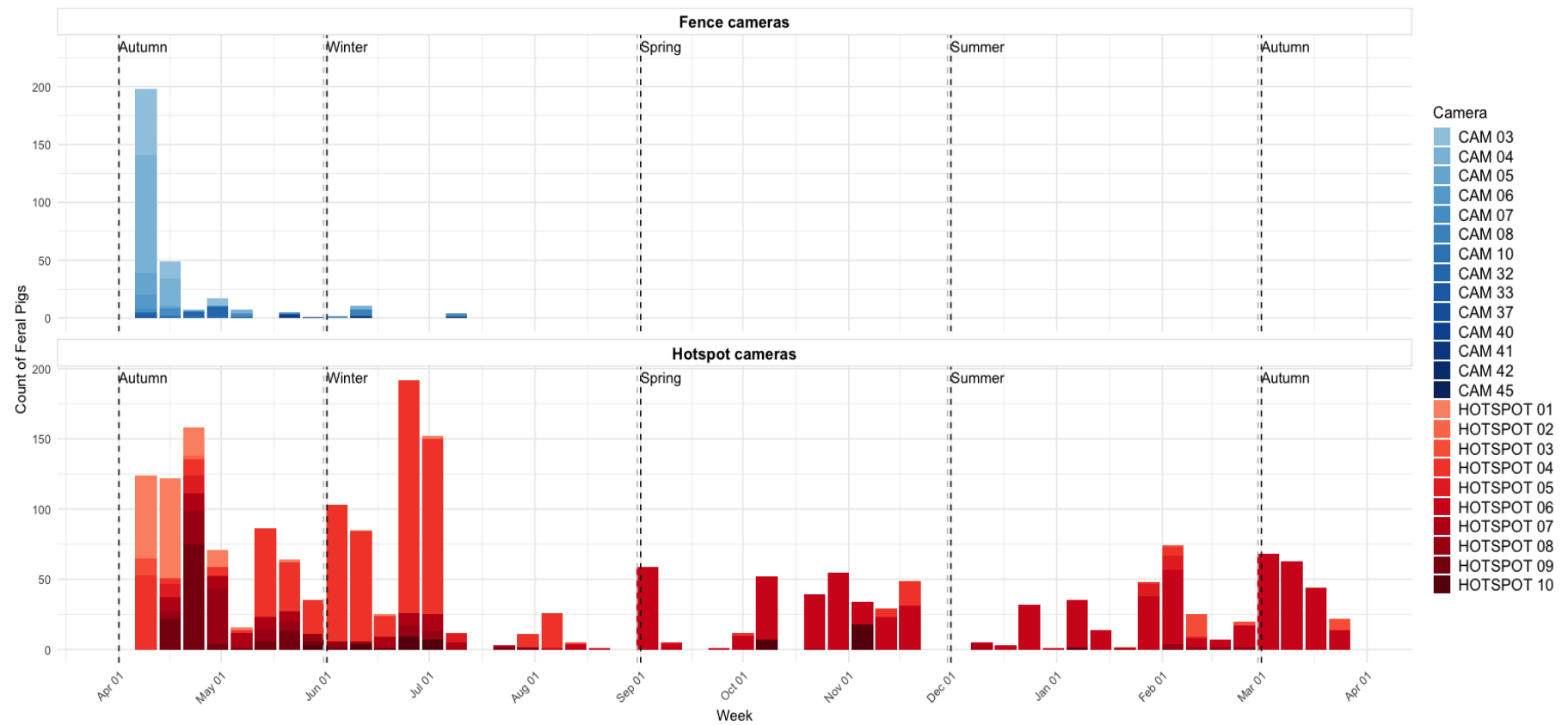


Figure 4.5: The crude count of feral pig encounters recorded by all cameras to demonstrate the influence of camera trap location on feral pig encounters.



Figure 4.6: Images capturing feral pigs by camera traps.

4.3.4 Camera trap location

Out of the total cameras deployed, 30% of the fence cameras ($n = 14/46$, shown in Figure 4.7), and 100% hotspot cameras ($n = 10/10$) detected feral pig encounters (Appendix B: Table B1). The location of camera traps were found to influence feral pig detections, as hotspot cameras recorded more encounters compared to fence cameras throughout the entire study period. Out of the fence cameras, cameras located along the northern perimeter recorded the majority of feral pig encounters during April 2023 (Figure 4.8). The north perimeter of the piggery was located adjacent to a river and had foliage protected covered areas with vegetation, and also experienced the most feral pig encounters compared to the east and west perimeters (Figure 4.7). A further breakdown of each detection from specific fence camera and where they are located are shown in Appendix B, Figure B1.

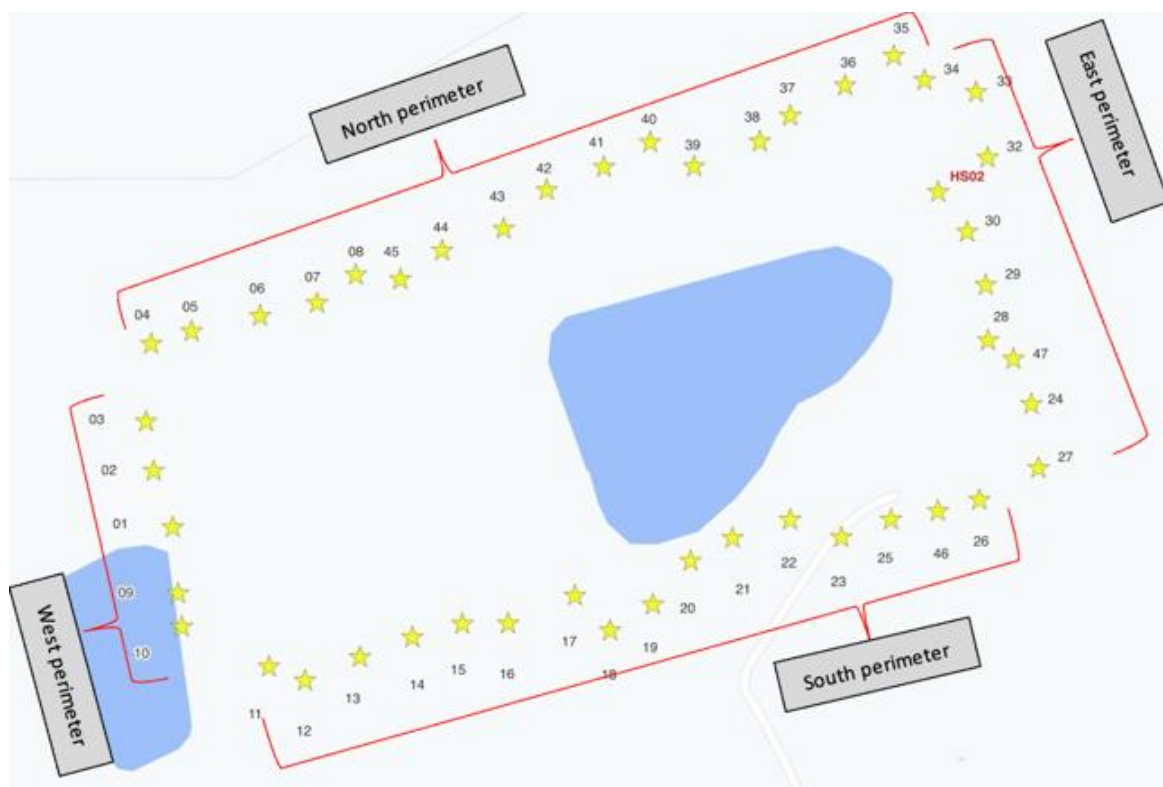


Figure 4.7: The boundary fence of the piggery categorised with fence cameras located along the north, east, south, and west perimeters to help explain temporal influences for feral pig encounters.

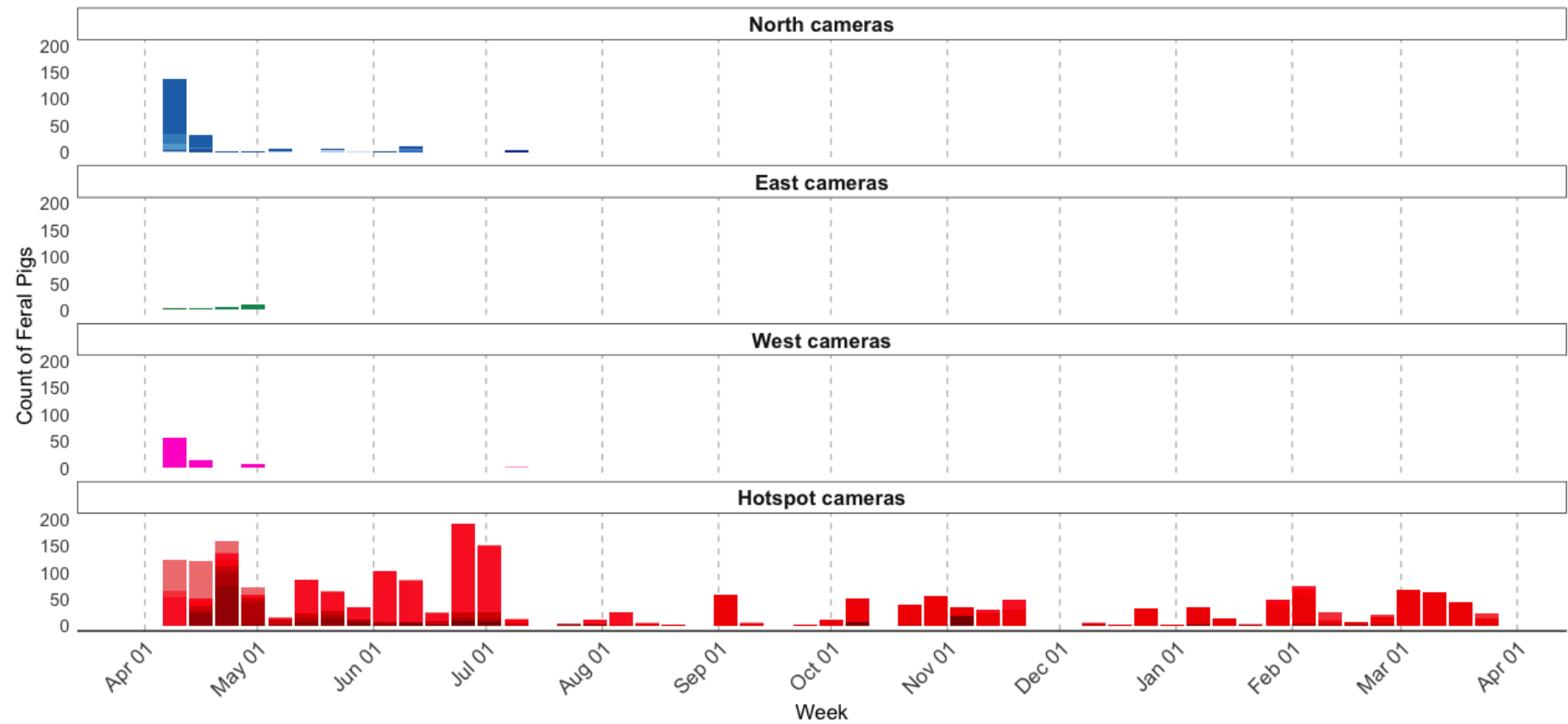


Figure 4.8: The crude count of feral pig encounters experiences by the fence cameras located along the north, east and west perimeters of the boundary fence. No encounters occurred along the south perimeter of the piggery, or after July.

4.3.5 Feral pig daily activity

A negative binomial regression model returned the best fit to the data out of the model forms tested (Appendix B, Table B2). Feral pig encounters were detected four times more frequently at hotspot locations than fence locations (Table 4.2), with increased encounters between midnight and 6 am compared to the remainder of the day. After adjusting for the number of cameras of each type, the rate of feral pig encounters detected per hotspot camera was 18 (95% CI 12 to 29) times that of fence cameras. Daily feral pig activity was similar for each camera location, with increased activity during the early morning hours. Activity peaked again at dusk for both locations (Figure 4.9).

Table 4.2: Multivariable negative binomial regression analysis of the association between feral pig encounters and camera trap location (hotspot and fence).

Variable	Coefficient	SE	95% CI	P-value
<i>Hotspot vs fence camera locations</i>	4.068	1.184	2.651, 6.244	<0.001
<i>Time of day</i>	Represented by spline (df=4, see Figure 4.9)			<0.001
<i>Intercept</i>	11.783	2.174	6.094, 22.78	<0.001

SE: Standard Error, CI: confidence interval, df: degrees of freedom

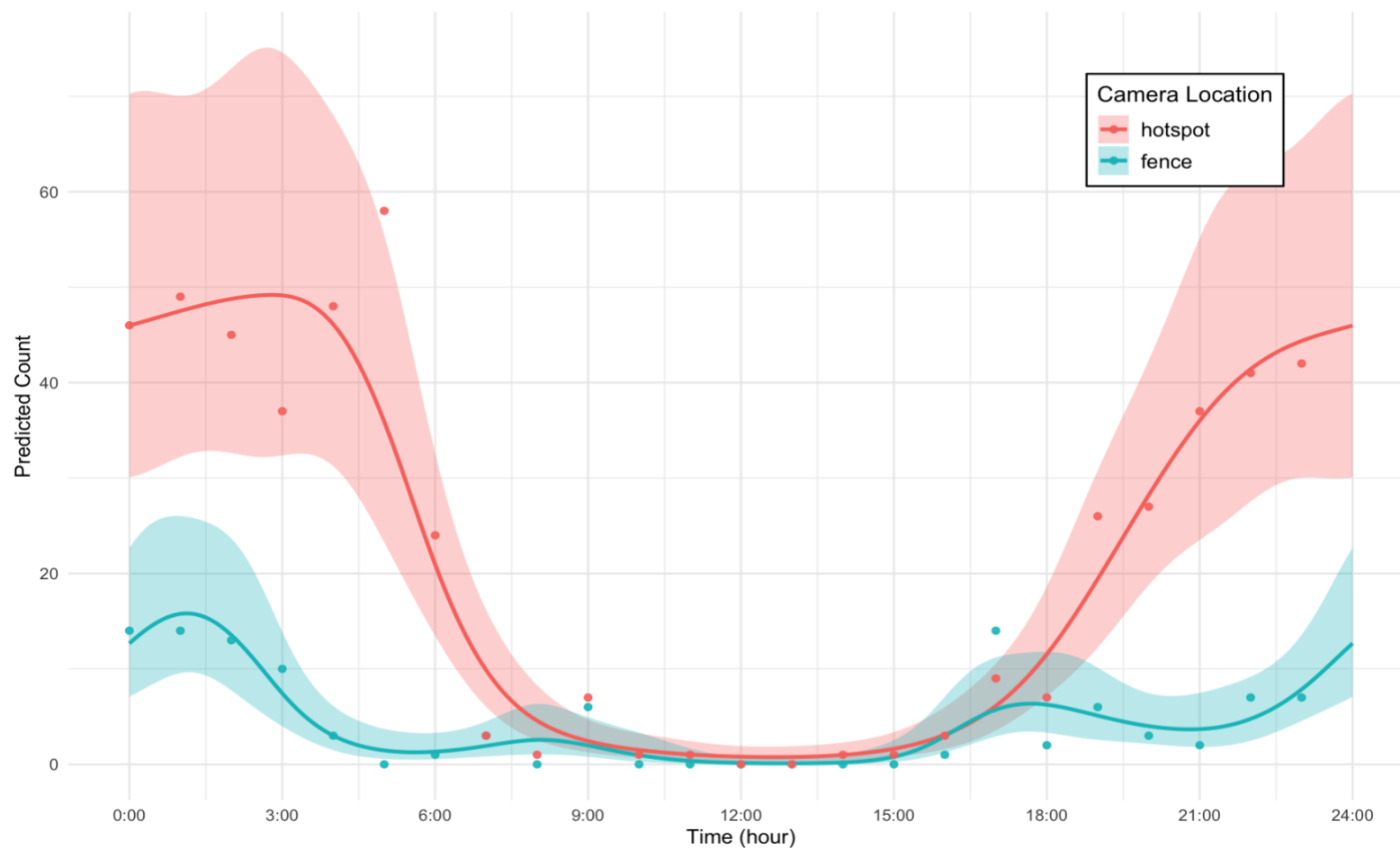


Figure 4.9: Cyclic spline generalised additive model demonstrating the temporal effect of hour of day and camera type (location) on feral pig activity around the piggery.

4.4 Discussion

This study presents details of an approach for monitoring feral pig activity around commercial piggeries, providing essential empirical data that can inform surveillance planning and disease modelling. Our findings show that the highest rates of feral pig encounters occurred in mid-autumn (April, in the southern hemisphere) predominantly during the pre-dawn hours, and were more frequently captured in hotspot locations compared to fence boundaries.

Understanding locations where feral pigs make contact with a piggery is pivotal in being able to target high risk areas and to either control the feral population to decrease the likelihood of them making direct or indirect contact domestic pigs or to enhance farm biosecurity. The negative binomial regression model showed that hotspot cameras were 18 times more likely to record feral pig encounters compared to fence cameras. This substantial difference supports the prioritisation of resources by placing cameras in known feral pig hotspot locations, thereby creating a more efficient monitoring system for industry stakeholders. Encounters along the fence line were concentrated on the northern perimeter adjacent to the river, corroborating findings from previous studies that attribute this trend to the proximity of water sources and the availability of foliage cover that provide refuge or nature corridor to assist movement for feral pigs^{146,163,326}. Observations showed that feral pigs attempted to breach the fence; however, their size often prevented successful intrusion. Instances where they might succeed represent a serious disease transmission risk¹¹². The eastern and western perimeters exhibited lower encounter rates, with activity discontinuing in May, except for one occurrence in July on the west side. Despite the presence of a dam and effluent pond nearby, these areas likely failed to attract feral pigs due to restricted access imposed by the piggery boundary fence and minimal foliage cover, leaving them exposed in open territory³¹⁷. No encounters were documented along the southern perimeter of the fence line, potentially due to the open landscape and frequent human incoming and outgoing activity, which tend to further deter feral pig presence by avoidance behaviours³²⁷.

For the hotspot areas feral pigs were detected consistently throughout the study period, proving their presence within the vicinity of the piggery even though they were not active along the fence line. Specifically, hotspot cameras 04 and 06 recorded the highest encounter rates. Hotspot camera 04, located on the eastern boundary in open territory, likely served as a passage route between the piggery and nearby scrublands, while hotspot camera 06, positioned 800 m from the perimeter fence in a southwestern scrubland area, provided refuge for feral pigs. The

fluctuation in encounter frequencies at hotspots throughout the year underscores the necessity of deploying cameras at multiple hotspot locations or repositioning cameras based on visual signs or changes in neighbouring crop rotations that might attract feral pigs ^{328,329}. Hotspot camera placement in this study was informed by prior local knowledge of feral pig activity, including farmer observations and landscape features known to attract pigs (e.g. water points, vegetation cover, and movement corridors). As such, it was not unexpected that hotspot cameras recorded higher detection rates than systematically placed fence-line cameras. However, this strategy may not be directly applicable to producers with no prior knowledge of feral pig presence or in areas of low or intermittent activity. In these contexts, a staged risk-based surveillance approach is recommended, whereby an initial systematic or perimeter-based deployment is used to identify areas of activity, followed by targeted hotspot monitoring once risk areas are identified. This adaptive framework allows surveillance to be implemented even in data-poor settings and supports scalable decision-making across different farm contexts. Feral pig detections predominantly occurred within 800 m (mostly within 500 m) of piggery sheds, with a noticeable decrease in encounters along the fence, particularly after July. These findings raise questions about the risk of direct nose-to-nose contact between feral and domestic pigs compared to indirect contact facilitated through the environment and scavengers, particularly if feral pigs do not tend to venture beyond hotspot locations. This behaviour may reflect the wariness and learned avoidance strategies of feral pigs in response to previously encountered deterrents such as pig proof fencing ³³⁰. Future studies across additional properties, incorporating GPS collars, are recommended to deepen our understanding of this behaviour. Throughout the study, substantial carnivorous scavenging by foxes was observed, highlighting disease transmission threats and biosecurity concerns. Similar predation has been documented in outdoor piggeries, where foxes prey on piglets ³³¹. Inadequate fencing around carcass pits poses a considerable risk for disease spread during outbreaks.

Feral pig activity displayed temporal variations, with the cyclic spline estimates showing an increased likelihood of encounters during nocturnal hours, particularly during the early morning. This observation aligns with findings from other studies in Eastern Australia and southern Spain, where feral pigs were most active between 11 pm and 5 am ^{104,112}. The crepuscular nature of feral pigs allows them to perceive reduced risks during night hours compared to daylight. Understanding these daily activity patterns can assist farm managers in scheduling control strategies to maximise their effectiveness, i.e. in surrounding refuge habitats during the day and

surrounding the piggery during the night. Furthermore, adjusting camera trap settings to focus on active periods will optimise camera battery life and SD card memory usage.

Our seasonal analyses showed that the highest encounter rates occurred during the autumn, followed by winter, spring, and summer. These variations are likely influenced by changes in environmental conditions and resource availability throughout the year. Previous studies have shown a generalised increase in wildlife visits during the dry seasons, attributed to heightened movement due to scarce natural food and water resources ¹¹². Given that northern areas in QLD experience a dry season from April to October, our findings align with these observations. Additionally, research indicates that feral pigs seek refuge from extreme temperatures, preferring habitats such as riverine woodlands, followed by woodlands, shrublands, and ephemeral swamps ¹⁴⁶. This preference offers insight into the reduced frequency of encounters during the summer months when temperatures peak. Hence, the heightened risk of feral pig encounters during the dry season necessitates proactive measures from farm managers to prepare for potential increases in feral pig activity.

Utilising automatic machine learning software to analyse camera trap images has proven effective in ecological studies, achieving high accuracy in species identification ^{332–335}. In this study, it served as a valuable tool for species identification and image storage. However, the extensive volume of data generated (56 SD cards approximately every eight weeks) rendered the system slow and time-consuming. The software employed (i.e., Wildlife Insights) requires user confirmation for each image tagged, negatively impacting on analytical efficiency. Consequently, it was more time-efficient in this instance to manually sort and identify feral pigs to minimise the risk of missing any feral pigs in the data. For scenarios involving fewer cameras or shorter study durations, automatic software can enhance data management and accessibility for producers, facilitating real-time analysis on an easy-to-use platform ³³². The software's capability to identify and sort numerous species with high sensitivity remains a noteworthy asset, although it incurs a subscription fee based on the volume of images processed, typically around \$0.01 AUD per image in 2024.

Based on the findings of this study, several recommendations are presented for the pork industry when deploying camera trap surveillance. A systematic approach utilising a hexagonal grid developed using a Geographic Information System such as QGIS ³¹⁶ ensures appropriate camera placements. This research provides a comprehensive surveillance protocol with resources that may not be available in commercial settings. Our finding that feral pigs were more

likely to be detected in hotspot areas provides a starting point for reducing the number of deployed cameras (and therefore surveillance program costs) while maintaining a sufficient surveillance system sensitivity.

Allocating cameras to hotspot areas, supplemented by installations at likely entry points or attractions along the fence, is likely to enhance monitoring efficiency. Seasonal camera movements or adjustments based on crop rotations should be considered to account for potential encounters, and camera settings should focus on periods of the day when feral pigs are most active (i.e., 5 pm to 6 am) to conserve resources. While the 12-month study period was, in our opinion, extensive, conducting surveillance for one week per month could be another way to reduce surveillance system costs.

Several limitations of this study should be acknowledged. The inability to distinguish between each feral pig due to similar characteristics made it difficult to accurately estimate if the same animal or sounders are interacting with multiple cameras on the same 24-hour period. This limits the ability to understand contact rates at the individual animal level. Accompanying the camera traps with GPS collaring could help understand the movement of sounders more accurately. The methodology was constrained by the absence of cameras in hotspot areas at Site 1, potentially overlooking critical data on feral pig activity. Furthermore, the study's focus on two sites limits to some extent the external validity of the findings. Further research is recommended across additional and diverse environments to confirm the adaptability of the methodology. Moreover, the subjective nature of hotspot location allocation highlights variability in detection abilities across properties. Some degree of caution should be applied when generalising findings or making cross-site comparisons.

4.5 Conclusion

This study offers critical insights into monitoring feral pig activity around commercial piggeries, presenting an effective methodology for surveillance that enhances biosecurity for commercial pig producers. We identify behavioural, temporal, and seasonal patterns in feral pig encounter frequencies, with the highest number of encounters occurring in autumn during the early morning hours. Hotspot cameras were markedly more effective than fence cameras, emphasising the need for strategic camera placement to optimise monitoring efforts. The data collected can help inform disease models on contact rates between feral and domestic pigs, and in turn support the development of targeted control strategies. Recommendations for pork producers include systematic camera deployment in hotspot areas and seasonal adjustments to

cater for potential changes in feral pig movement. While this research provides valuable findings, it also highlights areas for further investigations. Future studies should incorporate technologies like GPS tracking to deepen understanding of feral pig behaviour. Overall, this research represents a significant advancement in feral pig management, contributing to better biosecurity practices and safeguarding commercial pig operations.

Appendix B: Chapter 4 supplementary material

Table B 1: Investigating the appropriate model to assess the association between camera trap location (hotspot and fence) and the time of day on feral pig encounters.

Model	AIC value
<i>Negative binomial regression</i>	304.08
<i>Zero-inflated negative binomial regression</i>	306.99
<i>Poisson regression</i>	396.24
<i>Zero-inflated Poisson regression</i>	375.59
<i>Negative binomial regression model</i>	AIC value
<i>Nonlinear spline</i>	
<i>df = 2</i>	293.04
<i>df = 3</i>	295.90
<i>df = 4</i>	277.80
<i>df = 5</i>	279.21
<i>Quadratic</i>	
<i>hour</i>	321.54
<i>hour + hour²</i>	296.96
<i>hour + hour² + hour³</i>	298.81

Table B 2: Crude count of total feral pig encounters per camera trap within each month (April 2023 – March 2024).

<i>Camera</i>	<i>Autumn</i>		<i>Winter</i>			<i>Spring</i>			<i>Summer</i>			<i>Autumn</i>	<i>Total</i>
	April	May	June	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	
<i>CAM 03</i>	107												107
<i>CAM 04</i>	184	3	4										191
<i>CAM 05</i>	133												133
<i>CAM 06</i>	46												46
<i>CAM 07</i>	10	6	2	2									20
<i>CAM 08</i>			5										5
<i>CAM 10</i>				1									1
<i>CAM 32</i>	14	7											21
<i>CAM 33</i>	1												1
<i>CAM 37</i>	1	1											2
<i>CAM 40</i>		3											3
<i>CAM 41</i>		1											1
<i>CAM 42</i>			2										2
<i>CAM 45</i>				1									1
<i>Fence camera total</i>													534
<i>HS 01</i>	241	16	2	2									261
<i>HS 02</i>	3												3
<i>HS 03</i>	22				1					1	17	11	52
<i>HS 04</i>	76	114	359	139	34		2	26		1	6		757

HS 05	23	1	6			1			2	19		52
HS 06				7		64	113	105	37	73	101	689
HS 07	23	35	16	19			1		4			98
HS 08	37	47	11	14					2	10		121
HS 09	101	23	2	1	1							128
HS 10		2	15	7		7	18		1			50
Hotspot camera total												2211
Overall Total	1022	259	418	192	43	65	123	149	41	80	153	2746

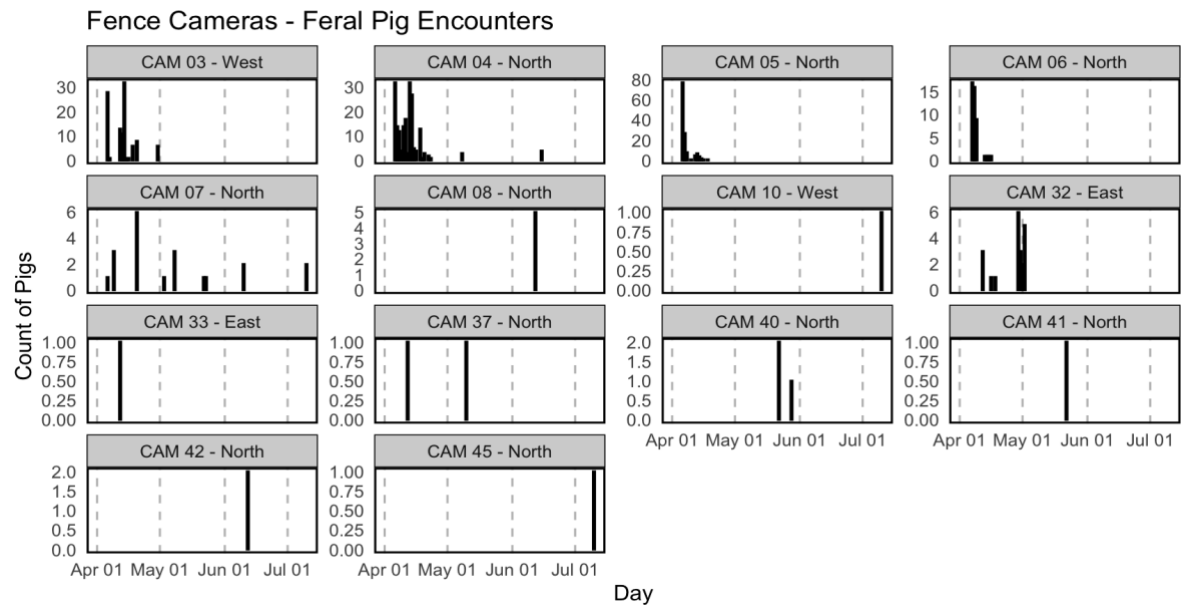


Figure B 1: Breakdown of fence camera ID and location with counts of feral pigs throughout the study period (no detections occurred after July).

5 Optimising camera trap surveillance for detecting feral pigs around commercial piggeries using an empirical dataset

5.1 Introduction

Monitoring the movement of feral pigs is crucial for understanding and managing various epidemiological and ecological impacts, such as disease transmission, pest management, and conservation efforts^{298,336,337}. By systematically tracking feral pigs, the frequency of their interactions with livestock and the surrounding environment can be monitored. This becomes especially important when infectious diseases are a threat by allowing measures to be implemented to reduce the risk of disease transmission (either from feral pigs to domestic pigs, or domestic pigs to feral pigs)^{338,339}. Studies have documented the role of feral pigs in the transmission of diseases such as African swine fever (ASF), and Japanese encephalitis virus (JEV), highlighting the importance of monitoring these populations to prevent disease outbreaks^{34,313}. Monitoring feral pig populations is also beneficial for effective pest management strategies, being an invasive species that cause agricultural and environmental damage³⁴⁰. Additionally, monitoring supports conservation efforts by assessing their impacts on native flora and fauna and guiding management strategies to mitigate these impacts^{298,299}.

Camera traps represent a pivotal tool for feral pig and other wildlife monitoring, by offering a non-invasive surveillance method that is useful for observing elusive species in their natural habitats³⁴¹. By capturing evidence of feral pigs using photos, researchers can track their presence, activity, and behaviour patterns over time. This data is helpful for understanding the impact of feral pigs on ecosystems, informing targeted management strategies, and mitigating their agricultural and environmental damage³⁴². Additionally, camera traps enable continuous monitoring, providing essential insights into feral pig ecology, and facilitating evidence-based decision-making for their control and conservation.

The presence of feral pigs near livestock enterprises such as piggeries, presents a substantial threat to the pork industry in Australia due to their ability to cause economic losses through crop damage, disease transmission, and habitat degradation^{298,299}. Camera traps offer an effective solution for monitoring feral pig populations and informing prevention and control strategies. By deploying camera traps in suspected areas of exposure such as hotspots, researchers and farmers can gather data on feral pig presence and potential for interactions with their animals, enabling targeted management efforts to mitigate agricultural damage and disease risks^{111,343}.

Continuous surveillance provided by camera traps facilitates real-time monitoring of feral pig movements, allowing for rapid response to emerging threats and evaluation of control measures' effectiveness over time. This proactive approach helps safeguard the pork industry's economic interests while protecting biosecurity and environmental resources.

Setting up camera trap arrays to detect feral pigs is complex due to the need to anticipate their behaviour and habitat preferences. Achieving optimal coverage requires careful consideration of factors such as population size, landscape characteristics, and monitoring objectives³⁴⁴. Selecting suitable locations involves identifying areas where feral pigs frequent, though their movements can be unpredictable. Balancing trade-offs between camera number, field of view, and duration of monitoring is crucial to ensure adequate coverage without overlap or gaps resulting in missed detection opportunities. Overall, the complexity lies in determining the best layout and positioning options to enhance detection probability of feral pigs while minimising false triggers and environmental disturbances to achieve efficient and cost-effective coverage^{345–347}.

With numerous factors influencing camera placement, such as terrain, vegetation, and wildlife behaviour, determining optimal camera configuration can be challenging. However, understanding the probability of detection enables the identification of the most effective locations for camera deployment. By calculating probability of detection based on factors such as camera location and distance from ecological factors (e.g., preferred habitat areas), researchers can prioritise high-risk zones and maximise detection rates. This approach allows for strategic placement of cameras to ensure comprehensive coverage while optimising resource allocation. By employing the most efficient configurations informed by probability of detection analysis, property owners can enhance monitoring effectiveness and reduce costs associated with camera deployment and maintenance.

The aim of this research was to evaluate how different camera trap coverage intensities and placement influenced the probability of detecting feral pigs. This information will provide guidance on how to optimise camera trap surveillance and efficiency for industry use.

5.2 *Methods*

5.2.1 *Data summary*

The empirical data collected from previous camera trap surveillance (Chapter 4) was used in this study, which entailed 12-months of data collected from 56 cameras (46 placed on fences and 10 in hotspots) positioned around a commercial piggery in south-east Queensland (Figure 4.4). The dataset contained date- and time-stamped encounters of feral pigs. As previously described in Chapter 4, feral pig encounters are where a feral pig/s are in the vicinity of a commercial pig farm of interest, with the potential to make direct or indirect contact with domestic pigs present on that farm. The confirmation of an encounter can be made by direct observation (i.e., in real time or via camera traps), or indirectly (i.e., the presence of feral pig footprints, crop damage). In the dataset used for this study, feral pig encounters were found to be highest in autumn (54% of detected encounters), peaking in April with a median of 22 feral pig encounters/day. The lowest number of feral pig encounters were recorded in summer (10%), with the fewest encounters detected in December (1.5%). In addition to seasonal factors, the frequency of pig encounters was associated with the presence of specific crops in the vicinity of the farm.

5.2.2 *Probability of detection*

Probability of detection refers to the probability of a device/person detecting an animal (if it is present within the field of view of the device) within a specified duration or time period³⁴⁸. The probability of detection is a function of the search ‘coverage’ of the area being investigated and varies in effectiveness depending on the coverage intensity of application. For this study, the detection probability of fence, hotspot, and all (fence and hotspot combined) camera layout scenarios were explored across yearly and monthly sampling scenarios to help examine the different detection probabilities across coverage intensities. Subsamples from the dataset were used to reconstruct lower coverage options. This provided the basis for subsequent analyses to understand the probability of detecting a feral pig using various camera trap coverage scenarios.

The probability of at least one success (i.e., the probability of detecting at least one feral pig within the CT array) can be expressed using the complement rule³⁴⁹, i.e.:

$$P(\text{at least one detection}) = 1 - P(\text{no detection})$$

To calculate $P(\text{no detection})$, we used the complement of the probability of detection (Pd) for a single event. If Pd is the probability of detecting a feral pig in one trial, then $P(\text{no detection})$ would be $1 - Pd$. So, the formula for the probability of at least one detection in multiple trials is:

$$P(\text{at least one detection}) = 1 - (1 - Pd)^n$$

where:

- Pd is the probability of detection in a single trial:

$$\Rightarrow Pd = \frac{\text{number of cameras that detected pigs during deployment period}}{\text{total number of cameras}}$$

- n is the number of trials or camera trap occasions.

This formula assumes that the trials are independent, meaning the probability of detection in one trial does not affect the probability of detection in another.

For example, a CT monitoring system providing 100% coverage around a property boundary used 47 CTs spaced 40 m apart. During April, 11 cameras detected pigs. The probability of at least *one* camera detecting pigs in this 100% coverage array during April is 98.6%:

$$P(\text{at least one detection}) = 1 - \left(1 - \frac{11}{47}\right)^{47} \approx 0.986$$

5.2.3 Impact of camera coverage on detections

By analysing detection probabilities across varying camera coverage intensities and placement scenarios, specific configurations that enhance monitoring efficiency can be determined. This information is important for informing biosecurity measures and surveillance strategies around commercial piggeries, ensuring that resources are allocated effectively to mitigate the risk of feral pig incursions.

Monte Carlo sampling was used to generate detection probabilities using various coverage intensities of camera traps by creating specific scenarios of camera surveillance arrays (Example in Figure 5.1). For each sample, cameras were selected at random and their detection results used to calculate the probability of detecting feral pigs. This resampling approach can be considered a form of bootstrapping, in that repeated subsamples of the original camera array were used to characterise variability in detection probability across coverage scenarios. The data

converged after running approximately 200 iterations based on median probability of detection, however 1000 iterations of each scenario were run to ensure convergence was strong. In this context, convergence referred to the point at which the estimated probability of detecting feral pigs stabilised across iterations, meaning that additional iterations do not greatly change the median probability of detection. This indicated that the simulation has reached a reliable and consistent estimate of detection probability.

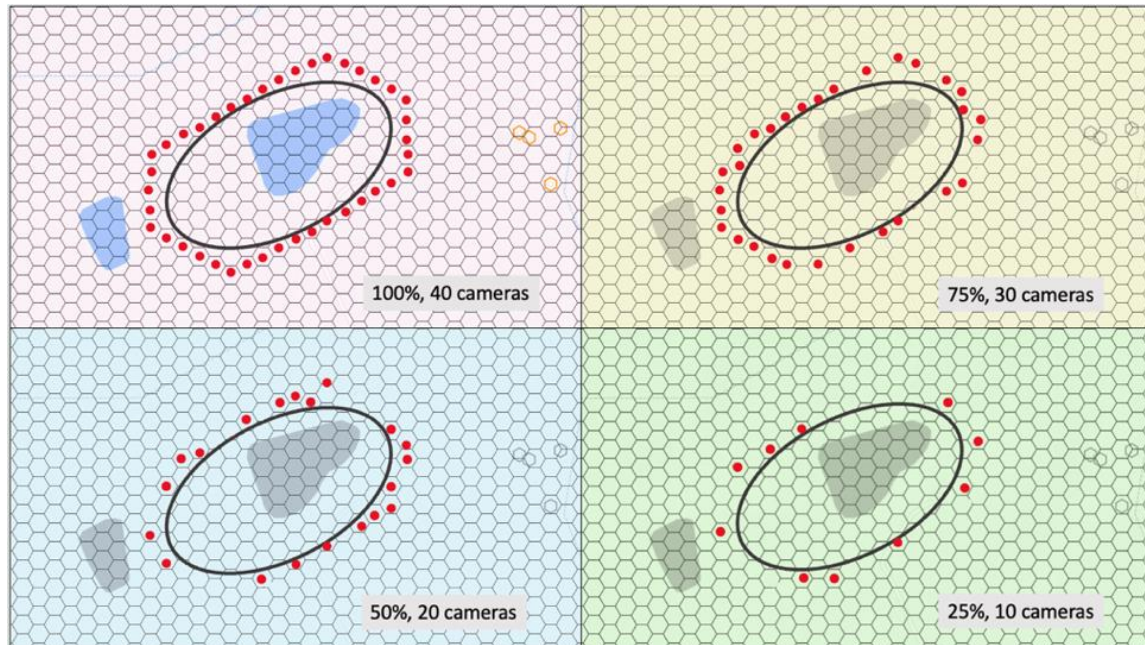


Figure 5.1: Example of various camera trap coverage options using the subset data from the comprehensive layout. The black line represents the piggery boundary fence, and the red dots represent individual camera traps. The shaded blue and grey areas represent effluent ponds at the piggery.

The monthly and yearly probability of detecting at least one feral pig within each coverage intensity scenario (10%, 20%, 40%, 60%, 80%, 100%) was investigated. The effect of different coverage intensities was compared using a method similar to that used by O'Connor et al (2017)³⁴⁴ by undertaking pairwise comparisons of the means of every group to the means of every other group (i.e. fence cameras vs hotspot cameras, and the coverage intensities 10-100% within the camera groups). The estimated marginal means (EMMs) derived from a generalised linear model (GLM) with a quasibinomial link (to account for overdispersion) were calculated by using the 'emmeans' package³⁵⁰ (Version 1.10.5) in R Development Core Team³⁵¹. Pairwise contrasts were tested to identify differences in detection probability between combinations. Given the structure of the data being non-linear and the nature of the comparisons, Sidak's

adjustment method was applied to control the family-wise error rate across multiple pairwise comparisons. This method was selected in preference to Tukey's adjustment as noted by O'Connor et al (2017) as Tukey's adjustment is only appropriate for one set of balanced pairwise comparisons, whereas this analysis involved independent comparisons across multiple levels of two factors (camera location and coverage intensities). The results were expressed as odds ratios, estimating the relative likelihood of detection across different scenarios and coverage intensities, with fence 100% coverage as the reference category.

To visualise the estimated marginal means (EMMs) of detection probability on the log odds scale, a plot was constructed using the '*ggplot2*' package in R Development Core Team³⁵¹. The log odds transformation was applied to ensure a linear relationship between detection probability and coverage intensity was demonstrated.

5.2.4 Impact of landscape features on detections

The most influential areas at the site were investigated within specific locations around the piggery to determine the best place to position cameras to determine if feral pigs are present.

Binary variables were determined in the dataset for whether detection occurred at the cameras in each of the following:

- bordering water source boundary
- along river corridor
- next to the dam
- next to effluent pond
- In bush/foilage cover
- In open territory
- Next to cultivation/crop
- Next to a road
- Next to pig sheds
- Next to farm housing
- Along the north (highest risk), east (low risk), south (lowest risk) and west perimeters (moderate risk) (classify on risk level) (Figure 4.7 in Chapter 4).

The probability of detection was calculated for each of these locations as:

$$Pd = 1 - \left(1 - \frac{k}{n}\right)^n$$

where k is the number of cameras that detected pigs in the subset, and n , the number of cameras in the subset.

5.3 Results

5.3.1 Random sampling of various coverage scenarios

The probability of detection across the different coverage intensities were investigated across a yearly and monthly sampling period. The values for all the detection probabilities for each coverage option are presented in Appendix C; Table C1 and Table C2.

5.3.1.1 Yearly sampling

Yearly detection probabilities (i.e., the probability that cameras positioned around the piggery for a period of 12 months would detect at least one feral pig if present) for different camera scenarios across various coverage percentages identified a clear increase in detection probability with higher coverage percentages (Figure 5.2). Fence and hotspot cameras together and hotspot cameras alone had higher detection probability compared to fence cameras alone, which reflected the distribution of the empirical data as feral pig encounters at the property fence were lower compared to hotspots. However, for all camera scenarios, detection probability increased as the coverage percentage also increased. This increase was less impactful at the fence cameras due to less feral pig encounters occurring at these locations.

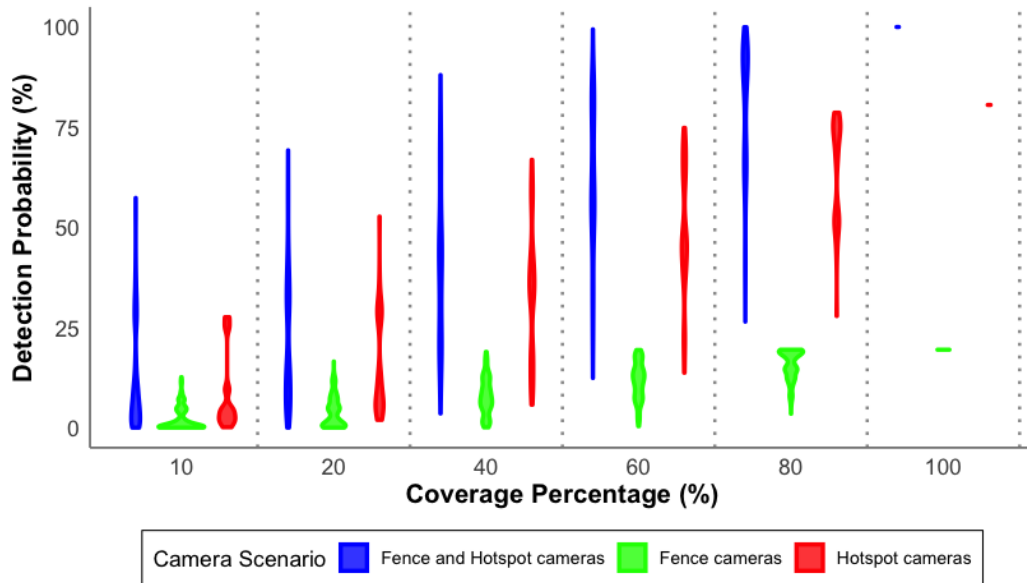


Figure 5.2: Line plot and violin plot demonstrating the various detection probabilities by fence and hotspot cameras across the different level of coverage intensities with yearly sampling.

5.3.1.2 Monthly sampling

The detection probabilities of different camera scenarios across each month are shown in Figure 5.3. Similar trends are seen across the months as for the yearly scenario, with the detection probability increasing with coverage percentage for all camera scenarios across all months, although the magnitude of increase varies among certain months.

Throughout the majority of the months assessed, hotspot cameras and the ‘fence and hotspot combined’ camera scenarios showed a steep increase in detection probability from 40% to 60% coverage intensities. Fence cameras had a near-zero detection probability (except for April 2023) regardless of coverage percentage (due to minimal feral pig detections occurring at fence cameras in the dataset). During April, the largest difference is seen as the detection probabilities for fence and hotspot cameras combined showed a consistent increase with coverage percentage compared to just fence or hotspot cameras alone. These findings are consistent with the spike in feral pigs detected by fence cameras in April due to the harvesting of the sorghum crop.

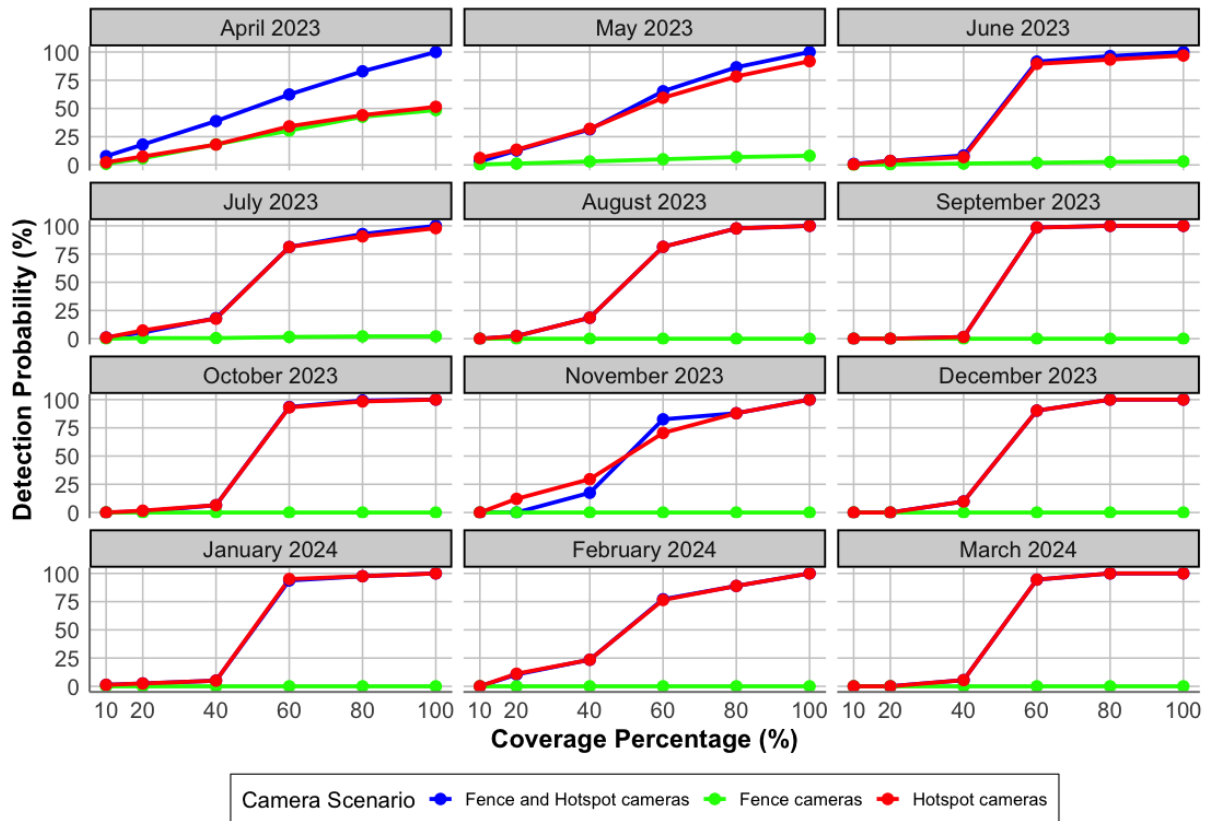


Figure 5.3: Line plots demonstrating the various detection probabilities by fence and hotspot cameras across the different level of coverage intensities with monthly sampling.

5.3.1.3 Comparison of various fence and hotspot cameras scenarios

There was variability in detection probabilities across each of the assessed scenarios and coverage intensities. Detection probabilities were again confirmed to be lowest for fence cameras at low coverage intensities (e.g., fence 10%), with an increase in detection probability as coverage intensity increased. Hotspot cameras had higher detection probabilities compared to fence cameras, particularly at higher coverage intensities (e.g., hotspot 60%, hotspot 80%, hotspot 100%), shown in Table 5.1.

Table 5.1: Comparison of model-derived predicted detection probabilities by camera coverage scenario.

<i>Scenario effect</i>	<i>Log OR</i>	<i>SE</i>	<i>OR</i>	<i>95% CI</i>	<i>Predicted probability (95% CI)</i>
<i>Fence, 10%</i>	-3.87	3.73	0.02	0.000, 804	0.001 (0.000, 0.610)
<i>Fence, 20%</i>	-2.09	1.62	0.12	0.001, 12.3	0.007 (0.000, 0.118)
<i>Fence, 40%</i>	-1.02	1.07	0.36	0.018, 7.36	0.019 (0.003, 0.103)
<i>Fence, 60%</i>	-0.48	0.9	0.62	0.048, 7.85	0.032 (0.008, 0.117)
<i>Fence, 80%</i>	-0.14	0.82	0.87	0.086, 8.90	0.045 (0.014, 0.133)
<i>Fence, 100%</i>	0.00	[Reference]	1.00	[Reference]	0.052 (0.018, 0.141)
<i>Hotspot, 10%</i>	-1.75	1.41	0.17	0.003, 9.36	0.009 (0.001, 0.106)
<i>Hotspot, 20%</i>	-0.01	0.8	0.99	0.104, 9.46	0.051 (0.018, 0.140)
<i>Hotspot, 40%</i>	1.14	0.66	3.14	0.480, 20.50	0.146 (0.079, 0.254)
<i>Hotspot, 60%</i>	4.32	0.64	75.17	12.2, 464	0.803 (0.689, 0.883)
<i>Hotspot, 80%</i>	5.08	0.7	160.73	22.5, 1150	0.897 (0.797, 0.951)
<i>Hotspot, 100%</i>	5.83	0.79	338.81	35.7, 3213	0.948 (0.859, 0.982)

OR: Odds ratio, SE: Standard error of the log odds, 95% CI: 95% confidence interval of the odds ratio.

Detection probabilities for all scenarios shown in Figure 5.4. Hotspot scenarios had higher detection probability than Fence scenarios with the same coverage percentages, and Hotspot scenarios with $\geq 40\%$ coverage had higher predicted probabilities of detection compared to the 100% fence reference category. Predicted probability of detection was $>80\%$ for Hotspot scenarios with as low as 60% coverage.

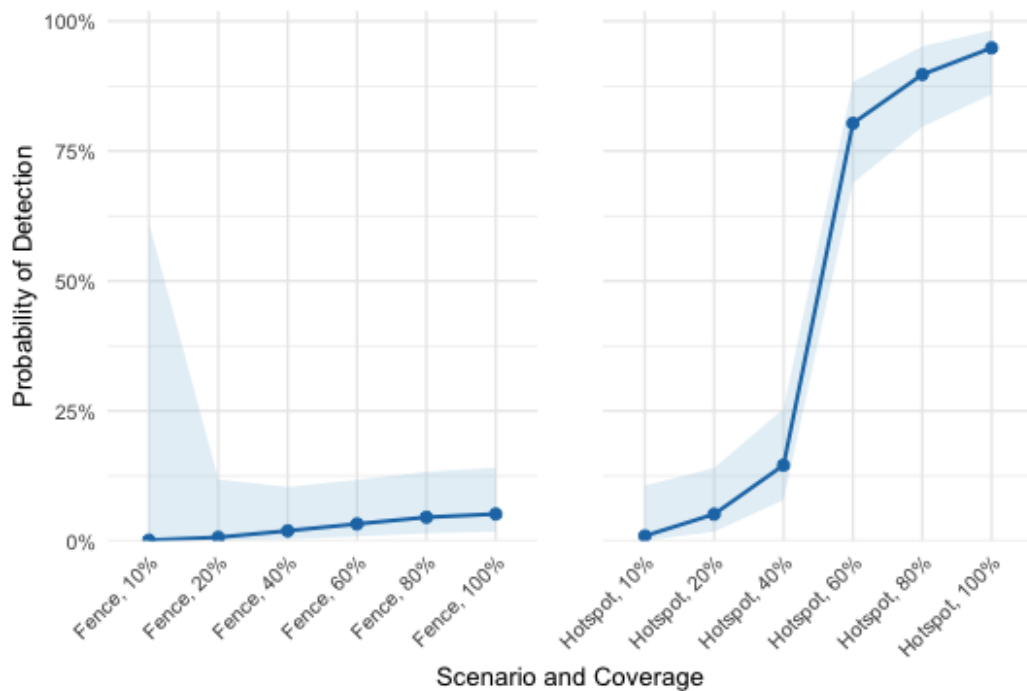


Figure 5.4: The estimated probability of detection with 95% confidence intervals across different scenarios and coverage intensities for fence and hotspot cameras, derived from logistic regression modelling.

5.3.2 Purposive sampling of location-based scenarios

The empirical data allowed further investigation into how specific ecological factors and locations around the piggery may influence where feral pigs were detected. It was found that there is a higher probability of detecting feral pigs around the piggery where there is neighbouring cultivation, watercourses, and bush cover (Figure 5.5). The probability values of each scenario and coverage percentage are provided in Appendix C, Table C3.

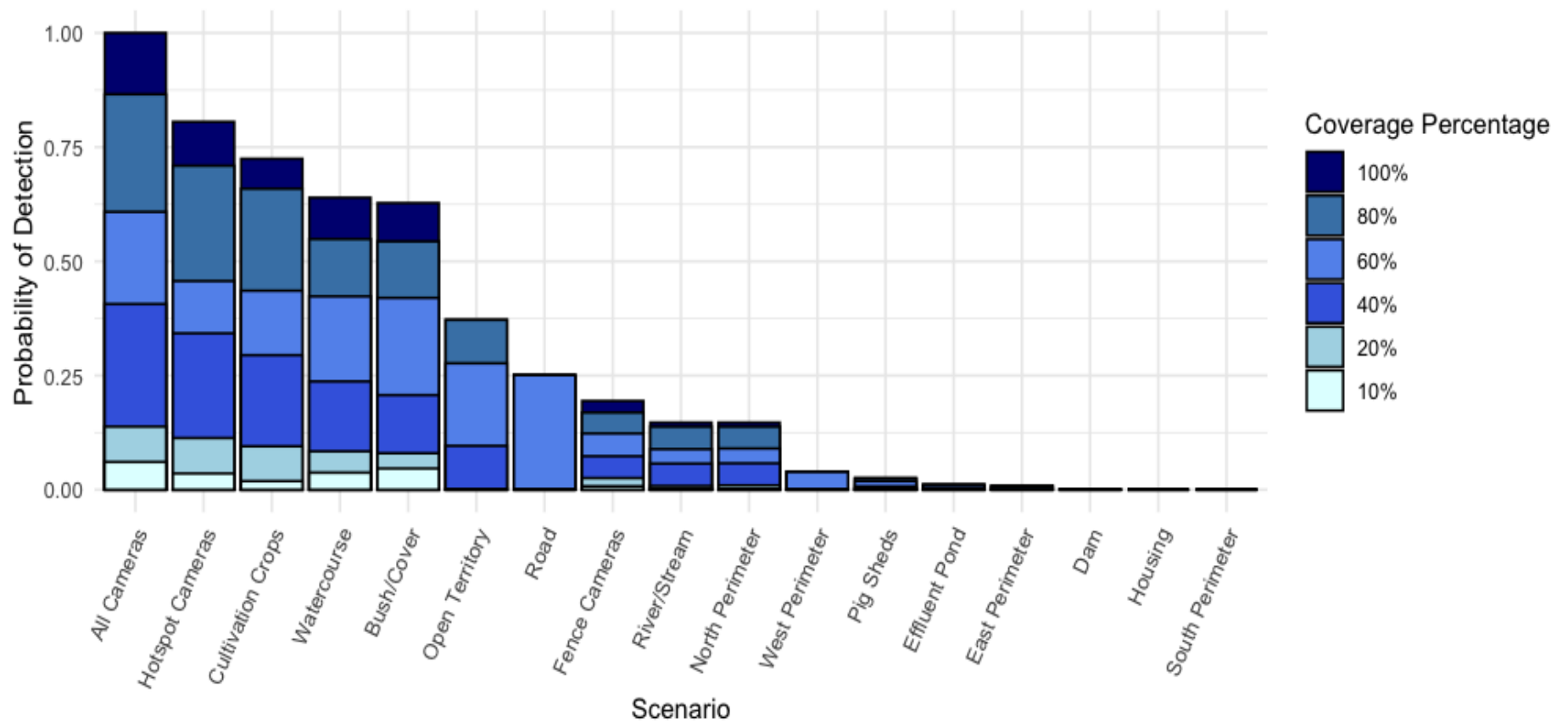


Figure 5.5: Probability of detecting feral pigs with cameras in specific locations around piggery.

5.4 Discussion

This study aimed to evaluate how different camera trap coverage intensities and placements can influence the probability of detecting feral pigs, providing guidance on how to optimise surveillance efficiency for the pork industry in similar landscapes. The results indicate that both the density of camera traps and their placement are key factors in determining feral pig detection probabilities. Optimal configurations were identified where detection rates greatly increased, specifically when cameras were in hotspot areas. These findings confirm logical assumptions that increased cameras also increase detection probabilities, however, also provides evidence-based tangible insights for improving surveillance while maintaining cost-effectiveness to the pork industry.

Several camera surveillance scenarios were tested, including fence cameras which followed a systematic coverage system, and hotspot cameras located in areas presumed to experience feral pigs or had evident sign of feral pig presence. Both scenarios were explored with varying levels of camera intensity. Hotspot camera coverage outperformed the fence systematic coverage in terms of detection probability. Systematic coverage, while providing a more comprehensive overview of what is happening at the property boundary, was less efficient in detecting pigs when activity was concentrated in other areas. These findings indicate that hotspot coverage offers the best trade-off between detection probability and resource efficiency, particularly in high-risk areas. However, the suitability of hotspot versus systematic camera placement is highly dependent on the objective of surveillance. Hotspot-based monitoring is most effective when the primary goal is early detection or confirmation of feral pig presence in high-risk areas, particularly when resources are limited. In contrast, systematic camera placement is better suited to exploratory surveillance where feral pig activity is unknown, as detections in these locations provide new spatial information rather than confirmation of anticipated risk. Accordingly, hotspot coverage should be interpreted as a targeted, risk-based strategy rather than a substitute for broader systematic surveillance, and an adaptive approach such as beginning with systematic placement and transitioning to targeted hotspot monitoring once activity is identified may provide the most informative and resource-efficient framework for producers. Pork producers and farm managers need to be able to identify these hotspot areas and prioritise camera coverage to those locations as part of their biosecurity strategy, particularly when resources are limited.

The research demonstrated a clear relationship between the intensity of camera trap coverage and the probability of detecting feral pigs. Higher densities of camera traps resulted in higher detection probabilities, which has also been found in similar studies using more than one camera in an array^{344,346,352}. It was found that around 60% of hotspot camera coverage, the detection probability increased, and the addition of more cameras contributed slightly to detection. As a result, increasing camera coverage beyond this intensity may not be the most cost-effective approach—acting as a threshold beyond which additional resources yield little added benefit.

The apparent steep increase in detection probability between 40% and 60% coverage in combined fence–hotspot camera scenarios observed in the results may reflect heterogeneity in individual camera contribution rather than additional coverage. During some periods of the study, particularly from June 2023 onwards, detection probability was dominated by a small number of high-yield hotspot cameras, such that camera arrangements including these cameras produced high sensitivity, while excluding them produced markedly lower sensitivity. As coverage increased, the probability of including at least one of these high-activity cameras rose non-linearly, generating an apparent threshold effect. This pattern was not observed during earlier periods (e.g. April–May 2023) when detections were more evenly distributed across cameras, supporting the interpretation that the steep slope reflects camera-level heterogeneity rather than a general property of coverage intensity. Accordingly, the 40–60% threshold should be interpreted cautiously, and future studies should explicitly account for variability in individual camera performance when assessing optimal surveillance configurations.

Additionally, purposive location placement of cameras was found to also be a factor that can influence detection probabilities. Cameras placed adjacent or near resource areas, such as water sources, cultivation, or bush cover, achieved higher detection rates compared to other areas around the piggery. These results suggest that knowledge of preferred habitat features, and animal behaviour plays a vital role in optimising detection probability. These findings align with other studies that showed additional cameras improves detection probability, however the magnitude of these increases in detections are influenced heavily by the species behaviour^{344,353}. For pork producers, this emphasises the need to focus surveillance efforts where pigs are most likely to congregate, which can considerably improve detection efficiency without increasing the overall number of cameras.

Seasonal changes were found to minimally influence detection rates, except for autumn being an outlier. Across the different seasons of the year, feral pig movement towards piggeries can vary due to ecological factors^{317,354,355}. As a result, being aware of these fluctuations and adapting camera coverages accordingly can assist in improving detection probabilities and conserving resources. For the empirical data used, there was a spike in detection during autumn which is reflected by the increase in detection probability within this season as there was a sorghum crop harvested in the area, likely attracting feral pigs to the property. This highlights how cultivation and cropping or harvesting can influence feral pig activity, and by reallocating or moving cameras during this time to detect feral pigs is recommended to ensure they are detected. Even though there were no major variations in detection probability across the remaining seasons, it is beneficial to be aware of the potential seasonal conditions and corresponding environmental changes or impacts can have on feral pig movement, resulting in potential encounters at the piggery. For example, during the summer or dry seasons, pigs tend to congregate around water sources³⁵⁶, which increases the likelihood of detection in these areas. Conversely, during the winter or wet seasons, pigs are more dispersed, making detection and movement predictions more challenging³⁵⁴. These seasonal variations highlight the importance of adapting camera surveillance efforts according to the time of year. The pork industry should, therefore, consider adapting the intensity of surveillance efforts depending on the time of year or cultivation rotations as an important component of an effective biosecurity strategy and efficacy of resources.

The findings of this study provide guidance for producers seeking to implement or enhance feral pig surveillance at their piggeries. Balancing the cost-effectiveness of resources in equipment and labour with the detection efficiency is key for practical surveillance in the pork industry³⁴⁶. The use of camera traps as a means of animal surveillance has been found to have high sensitivity and cost efficiency. For example, a study compared four survey methods (helicopter surveys, thermal imaging camera, ground hunter with dogs, and camera traps) for invasive Bennett's wallabies in South Island, New Zealand, and found camera traps had 82% detection probability (assuming full coverage of a 100-ha area) and was 62% cheaper than using helicopter surveillance³⁴⁸. While increasing the number of cameras, especially from one camera to two cameras or more, can improve detection rates as seen in similar studies^{344,353}, this comes with cost implications. The results of this study indicate that around 60% coverage is sufficient, and additional coverage contributes little to detection outcomes. This reiterates that a more efficient strategy relies on camera placement rather than increasing camera numbers³⁴⁴.

Importantly, each layout and quantity of cameras will be different for individual properties, as a result detection probability objectives should be considered on a per-site and per-species basis in relation to the property size, location, season, and feral pig density. This information provides the pork industry with a clear, cost-effective surveillance strategy that minimise wasting of resources and improves biosecurity approaches. By focusing on optimal camera densities and strategic placement, producers can maximise the probability of detecting feral pigs, which in turn can help prevent potential disease transmission events. These recommendations will be critical for reducing biosecurity risks, particularly in areas where feral pigs pose a threat to livestock. Specifically, pork producers should aim to deploy cameras in high-activity zones, such as near natural resources or during harvesting of crops, while avoiding unnecessary costs by refraining from deploying excessive camera numbers in low-activity areas^{346,353}.

While these findings provide practical guidance for surveillance design, it is important to consider how the random resampling (bootstrapping) approach used to estimate detection probability may influence interpretation of sensitivity and uncertainty. As feral pig activity around piggeries can be spatially clustered, random subsampling can generate camera arrays that are operationally unlikely in practice, particularly those that disproportionately exclude cameras from high-activity areas. Such configurations may have little chance of detecting pigs and therefore contribute to lower estimated detection probabilities for a given number of cameras. Consequently, this approach may underestimate true detection sensitivity and overestimate uncertainty relative to how reduced camera arrays would typically be deployed in practice. In real-world surveillance scenarios, particularly where prior information is limited, reduced camera deployments would more likely be implemented systematically (e.g. evenly spaced perimeter or grid-based layouts). Accordingly, detection probabilities presented here should be interpreted as conservative under clustered activity conditions, and future work could compare random and structured down-sampling strategies to refine point estimates of detection sensitivity.

There are several limitations to this study to be considered. First, the findings are context-specific and may not be applied to other environments or regions where feral pig activity is different. The study also focused primarily on camera traps, without integrating additional technologies such as GPS collars, drones, or thermal imaging, which could potentially improve detection rates. Future studies should explore potentially integrating these technologies to build a more comprehensive surveillance strategy if they are of interest to the pork industry to complement camera traps. Future research should also attempt to expand the scope of

surveillance studies across different habitats, regions, and environmental contexts to improve the external validity of the study. Additionally, further work is required to assess the effectiveness of these methods in detecting feral pigs in more complex or difficult terrains.

5.5 Conclusion

The findings in this chapter reveal considerable variation in detection probabilities between fence and hotspot cameras, emphasising the importance of camera placement in surveillance strategies. For the study site used, cameras at fence locations (around the boundary), exhibited lower detection rates compared to hotspot locations, which often concentrate feral pig activity. These differences underscore the need for tailored surveillance designs to align with specific operational goals, such as biosecurity monitoring or risk assessment for disease spread. These results have practical implications for optimising surveillance efforts in commercial piggeries and other agricultural contexts. By integrating these findings into risk assessment tools, producers can enhance biosecurity measures and mitigate potential threats posed by feral pig incursions.

Appendix C: Chapter 5 supplementary material

Table C 1: Probability of detection based on various camera trap coverage intensities (yearly and seasonally sampling)

Camera coverage	Sampling period probability of detection (mean %)				
All cameras (n=56)	Yearly	Seasonally			
		Summer	Autumn	Winter	Spring
		1.00	1.00	1.00	1.00
		0.81	0.93	0.82	0.96
		0.62	0.86	0.61	0.89
		0.39	0.14	0.39	0.10
		0.20	0.07	0.19	0.04
		0.11	0.01	0.09	0.01
Fence cameras only (n=46)	Yearly	Summer	Autumn	Winter	Spring
		0.19	0.00	0.35	0.03
		0.16	0.00	0.30	0.02
		0.12	0.00	0.22	0.02
		0.08	0.00	0.13	0.01
		0.04	0.00	0.05	0.00
		0.02	0.00	0.01	0.00
		0.02	0.00	0.01	0.00
Hotspot cameras only (n=10)	Yearly	Summer	Autumn	Winter	Spring
		0.81	1.00	0.65	0.97
		0.64	0.93	0.52	0.93
		0.49	0.85	0.40	0.87
		0.33	0.15	0.27	0.10
		0.15	0.07	0.13	0.04
		0.08	0.01	0.06	0.01
		0.08	0.01	0.06	0.01

Table C 2: Probability of detection based on various camera trap coverage intensities (monthly sampling)

Camera coverage	Probability of detection (Monthly)											
All cameras (n=56)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	0.98	0.89	1.00	0.83	0.86	0.96	0.93	0.98	1.00	0.99	0.88	1.00
	0.94	0.77	0.95	0.62	0.65	0.92	0.81	0.81	0.98	0.93	0.83	0.90
	0.05	0.24	0.06	0.39	0.31	0.08	0.18	0.19	0.02	0.07	0.17	0.10
	0.03	0.10	0.00	0.18	0.13	0.04	0.05	0.02	0.00	0.01	0.00	0.00
	0.01	0.00	0.00	0.08	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	0.01	0.00	0.00	0.08	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Fence cameras only (n=46)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
	0.00	0.00	0.00	0.49	0.08	0.03	0.02	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.43	0.07	0.03	0.02	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.30	0.05	0.02	0.02	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.18	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.06	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00

<i>10% coverage</i>	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Hotspot cameras only (n=10)</i>	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
<i>100% coverage</i>	1.00	1.00	1.00	0.51	0.92	0.97	0.98	1.00	1.00	1.00	1.00	1.00
<i>80% coverage</i>	0.98	0.89	1.00	0.44	0.78	0.93	0.91	0.98	1.00	0.98	0.88	1.00
<i>60% coverage</i>	0.95	0.76	0.95	0.34	0.59	0.89	0.81	0.81	0.98	0.93	0.70	0.90
<i>40% coverage</i>	0.05	0.24	0.06	0.18	0.32	0.07	0.18	0.19	0.02	0.07	0.30	0.10
<i>20% coverage</i>	0.03	0.11	0.00	0.07	0.14	0.04	0.07	0.02	0.00	0.02	0.12	0.00
<i>10% coverage</i>	0.01	0.00	0.00	0.02	0.06	0.00	0.01	0.00	0.00	0.00	0.00	0.00

*Order of table in not the sampling order, sampling period begin in April and completed in March

Table C 3: The probability of detection within various locations at the piggery using various levels of coverage intensities

<i>Camera locations</i>	<i>Camera coverage</i>					
	100%	80%	60%	40%	20%	10%
<i>All cameras</i>	1.00	0.87	0.61	0.40	0.15	0.06
<i>Hotspot locations</i>	0.81	0.69	0.47	0.35	0.09	0.04
<i>Cultivation crops</i>	0.73	0.66	0.44	0.29	0.10	0.02
<i>Watercourse</i>	0.64	0.55	0.42	0.24	0.08	0.04
<i>Bush/scrub cover</i>	0.63	0.54	0.42	0.27	0.08	0.05
<i>Open territory</i>	0.37	0.37	0.28	0.10	0.00	0.00
<i>Road</i>	0.25	0.25	0.25	0.00	0.00	0.00
<i>Fence cameras</i>	0.19	0.17	0.12	0.07	0.03	0.01
<i>River/stream</i>	0.15	0.14	0.09	0.06	0.01	0.00
<i>North perimeter of fence</i>	0.15	0.14	0.09	0.06	0.01	0.00
<i>West perimeter of fence</i>	0.04	0.04	0.04	0.00	0.00	0.00
<i>Pig sheds</i>	0.03	0.02	0.02	0.01	0.00	0.00
<i>Effluent pond</i>	0.01	0.01	0.01	0.00	0.00	0.00
<i>East perimeter fence</i>	0.01	0.01	0.01	0.00	0.00	0.00
<i>Dam</i>	0.00	0.00	0.00	0.00	0.00	0.00
<i>Housing</i>	0.00	0.00	0.00	0.00	0.00	0.00
<i>South perimeter fence</i>	0.00	0.00	0.00	0.00	0.00	0.00

6 Quantitative risk assessment tool to determine the probability of feral pig encounters at piggeries

6.1 Introduction

Disease transmission between wild and domestic animals is an increasing concern, particularly regarding wild pigs and the pathogens they may carry. Feral pigs (the Eurasian wild boar, *Sus scrofa*) are natural reservoirs of many harmful pathogens that can spread to other animals or humans, such as African swine fever (ASF), foot and mouth disease (FMD), hepatitis E and Japanese encephalitis (JE) ^{34,126,133,339,357}. In Australia, like many countries, wild populations of *Sus scrofa* are abundant. They are an invasive pest due to being non-native animals that have a negative impact on both environmental and agricultural resources ^{137,229,358}. Feral pigs are omnivores which allows them to thrive in various habitats. Their distribution and density is difficult to measure accurately because it fluctuates depending on seasonal conditions, the surrounding landscape, and motivations to migrate, in addition to their high reproductive frequency ^{148,307,359}. This creates difficulty in monitoring their movements can be a disease transmission risk to domestic pig populations.

Disease spillover from feral to domestic pigs has previously been reported ^{360,361}. However, a recent review found that for ASF specifically, there is limited evidence demonstrating that transmission between feral and domestic pigs contributes to ASFV spread via direct contact unless domestic pigs are managed in free-ranging farming systems. In this situation indirect transmission could be more common between the two populations ³². Although, the role of wild pigs in disease transmission might be underestimated and underreported ^{28,152,306}. Documented spillover risks are unlikely to be generalisable between countries/continents (i.e., estimates for Europe might not be valid for Australia) due to differences in population densities, population distributions, farming methods, biosecurity regulations and translocation capability. Hence, with the paucity of reports and limited quantitative data available to guide decision making it is difficult to prepare for potential disease outbreaks that might arise from spillover. Further location specific studies are needed to address this research gap.

Feral pigs occupy up to 45% of the land mass of Australia and, in 2023, were estimated to be the cause of more than AUD 100 million direct costs to the agricultural sector each year ^{138,242}. There are approximately 4,300 registered pig production sites in Australia which were estimated to have contributed AUD 5.3 billion to the national economy in 2022 ^{35,362}. The potential

interactions between wild and domestic pigs are a concern due to the risks posed by feral pigs and their ability to be hosts of many endemic and exotic diseases ²⁶. While Australia is currently free of most of these diseases the pork industry and pig producers must be as best prepared as possible to reduce the impact of potential outbreaks. An Australian study that investigated the movement of feral pigs by fitting them with Global Positioning System (GPS) collars found that feral pigs regularly came within 5 km of commercial piggeries, with one pig frequently visiting within 500m ³⁴. These findings demonstrate that feral pig interactions with commercial piggeries is possible and consequently pose a disease transmission risk, particularly for piggeries located in habitats preferred by feral pigs. As a result, effective biosecurity is of paramount importance and to assist in delivery of effective biosecurity it is necessary to know at what times of the year, time of day, and at what locations around a commercial piggery where direct or indirect contact between feral and domestic pigs might be likely to occur ³⁶³.

Estimating the likelihood of feral pigs approaching a commercial piggery boundary is one of the first tasks in assessing the risk of disease transmission between feral and domestic pigs in this scenario. From there, the probability of feral pigs crossing or breaching a fence line should also be considered ¹⁶⁴. Feral pigs have shown an interest and re-visitation to properties that are used for agricultural farming (e.g., corn, sorghum, and wheat) that provide them with food as well as protective cover ^{104,160}. Commercial piggeries that are located nearby these crops are likely to be at an increased risk of feral pig incursions. There are several factors that can contribute to the likelihood of feral pigs approaching properties, such as the density of feral pigs in the area, habitat and vegetation composition, proximity to a water sources, the type of production system, the presence of sows in oestrus and the level of biosecurity ^{126,162,305,339,364,365}. Thus, commercial piggery managers need to conduct ongoing surveillance to detect feral pig presence and to enhance their biosecurity measures accordingly.

Surveillance is defined by the World Organisation for Animal Health (WOAH) as the systematic ongoing collection, collation and analysis of information and the timely dissemination of that information to those who need to know so that appropriate action can be taken ³⁶⁶. Feral pig surveillance can be indirect – for example, noticing physical signs (evidence of footprints, tracks, or wallowing) of feral pigs within an area and reporting it – or direct, by using animal monitoring or tracking devices such as Global Positioning System (GPS) collars or camera traps ^{336,366}. Feral pigs are an intelligent and resourceful species by nature, and are crepuscular being most active during dusk or night ^{317,367,368}. Thus, detecting their presence

around commercial piggeries requires use of appropriate surveillance techniques, such as camera traps.

A risk assessment is a constituent part of the risk analysis process, which additionally includes of hazard identification, risk management and risk communication ^{369,370}. A risk assessment is associated with the systematic compilation of data related to an unwanted event (i.e., ASF incursion or feral pig encounters), providing an objective basis for risk management decisions ³⁷¹. As a result, they are useful decision-support tools to aid in mitigating complex issues, such as the selection and application of the most efficient control measures during an animal disease outbreak ³⁷¹. For example, risk assessments have been developed to quantify the risk of ASF introduction into countries, assess cross-border spread of ASF in South-East Asia, and also to inform compartmentalisation of domestic and feral pigs in ASF preparedness in Australia ^{164,372,373}. As a result, it is an appropriate tool to help assess the probability of a feral pig encounters at commercial piggeries to help mitigate the likelihood of contact rates that may lead to disease transmission events.

The objective of this study was to develop a quantitative risk assessment tool to determine the probability of feral pig encounters occurring at the boundary of commercial piggeries in Queensland (QLD), Australia. The intention is for pork producers to use such a tool to assess their farm's likelihood of experiencing a feral pig encounter, informing how they deploy biosecurity and control measures (e.g., improved fencing) to mitigate identified risks.

6.2 *Materials and methods*

In this study, the external population included piggeries across Australia, representing the broader industry for which the findings may have relevance³⁷⁴. These facilities vary in size, management practices, and biosecurity measures, reflecting the diversity of pig production systems. Within this population, 27% of Australia's registered pork production sites are in Queensland³⁷⁵. Hence, the target population for this study consisted of piggeries in Queensland specifically, where the study aimed to generate externally valid inferences³⁷⁶. The sampled population was restricted to piggeries in Southeast Queensland, where empirical data were utilised to compare results with. Finally, the study population contained the specific piggery in the region that participated in the research, forming the basis for internally valid inferences.

A quantitative risk assessment was developed using a scenario tree framework³⁷⁷. The overall outcome of the risk assessment was an estimate of the daily probability of a feral pig encounter occurring at a piggery in Queensland in the different seasons of the year (i.e. the occurrence of at least one feral pig encounter at a piggery during any day within autumn). This assessment is intended to remain valid for the next 5-10 years in Australia, at which point reassessment may be necessary. This study built on a previous qualitative risk assessment tool developed in an honours thesis by Barrett et al (2021)¹⁶⁴. This work used a similar scenario tree pathway and parameterisation approach, described in the section below.

The study involved three stages:

1. Development of a scenario tree for feral pig encounters at domestic piggeries.
2. Parameterisation of the scenario tree using available literature and expert elicitation.
3. A case study to demonstrate implementation of the quantitative risk assessment.

Expert elicitation was critical to parameterising the scenario tree for nodes for which empirical data were unavailable. A structured elicitation process was followed to ensure consistency and reliability in expert responses, using established techniques to minimise bias and enhance the accuracy of the estimates^{378–380}. The expert elicitation process was conducted with the approval of the Human Ethics Committee of the University of Melbourne (review reference number: 2023-26796-40025-3). Further definitions of specific terminology used throughout this study can be found in Table D1 of Appendix D.

6.2.1 Development of a scenario tree for feral pig encounters at piggery

The pathway by which a feral pig might contact domestic pigs is shown in the scenario tree in Figure 6.1. The probability of an encounter between domestic and feral pigs was dependent on the location of the farm, feral pig abundance, and the likelihood of feral pig movement around the farm. The influence of seasonal conditions, and effectiveness of feral pig reduction through several control measures were also considered. The steps of the assessment process are shown in further detail in Table D2 of Appendix D.

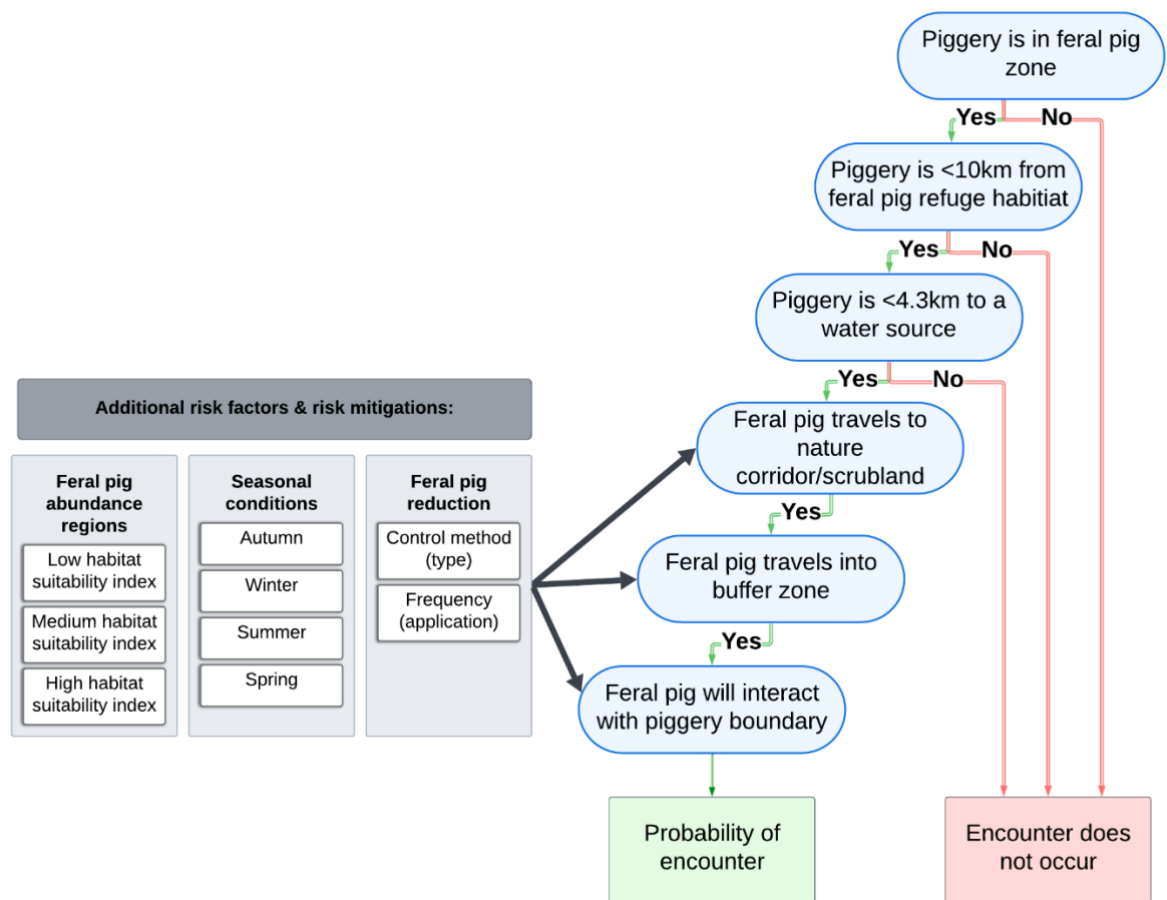


Figure 6.1: Risk pathway to experience a feral pig encounter at piggery (figure created using LucidChart^{®381}).

6.2.2 Parameterisation of the scenario tree using available literature and expert elicitation

The nodes were parameterised using a process involving the following steps:

1. Description and justification of the node outcomes using peer-reviewed literature.
2. Assignment of outcome or probabilities to the nodes using expert elicitation.
3. Assessment of additional risk factors and mitigation strategies that influence feral pig encounters.
4. Multiplication of the probabilities assigned to each node to produce a summary the likelihood risk estimates.

6.2.2.1 Description and justification of nodes

For this risk assessment, a literature review was conducted to justify the guidelines used in each node. The background research and justification for these nodes was provided in Appendix D, Table D3.

i) Node 1: Piggery is in a feral pig zone

The distribution of feral pigs and domestic pig herds across Australia is shown in Figure 6.2^{167,382}. Piggeries were defined as being in a feral pig zone if they were in areas of feral pig occurrence.

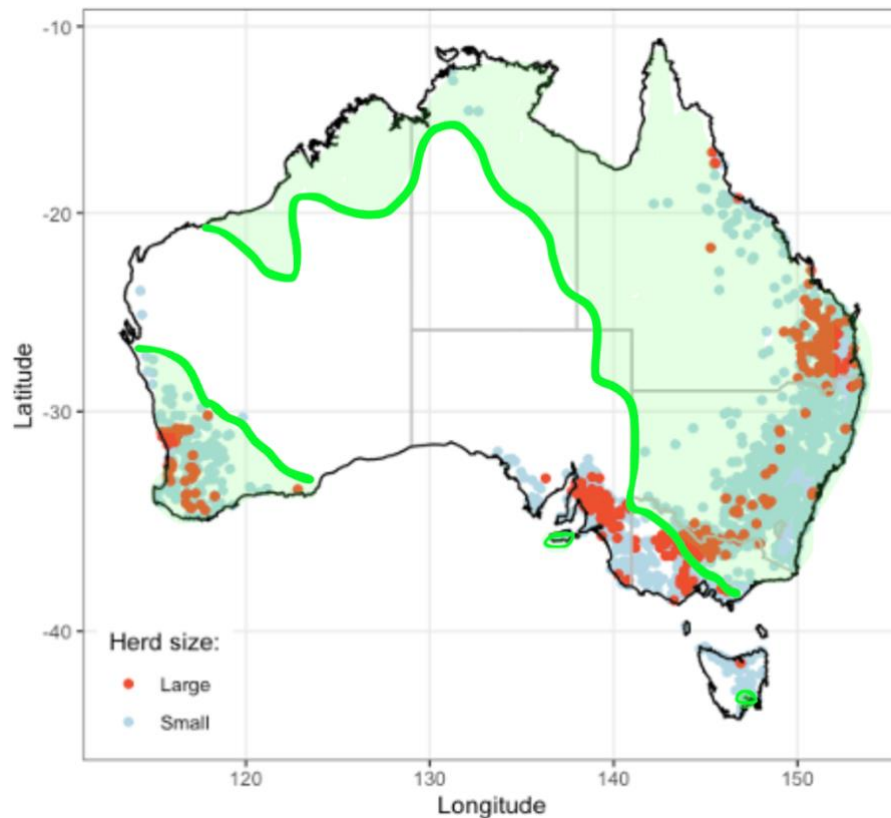


Figure 6.2: Feral pig zone identified by the feral pig density map ³⁸²(shaded in green) overlaid on the distribution of large-scale and small-scale pig herds around Australia based off the 2014 Census data produced in Australian Animal Disease Spread model (AADIS) curated for the FMD simulation in Australia ¹⁶⁷.

ii) Node 2: Piggery proximity to feral pig refuge habitat

If a piggery was located within 10 km of a refuge habitat (using the conservative estimate), the 'Yes' node was chosen and the risk pathway continued.

iii) Node 3: Piggery proximity to a water source

If a piggery was within 4.3 km from a watercourse in addition to being within 10 km of refuge habitats were deemed to be high risk of feral pig encounters. A water source was defined as any form of available water, including watercourses (rivers, creeks, streams) and waterbodies (lakes, dams, ponds).

iv) Node 4: Feral pig movement from refuge habitat into nature corridors/scrubland

For this node, feral pig abundance, and the type and intensity of control methods conducted within the area of interest are expected to influence the probability of feral pig movement from

their refuge habitat. Experts were asked questions to estimate the probability of a feral pig encounter based on these circumstances. In the risk assessment, considerations included: the location of the farm regarding the estimated feral pig abundance based on the HSI region, seasonal conditions, and the feral pig reduction type and frequency of methods being conducted (if any).

v) Node 5: Feral pig movement from nature corridor/scrubland into buffer zone of the piggery

For this node, experts were asked to provide probability estimates for feral pig movement, considering the context of the risk assessment such as the location of the farm regarding the estimated feral pig abundance based on the HSI region, the seasonal condition, and the feral pig reduction (if any) type and frequency.

vi) Node 6: Feral pig movement from buffer zone to the piggery boundary fence

This node was answered by experts the same as node 5, considering the different movement motivations associated within the corresponding areas.

6.2.2.2 Additional risk factors and mitigation strategies

i) Habitat suitability and seasonal conditions

Feral pig habitat suitability was highest in the north and eastern regions of the country, as shown Figure 6.3³⁸³ and used to categorise the feral pig HSI regions for this study (described in Table 6.2). It was expected that feral pig abundance levels can fluctuate during throughout the year due to availability of resources. For this reason, experts were asked to provide seasonal probability estimates relating to feral pig movement (nodes 4-6).

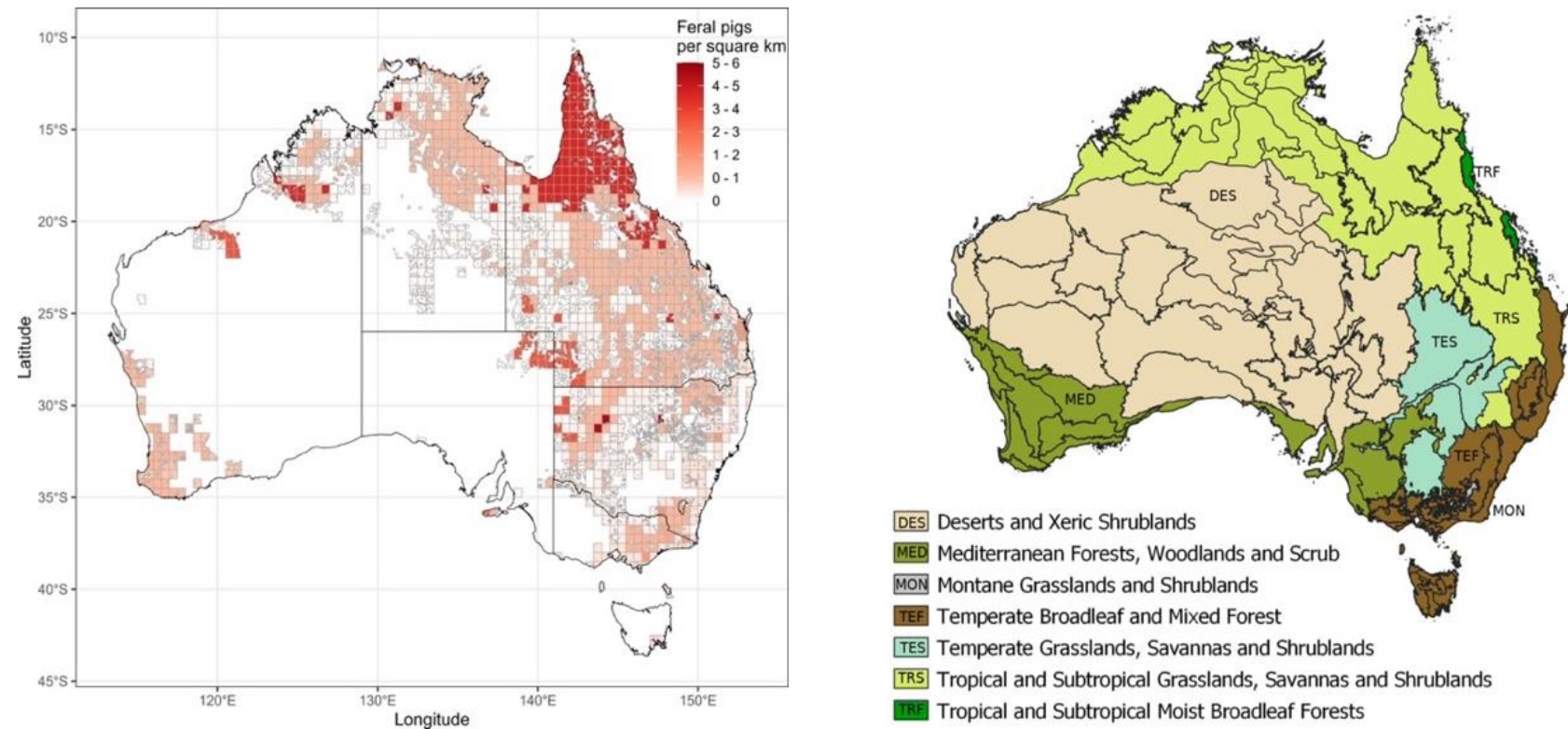


Figure 6.3: Left plot - Distribution of feral pigs across Australia curated in 2020³⁸², and Right plot – Ecoregions in Australia³⁸³.

Table 6.1: Habitat suitability index categories and corresponding ecoregions in Queensland, combined with the estimated feral pigs abundance across Australia curated in 2020³⁸² shown in Figure 6.2.

<i>HSI region categories</i>	<i>Estimated pig abundance</i>	<i>Ecoregion</i>
<i>High</i>	4-6 pigs/km ²	TRS: Tropical and subtropical grasslands, savannas and shrublands (Far north QLD). TRF: Tropical and Subtropical Moist Broadleaf forests (Far Northeast QLD).
<i>Medium</i>	2-3 pigs/km ²	TRS: Tropical and subtropical grasslands, savannas and shrublands (Inner to Southeast QLD). TEF: Temperate Broadleaf and Mixed Forest (South-east QLD). TES: Temperate Grasslands, Savannas and Scrublands (South QLD).
<i>Low</i>	0-1 pigs/km ²	TRS: Tropical and subtropical grasslands, savannas and shrublands (Inner to Southeast QLD). DES: Deserts and Xeric shrublands (West QLD).

ii) Feral pig control for population reduction

For risk mitigations, four commonly used control methods were assessed: (1) trapping; (2) ground shooting; (3) aerial shooting; and (4) and poison baiting. Each were allocated different application frequencies: daily, weekly, monthly, seasonally, or yearly. Experts took these factors into consideration when completing the elicitation and provided estimates for each node. The effectiveness of feral pig control effort was assumed that each method was applied to achieve the highest reduction percentage possible, given sufficient resources. For example, if yearly aerial shooting was used, it was assumed that this was done once per year but when it was used efforts were made to achieve the desired knockdown percentage, even if it meant that shooting had to be carried out over 3 to 4 days. Similarly, if trapping was used, it was assumed that enough traps were set to cover the entire farm perimeter, not just one trap (for example) per farm.

6.2.2.3 Assignment of outcome or probabilities to the nodes using expert elicitation

The expert elicitation followed the structure and steps of the 'IDEA' protocol for quantifying uncertainty with experts, representing the key steps of 'Investigate', 'Discuss', 'Estimate', and 'Aggregate'³⁷⁸. The IDEA method mixes elements of behavioural and mathematical aggregation protocols, which makes it a mixed method in the family of the Delphi protocols^{379,380}.

The elicitation involved five feral pig experts who had a minimum of five years' experience in Australian feral pig ecology in Queensland and/or a postgraduate qualification in a relevant field and currently working in the related topic. Experts were sourced based on

recommendations from industry partners (Australian Pork Limited and SunPork) and recruited via email. The questionnaire was provided to the experts in advance (example of questions shown in Questionnaire 1 of Appendix D).

The elicitation was initiated by teleconference between the primary researcher and each expert individually. During the teleconference, each of the questions were reviewed with responses to each provided immediately or completed later. The questions were split into two sections: (1) location; and (2) control measures. Experts were asked to provide probability estimates of their best estimate (median), lower bound (5% percentile), and upper bound (95% percentile) values to each of the questions asked. This approach is used to represent the experts' subjective distributions associated with the elicited probabilities^{380,384}.

Once all initial responses were collected, the experts were notified and given a summary of anonymised results. A discussion between the experts was held by teleconference; however, this was to share opinions of ideas and to ensure interpretation of the questions were consistent across the group. The purpose of this discussion was to share and elaborate on opinions within each node, and (unlike a behavioural aggregation) consensus between experts was not sought. After this discussion, experts were provided with the opportunity to revise their initial probability estimates.

Once the experts returned their final estimates, beta distributions were fitted on their best estimates and upper and lower bounds. Each question/expert combination resulted in a fitted beta distribution. These distributions were mathematically aggregated using an equally-weighted linear combination of distributions³⁸⁴. This was achieved using the `riskDistributions` package (version 2.1.2)³⁸⁵ in R³⁵¹ to fit (using the `'get.beta.par()'` function) and then sample (using the `'rbeta.par()'` function to draw 1000 samples for each expert). These (empirical) distributions were averaged element-wise across the experts—meaning the first sample from each expert was averaged together, then the second sample, and so on—resulting in a single aggregated empirical distribution that equally reflects all expert inputs. From the empirical aggregated distributions, the 5th percentile (lower bound), 50th percentile (median), and 95th percentile (upper bound) were extracted and used to summarise the best estimate and the uncertainty around that represent the group/combined expert judgments. This method allowed accounting for individual uncertainty while providing an overall probability distribution for each combination of factors.

6.2.2.4 *Multiplication of the probabilities assigned to each node to return a summary risk estimate*

To provide a summary estimate of feral pig encounter risk the probability estimates for nodes 4 to 6 were multiplied:

$$\begin{aligned} & \textit{Probability of encounter} \\ &= \textit{Node 4} \times \textit{Node 5} \\ &\times ((\textit{Node 6}(1 - (\textit{control a})(\textit{control b})(\textit{control c})(\textit{control d})))) \end{aligned}$$

6.2.3 *Case study to demonstrate implementation of the risk assessment at the farm level*

The feasibility and plausibility of our risk assessment methodology was assessed by applying it to a piggery where feral pig encounters were known to have occurred and the frequency of encounters enumerated. This demonstrated the tool's ability to estimate the likelihood of a feral pig encounter using a real-life scenario. Results from the camera trap analyses in Chapter 3 found that feral pigs were present in the buffer zone around the piggery boundaries throughout the year. However, the number of feral pig encounters varied dependent on season with the highest frequency occurring in the autumn (Figure 4.6). For the case study scenario described below, the winter detections were converted from our empirical data into a percentage by determining the median and dividing it by the total camera trap nights (median detections / total camera trap nights). This probability represented the daily probability throughout winter after controls measures had been applied within the real-life scenario and used to compare against the risk assessments outputs (Section 6.3.2).

6.2.3.1 *Case study scenario*

The farm manager of a piggery in southeast Queensland surrounded by woodlands and close to a river, wanted to assess the likelihood of a feral pig encounter in the upcoming winter season (June-August) to plan for adequate control. The farm manager conducts feral pig control once a year (annually) using a combination of ground shooting, poison baiting and trapping to reduce the population by 70% knock-down.

6.3 Results

6.3.1 Parameterisation of the scenario tree using available literature and expert elicitation

The quantitative estimates given by the experts for the nodes estimate the probability of movement of an individual feral pig per season, shown in Figure 6.4. These results are provided in the sections below, and the specific values for each node can be found in the Appendix D Table D3.

6.3.2 Summary of nodes informed by expert elicitation

Overall, the probability of an individual feral pig movement per season varied across the refuge habitat, nature corridor/scrubland and buffer zone, and were influenced by the different habitat suitability regions (Figure 6.4). Across most nodes, the dry and winter seasons exhibited the higher probabilities of movement, particularly in high HSI regions.

6.3.2.1 NODE 4 - Feral pig will move from a refuge habitat to a nearby nature corridor or scrubland:

In the refuge habitats, the probability of movement towards a nature corridor/scrubland was mostly constant across all seasons, although the highest probabilities were found in winter (0.75, 90% CI: 0.26, 0.92) and the dry season (0.80, 90% CI: 0.16, 0.93) in high HSI regions. Movement was less likely in the wet and summer seasons, particularly in low HSI regions.

6.3.2.2 NODE 5 - Feral pig will move from the scrubland/nature corridors into the buffer zone:

Movement from nature corridors/scrublands into a nearby buffer zone varied across seasons and HSI regions. Winter had the highest movement probabilities in medium HSI regions (0.69, 90% CI: 0.13, 0.92), followed by low (0.65, 90% CI: 0.08, 0.92) and high HSI regions (0.60, 90% CI: 0.16, 0.93). Whereas, probability decreases in spring and summer, especially in low HSI regions (0.39, 90% CI: 0.06, 0.92 and 0.32, 90% CI: 0.06, 0.92 respectively).

6.3.2.3 *NODE 6 - Feral pig in the buffer zone will approach the boundary fence of a nearby commercial piggery:*

Feral pig movement in the buffer zone towards the piggery boundary had the highest probabilities, with consistently high values across all HSI regions and seasons. The dry season exhibited the highest probability (0.80, 90% CI: 0.13, 0.99) in the high HSI region, followed closely by all other seasons and HSI regions indicating overall consistent yearly likelihood of feral pig movement towards the piggery boundary once within the buffer zone.

6.3.2.4 *RISK MITIGATION - Percentage of feral pig activity reduction that can be achieved by conducting control measures*

Control within the nature corridor/scrubland and buffer zone of the piggery had similar probabilities of reducing feral pig activity across all HSI regions (Figure 6.5). For all the control methods the percentage reduction achieved was greater when controls were applied frequently (i.e., daily, weekly or monthly compared to seasonally and yearly) and only slightly higher in regions of lower feral pig density (i.e., low HSI compared to medium and high HSI), shown in Figure 6.6.

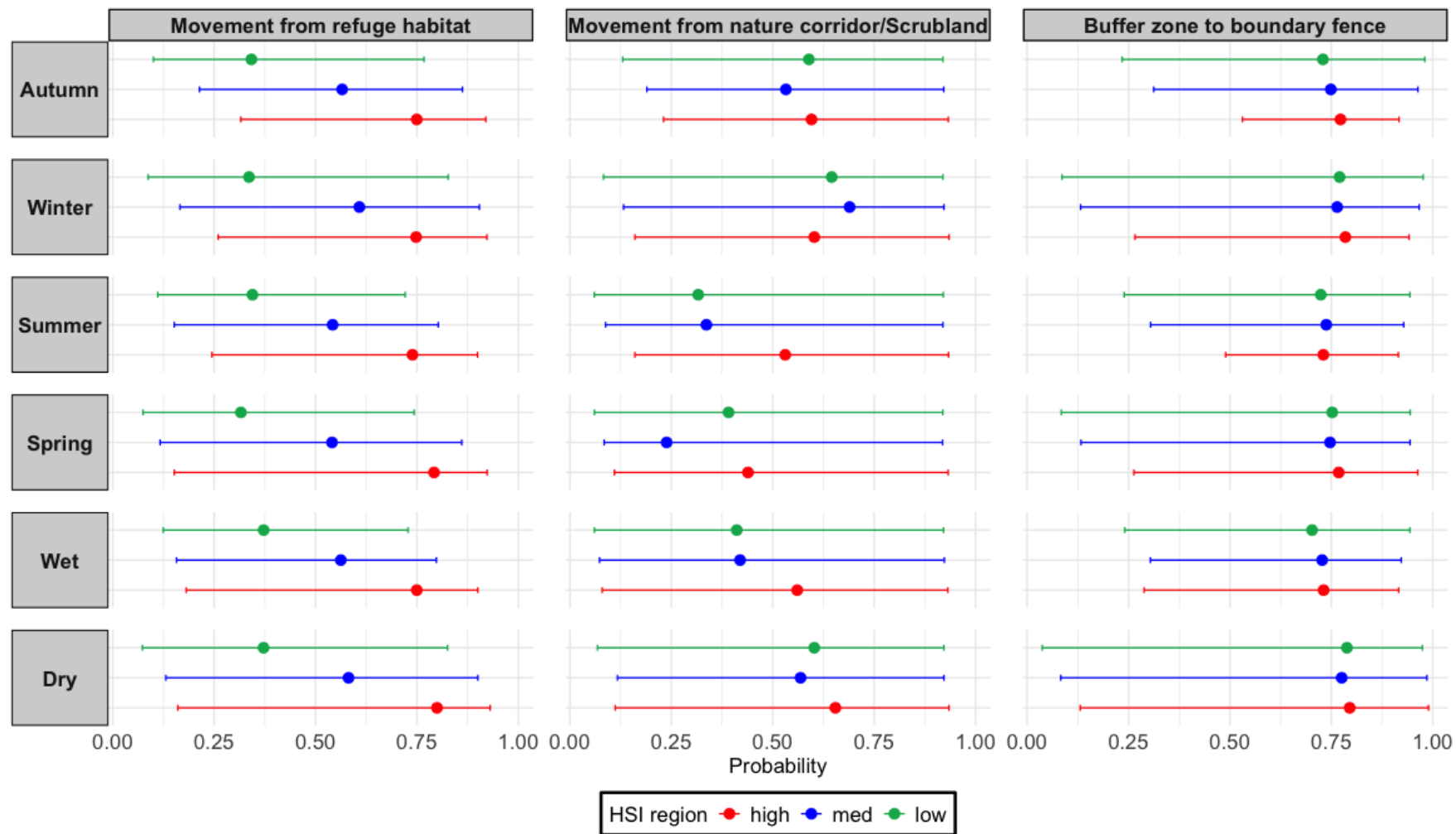


Figure 6.4: Error bar plot showing the averaged beta distribution parameters to produce the 5th percentile (lower bound), the median (50th percentile), and the 95th percentile (upper bound) to be used in the risk assessment.

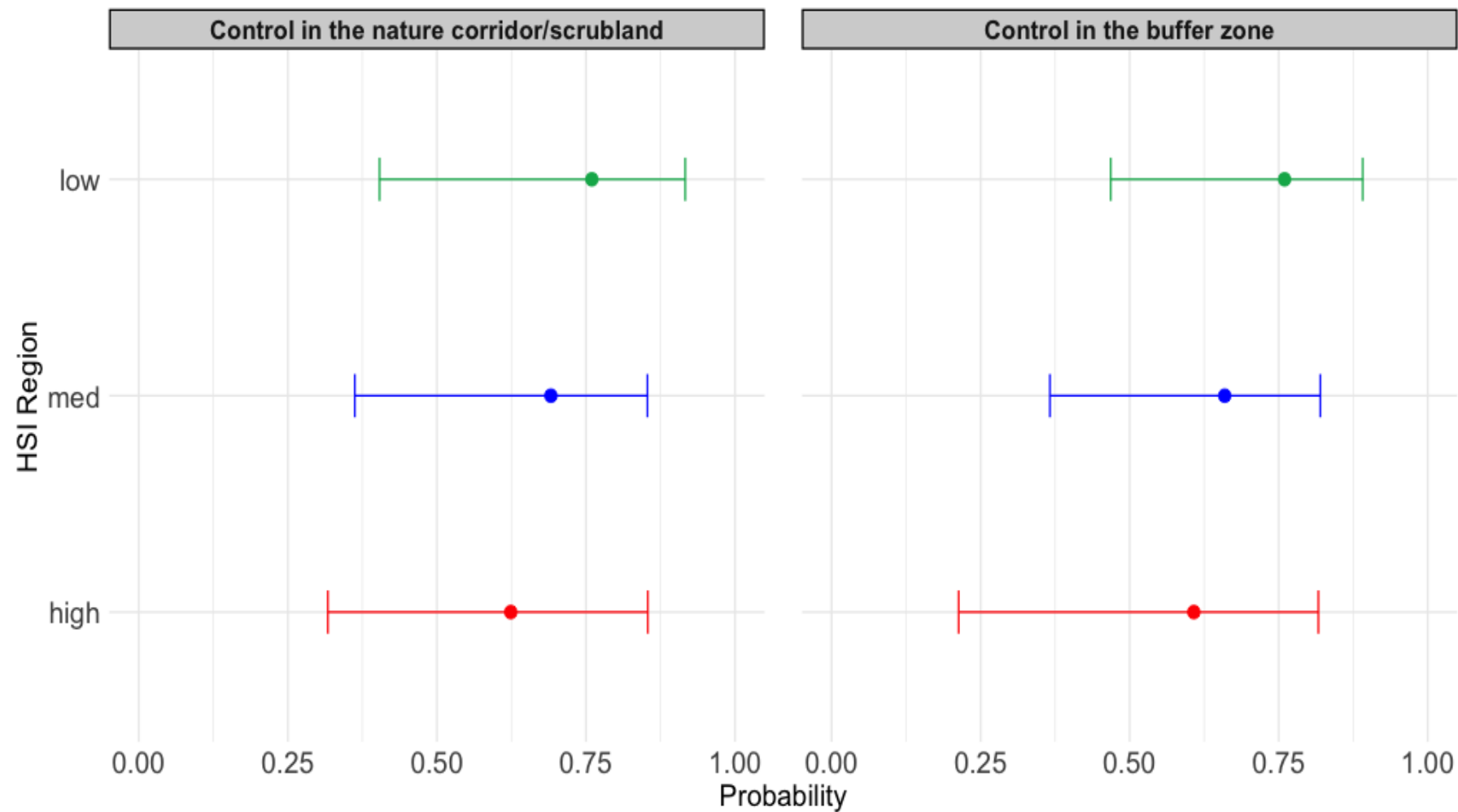


Figure 6.5: Probability of feral pig reduction by conducting general control around the piggery: showing the 5th percentile (lower bound), the median (50th percentile), and the 95th percentile (upper bound) parameterised by the expert elicitation.

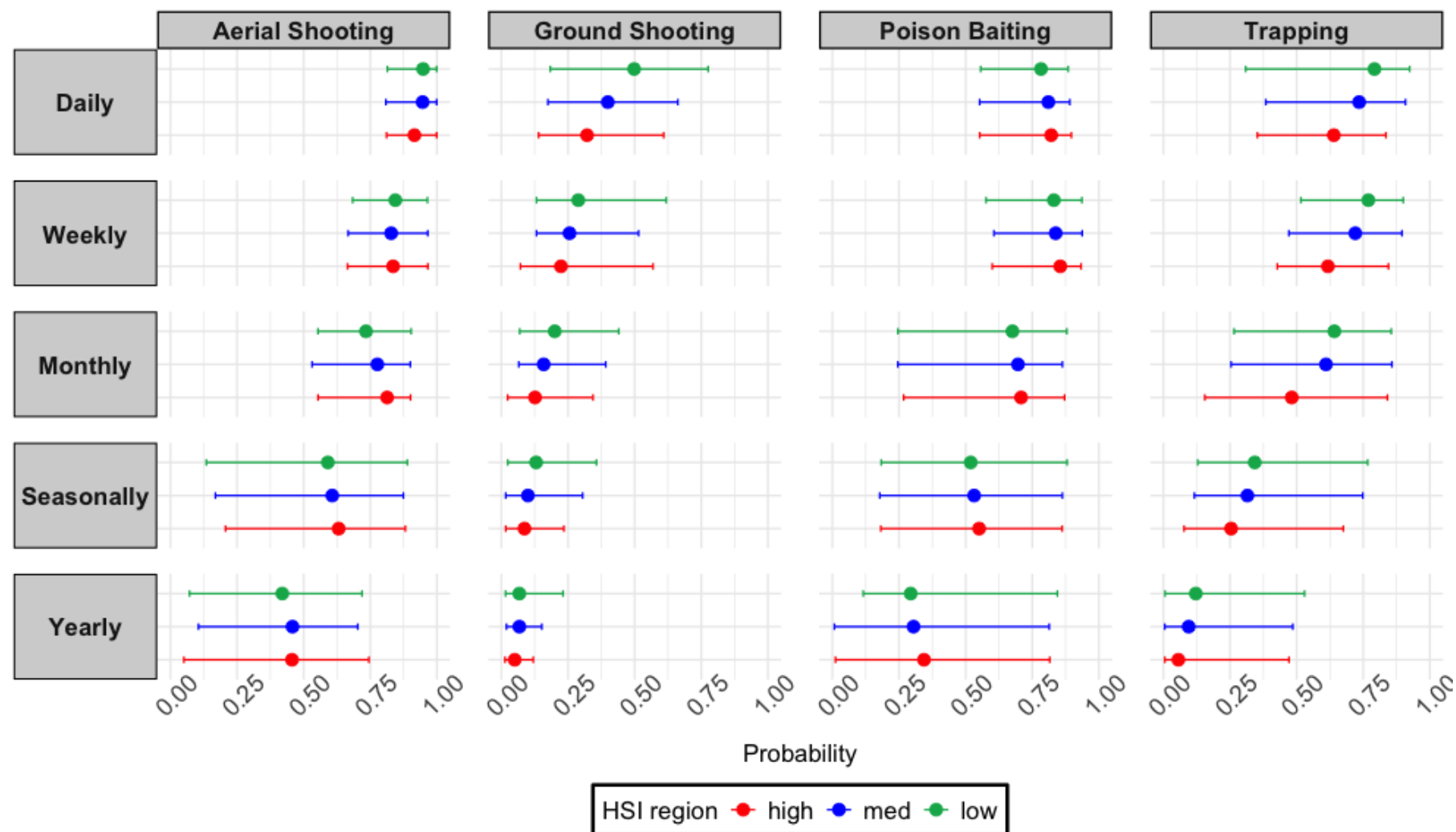


Figure 6.6: Probability of feral pig reduction by conducting specific control methods at various frequencies: showing the 5th percentile (lower bound), the median (50th percentile), and the 95th percentile (upper bound) parameterised by the expert elicitation.

6.3.3 Case study to demonstrate the implementation of the risk assessment

The values used for each node of the risk pathway for the case study scenario are shown in Table D4 in Appendix D. For this scenario, the median daily probability of a feral pig encounter throughout winter was assessed with and without the application of controls. The piggery was in a region where feral pigs are endemic, within 10 km of a feral refuge habitat, and < 5 km to a water source. The median probability that a feral pig will travel from their refuge into the nearby nature corridor or scrubland was estimated to be 0.61 (90% CI 0.17, 0.90) and then to travel from the nature corridor or scrubland into the buffer zone of the piggery was 0.69 (90% CI 0.13, 0.92). It was then estimated that the median probability that a feral pig within the buffer zone will approach the piggery was estimated to be 0.76 (90% CI 0.13, 0.97). As a result, the most likely (median) probability that a feral pig will interact with the piggery during the winter was $(0.61 \times 0.69 \times 0.76)$ 0.32 if no controls were implemented.

When including the influence of specific controls to reduce the feral pig population, it was estimated in the buffer zone on a yearly basis. Trapping and ground shooting had a median probability of reduction by 0.10 (90% CI 0.01, 0.49) and 0.7 (90% CI 0.02, 0.15) respectively. Whereas poison baiting reduced it by 0.30 (90% CI 0.01, 0.81). Overall, the most likely probability that a feral pig will interact with the piggery during the winter when these control measures were applied once a year was $0.13 (0.61 \times 0.69 \times ((0.76(1-(1-0.1) \times (1-0.07) \times (1-0.30)))))$.

The calculations for these estimates are included in Appendix D in Table D5, which includes further scenarios that were investigated using the lower bounds and upper bounds of the probability estimates for each node, as well as values to represent worst- and best-case scenarios.

6.3.3.1 Case study comparison to empirical data

The encounters from Chapter 4 (Table 4.1) were compared to the case study scenario results to validate the risk assessment tool and assess its ability to estimate encounter probabilities under real-life conditions. The median number of encounters per day in winter was calculated from crude detection counts, resulting in 1 detection per day.

This was converted into a percentage by dividing the median number of detections by the total number of camera trap nights. The total number of camera trap nights was determined by multiplying the number of days in the winter study period by the number of cameras: $92 \text{ days} \times 56 \text{ cameras} = 5,152 \text{ camera trap nights}$.

The median probability of a feral pig interacting with the piggery during winter was then calculated as:

$$\text{Median probability} = \left(\frac{1 \text{ detection}}{5,152 \text{ camera trap nights}} \right) * 100 = 0.0194\% \approx 0.02\%$$

This value represents the estimated daily likelihood of at least one feral pig detection per camera trap night in winter was 0.02, based on the empirical data median encounter rate.

This probability from the case study was lower than the risk assessments 'most likely' outcome of 0.13 if control measures were applied, and below the outcome of 0.32 if no controls were applied.

6.4 Discussion

By quantifying the probability of feral pig movement towards the boundaries of commercial piggeries in Australia, this study identified an increased risk of feral pig encounters for piggeries during winter (June-August) and the dry season (May-October) in Queensland, particularly those in higher HSI regions where feral pigs are estimated to be in higher abundance. During dry climate cycles in Queensland the least amount of rainfall occurs³⁸⁶, indicating feral pig movement is likely to increase when the environment is dry and this is when control measures should be prioritised. These findings are consistent with other studies that have investigated feral pig abundance and behaviour during different times of the year^{145,245,355}. The probability of movement of feral pigs varied depending on both spatial and temporal factors, such as HSI region patterns during the different seasons of the year. These regions in conjunction with seasonal conditions inform the likelihood of movement of feral pigs from refuge habitats into nature corridors, into buffer zones, and ultimately the boundary fence of a piggery, particularly when food resources become scarce. In addition, these findings confirm the importance of maintaining the application of control measures to reduce the probability of feral pig encounters, recognising that they are imperfect because the type and frequency of application influences effectiveness.

High HSI areas are broadly categorised as those where feral pigs are most abundant and are assumed to be accompanied by abundant food sources, water availability and protective cover, which result in piggeries also within these regions are placed at a higher risk of encounters^{145,148,387}. This was reflected in the responses of the experts, that indicated feral pigs in high HSI regions are more likely to move from refuge habitats into nature corridors compared to the other regions³⁸⁸. Additionally, with an expected higher abundance of animals within an area they are more likely to venture out of refuge habitats towards these surrounding nature corridors in compared with other areas as moving further away from refuge was not necessary³⁸⁹. Conversely, regions of lower HSI may not provide the same resources outside their refuge habitat, leading to lower probability of movement within these regions, unless they are forced to leave in search of resources. This was observed in expert estimates within the nature corridor/scrubland and buffer zone areas, as all estimates for HSI regions were assigned similar movement probabilities during most seasonal conditions (summer, spring, wet and dry seasons). This underscores the need for pig producers to be aware of the environment in which their piggeries are located and to assess their location within a given HSI region to determine if there are factors motivating feral pigs to move towards their farm.

The study demonstrated seasonal variations in feral pig activity. This was due to experts' opinions that resource availability was affected by season, consistent with studies of movement association with seasonality³⁵⁴. For instance, autumn can be a critical period for pig movement as food resources increase, encouraging pigs to migrate toward areas with better foraging opportunities in tolerable weather conditions³⁹⁰. In contrast, spring and the wet season promote vegetation growth, reducing the need for pigs to leave refuge habitats in search of food. During summer and the dry season, when food and water are scarce, feral pigs located away from water sources may be more inclined to seek resources near commercial piggeries³⁵⁴. However, those already in resource-rich areas are less likely to move during harsh climatic conditions³⁸⁷. A study modelling feral pig habitat suitability and seasonal variability in Queensland found that the risk of feral–domestic pig interactions was highest where low-biosecurity piggeries overlapped with areas of high feral pig densities, particularly during favourable breeding periods¹⁴⁵. This aligns with evidence suggesting that piggeries may attract feral pigs, especially solitary males¹⁶⁰. However, GPS collar data from another Queensland study showed only marginal seasonal variations in home range size, with male pigs having larger ranges in autumn at two study sites, in summer at another, and in winter elsewhere³¹⁷. This study found no statistically significant differences in home range estimates across seasons, sites, or sex. Similarly, research in tropical north Queensland found no seasonal influence on home range size between the wet and dry seasons³⁹¹. Beyond seasonal cycles, other environmental factors can influence feral pig movement. Transitions between seasons, extreme climatic events such as La Niña or El Niño, and climate change may alter feral pig abundance and movement patterns. The model has now been updated to use a cyclic smooth term, implemented as a cyclic cubic regression spline ($bs = "cc"$) within a generalised additive model framework. This ensures continuity at the day boundary (0:00/24:00) and avoids edge effects when modelling diel activity patterns. The Methods section and corresponding figure have been updated accordingly.. The rise of global warming has been linked to increased wild pig populations due to higher food availability during warmer winters and springs, as well as shorter reproductive cycles leading to increased litter turnover³⁹³. Conversely, other studies suggest that higher temperatures reduce juvenile body mass, which may lower female reproductive success and decrease population growth rates³⁹⁴. These findings highlight the complexity of seasonal fluctuations, which vary between individuals, sites, and landscapes depending on resource availability^{354,395}. Thus, understanding seasonal dynamics, alongside location and land use (e.g., cultivation or livestock operations), is crucial for predicting feral pig movement toward piggeries. These insights can inform the timely implementation of biosecurity measures to mitigate risks.

The case study demonstrated the application of the risk assessment tool and its potential for evaluating feral pig interactions with commercial piggeries. The probability estimate generated by the

risk assessment was found to be larger compared to the value from the empirical data from in Chapter 4. Further testing is needed to validate its broader applicability. Notably, the estimated daily likelihood of detecting at least one feral pig per camera trap night during winter was 0.02 based on empirical median encounter rates, which was substantially lower than the 'most likely' outcomes generated by the expert-informed risk assessment (0.13 when control measures were applied and 0.32 when no controls were applied). This discrepancy likely reflects known limitations of expert elicitation, including precautionary bias and challenges in accurately quantifying rare, spatially heterogeneous events in data-poor systems. Expert-derived parameter ranges may therefore overestimate baseline risk and uncertainty relative to field-based observations. While expert opinion remains valuable for preparedness modelling where empirical data are limited, these findings highlight the importance of using field-derived estimates (such as seasonal visitation rates, encounter frequencies, and spatial clustering of feral pig activity) to parameterise risk models more realistically. Sensitivity analysis of expert-elicited parameters represents a critical next step, enabling assessment of which assumptions most strongly influence model outputs and guiding prioritisation of future empirical data collection. Since encounter probabilities vary between farms due to site-specific factors such as landscape features, resource availability, and surrounding land use, the tool enables producers to tailor biosecurity protocols for both surveillance and prevention. By incorporating HSI region, seasonal conditions, and feral pig control strategies, the risk assessment helps determine the appropriate level of biosecurity measures needed to mitigate encounters. For instance, producers in high HSI areas during the dry season may require heightened surveillance compared to other regions. The tool also allows producers to evaluate the effectiveness of their control strategies and adjust them as needed. For example, a producer implementing frequent control measures during high-risk periods may experience fewer feral pig encounters, allowing them to scale back controls when the risk is lower to conserve resources. Integrating this risk assessment tool into existing biosecurity frameworks could enhance its effectiveness. Collaborations with government agencies, industry bodies, and local stakeholders could support its adoption, ensuring a more coordinated approach to feral pig management. By aligning the tool with national biosecurity strategies, producers can better address the challenges posed by feral pig encounters and contribute to a more comprehensive and collaborative approach to disease prevention.

While the risk assessment methodology employed in this study is believed to be robust and grounded in established practices, the validity of its results is inherently dependent on the accuracy and truthfulness of the probability estimates provided by experts. The scenario tree framework, combined with systematic probability assignment and aggregation, offers a reproducible approach for quantifying encounter risks. However, the quality of the outputs is only as reliable as the input data.

An important consideration in this study was the variability and the broad range in the estimates given by the experts, which reflects the true nature of the many unknowns and high uncertainty of feral pig movement and behaviour which are influenced by a multitude of factors, including environmental conditions, food availability, and human interactions^{143,247,317}. There was marked variation in the node level probability estimates across each of the five experts included in this study (Appendix D, Figure D1). While expert opinion can be invaluable in contexts in which empirical data are scarce, it is inherently subjective and can introduce biases despite efforts to minimise this. Experts can differ in their assessments based on individual experiences, knowledge gaps, or differing interpretations of data. This subjectivity creates uncertainties which are reflected in the parameter estimates, which might affect the reliability of the risk assessments. Such variability emphasises the need for additional data to further inform this topic. Continued research efforts should focus on gathering empirical data through monitoring programs, field studies, and technological advancements such as GPS tracking. Future amendments to the tool could also further categorise the different HSI regions to include mapping ecological features to underpin more refined areas in the landscape, such as water sources, cultivation, open herbaceous and woody vegetation, because these are main features that are assumed to influence feral pig movement and habitats^{104,148}. This will enhance the robustness of the risk assessment tool and improve its predictive capabilities. By integrating a broader range of data, future iterations of the tool can more accurately reflect the dynamics of feral pig populations and their interactions with commercial piggeries, ultimately providing better guidance for producers. Also accounting for unseasonal weather conditions such as La Niña or El Niño events, would make this tool more robust during those circumstances.

6.5 Conclusion

This study developed a risk assessment tool to quantify the probability of feral pig encounters at the boundaries of commercial piggeries in Queensland, Australia. By incorporating spatial and temporal factors such as habitat suitability and seasonal conditions, the tool provides valuable insights into the movement patterns of feral pigs and the environmental considerations that motivate their behaviour. These insights underscore the importance of tailoring biosecurity measures to local environmental conditions to mitigate the risk of feral pig incursions. By continuing to gather empirical data to refine and expand its capabilities, the tool can serve as a valuable resource for the pig industry seeking to enhance biosecurity measures and reduce their risk of potential feral pig incursions.

Appendix D: Chapter 6 supplementary material

Table D 1: Descriptions of the terminology and definitions used within the study.

<i>Terminology</i>	<i>Definition</i>
<i>Feral pig encounter/s</i>	The instance where a feral pig is present in the vicinity of the farm in question, with the potential to make direct or indirect contact with domestic pigs. The confirmation of an encounter may be made by direct observations (i.e., in real time or via camera traps), or indirectly by environmental evidence (i.e., footprints, crop damage).
- <i>Direct contact</i>	Occurs when animals make contact with each other via physical contact such as when they share a paddock, pen or confined in a truck ^{7,17} .
- <i>Indirect contact</i>	Occurs when animals make contact with an environment where animals have been present or make contact with items (e.g., fomites, biological vectors, mechanical vectors, vehicles, swill feed) that have had animal contact ^{17,33,37} .
<i>Risk</i>	Refers to the likelihood of hazard occurrence and the likely magnitude of the biological and/or economic consequences of that hazard to animal or human health ³⁹⁶ , The various components of risk assessment represented as nodes are discussed in Section 6.2.2.
<i>Probability</i>	A numeric estimate (ranging from 0 to 1) quantifying how likely an event is to occur.
<i>Refuge habitat</i>	A location that provides feral pigs with reliable and adequate supply of food, water, cover from thermal shelter via shade, and protection of direct sources of mortality or debilitation from predators and environmental disturbances.
<i>Nature Corridor</i>	Linear strips of vegetation that act as a passage for movement and habitats for wildlife, which are also associated with waterways, farm boundaries or roads.
<i>Buffer zone</i>	An open space between the piggery boundary fence and the nearby nature corridor or scrubland (which act as shelter to feral pigs).
<i>Habitat suitability index</i>	The category given to geographic regions to indicate the abundance of feral pigs expected to be within the area (defined further in Section 6.3.4, Table 6.2).

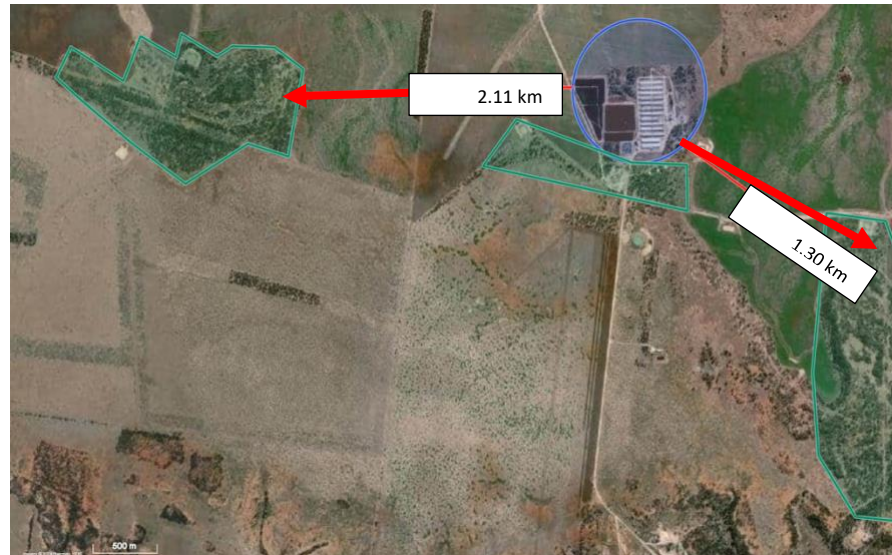
Table D 2: Risk assessment nodes for feral pig encounters at piggeries.

Node	Branch of node	Source
1. Is the piggery in a region that has feral pig occurrences?	YES: 1.0, proceed to the next node NO: 0	Literature, maps
2. Is the piggery within <10km of a feral pig refuge habitat?	YES: 1.0, proceed to the next node NO: 0	Literature, maps
3. Is the piggery located within <4.3km to a water source	YES: 1.0, proceed to the next node NO: 0	Literature, maps
4. The probability that a feral pig will travel from their refuge habitat into nearby nature corridors/scrubland.		
(i) what HSI region is the piggery in?	High HSI Med HSI Low HSI	Expert opinion
(ii) What is the seasonal condition?	Autumn Winter Summer Spring Wet Dry	Expert opinion
5. The probability that a feral pig will travel from the nature corridors into the buffer zone.		
(i) what HSI region is the piggery in?	High HIS Med HSI Low HSI	Expert opinion
(ii) What is the seasonal condition?	Autumn Winter Summer Spring Wet Dry	Expert opinion
(iii) What control method is being used in surrounding nature corridors/scrubland and how frequent?	NA: no control Non-specific control Specific control ⇒ Trapping (weekly/monthly/seasonally/yearly) ⇒ Ground shooting (weekly/monthly/seasonally/yearly) ⇒ Aerial shooting (weekly/monthly/seasonally/yearly) ⇒ Poison baiting (weekly/monthly/seasonally/yearly)	Expert opinion
6. The probability that a feral pig within the buffer zone (that is <1km long) will interact with the piggery boundary fence.		
(i) what HSI region is the piggery in?	High HIS Med HSI Low HSI	Expert opinion
(ii) What is the seasonal condition?	Autumn Winter Summer Spring	Expert opinion

		Wet Dry	
(iii)	What control method is being used in the buffer zone and how frequent?	NA: no control Non-specific control Specific control ⇒ Trapping (weekly/monthly/seasonally/yearly) ⇒ Ground shooting (weekly/monthly/seasonally/yearly) ⇒ Aerial shooting (weekly/monthly/seasonally/yearly) ⇒ Poison baiting (weekly/monthly/seasonally/yearly)	Expert opinion
NA: Not applicable			

Table D 3: Summary of literature review for use and justifications of the risk assessment nodes.

Node	Justification
Node 1: piggery is in a feral pig zone	The area where there is overlap of where feral pigs are distributed and where domestic pig herds are located across Australia ^{167,382} . This can be determined by observing geographical maps of the two populations.
Node 2: piggery proximity to feral pig refuge habitat	Feral pigs are known to reside in habitats that offer them ease of access to essential resources (food, water, and shelter) and protection from predators and harsh weather conditions. Feral pigs have been found to prefer habitats that consist of medium woody or herbaceous vegetation with a 20-40% foliage protection cover (FPC), and actively avoid dense forests ³¹⁷. These natural features combined create refuge habitats for feral pigs to survive, and properties located near these habitats are deemed to be at a higher risk of feral pig encounters. A study involving an expert elicitation estimated that the likely distance feral pigs move away from their refuge habitats would range from 5 to 10 km ¹⁶⁴. These findings were similar to another study conducted in north Queensland that used radio-tracking collars on feral pigs, found to have an aggregated mean home range of 8 km (± 2.4km) ³⁹¹. A further study in north west NSW investigated the effect of proximity to various landscapes on feral pig refuge, and found feral pigs cannot persist in areas more than 10 km from extensive riverine woodlands ¹⁴⁴. This can be determined using Google maps ³⁹⁷ or Near Map ³⁹⁸, and measuring the distance from the piggery of interest to the surrounding potential refuge habitats by identifying areas of vegetative cover in the area. For example, in Figure below there are refuge habitats identified by nearby nature corridors and dense woody vegetation/scrubland approximately 1.3 km southeast and 2.1 km west of the example piggery, with an additional potential area of scrubland just below the farm that could provide refuge to feral pigs. These are within 10 km of the piggery, as a result in the risk pathway, 'yes' would be selected.



Example of the use of a satellite map produced in 'Near map'³⁹⁸ 2024, to measure the distance of the piggery (circled in blue) to the nearby refuge habitats (highlighted in green) which consist of protected nature corridors and scrubland where feral pigs may seek protection and cover. The highlighted area just below the piggery (in the buffer zone) could also be a potential refuge habitat with the wooded vegetation.

Node 3: piggery
proximity to a water
source

Feral pigs require access to water for drinking and body temperature regulation¹⁶¹. Studies have investigated the influence of water in attracting feral pigs to an area, and it is commonly used as a risk factor in determining the probability of a feral pig encounter/interaction^{112,163,326,339,387}. The approximate distance feral pigs travel to reach water varies and can depend on their assumed home range, climatic conditions, and motivation^{146,358,399}. A study found that feral pigs travelled up to 10 km to reach agricultural crops containing sorghum, highlighting their ability to travel large distances when required⁴⁰⁰. A study in Queensland assessed the revisitation of sites by feral pigs. Watercourses were the only habitat variable that maintained statistically significant across the three sites that were investigated, and 51% of all highly revisited sites were located within 150 m of a watercourse¹⁰⁴. The same study found that the average daily distance travelled was 3.6 km by females and 4.9 km by males. An expert elicitation found that feral pigs would travel up to around 5 km away from a water source, although this may be shorter (1 to 2 km) in hot weather, or larger (up to 10 km) if needed¹⁶⁴. A study in Texas, USA found the maximum distance GPS collared pigs travelled to water was 4.3 km (with an average of 1 km)⁴⁰¹.

Node 4: feral pig
movement from
refuge habitat into
nature
corridors/scrubland

The movement of feral pigs to nature corridors or scrubland surrounding a piggery is location- and landscape-dependent and is assessed for each piggery of interest in the risk assessment tool. Feral pigs tend to only venture from refuge habitats when food/water availability is scarce¹⁶⁴. In Australia this usually occurs during the autumn, winter and spring where there is decreased rainfall resulting in a decline in habitat suitability and a subsequent increase in the probability of feral pigs entering nature corridors or scrubland³⁵⁵. However, feral pig movement may differ between seasons to cater for environmental conditions and available resources. A study in Australia (NSW) found that feral pigs preferred

	riverine woodland during the autumn, spring, and summer, but shrubland during the winter as this environment provides higher food availability ^{146(p199)}. Conversely, if feral pigs have all they require in their refuge habitat, it is assumed they are less likely to venture out into nature corridors and/or scrubland.
Node 5: feral pig movement from nature corridor/scrubland into buffer zone of the piggery	The buffer zone around a piggery was defined as open space between the piggery boundary fence and nearby nature corridors or scrublands, which may provide shelter to feral pigs. Similar to Node 4, the likelihood a feral pig moving from the nature corridor/scrubland into a buffer zone was expected to be location- and landscape-dependant, varying between different seasons. Additionally, if feral pigs have moved into the nature corridor/scrubland they are usually resource-driven (such as food, water, or mating) and the probability of entering the buffer zone of the piggery in search for these resources.
Node 6: feral pig movement from buffer zone to the piggery boundary fence	Feral pigs within the buffer zone are highly likely to approach the piggery boundary (or breach the fence if able) due to their social and inquisitive behavioural traits, with studies documenting numerous cases of wild-domestic interactions particularly where domestic pigs are managed outdoors ^{162,326}. However, the probability of this occurring may vary dependent on location and climatic conditions which influence feral pig abundance and resource availability. For example, a study found a generalised increase in the number of wild boar visits during the dry season which reflects a lack of food and water availability ¹¹².
Additional risk factors	Additional factors need to be considered when estimating the probability of feral pig encounters with domestic piggeries, such as landscape features or seasonal conditions ^{145,355}. Individual efforts of feral pig control implementation at a farm level can also have implications on the presence of feral pigs and the probability of them interacting with animals within the farm³⁵⁷. The type and frequency of these will influence their effectiveness, for example weekly compared to yearly) was likely to be more effective at decreasing the overall risk of a feral pig.

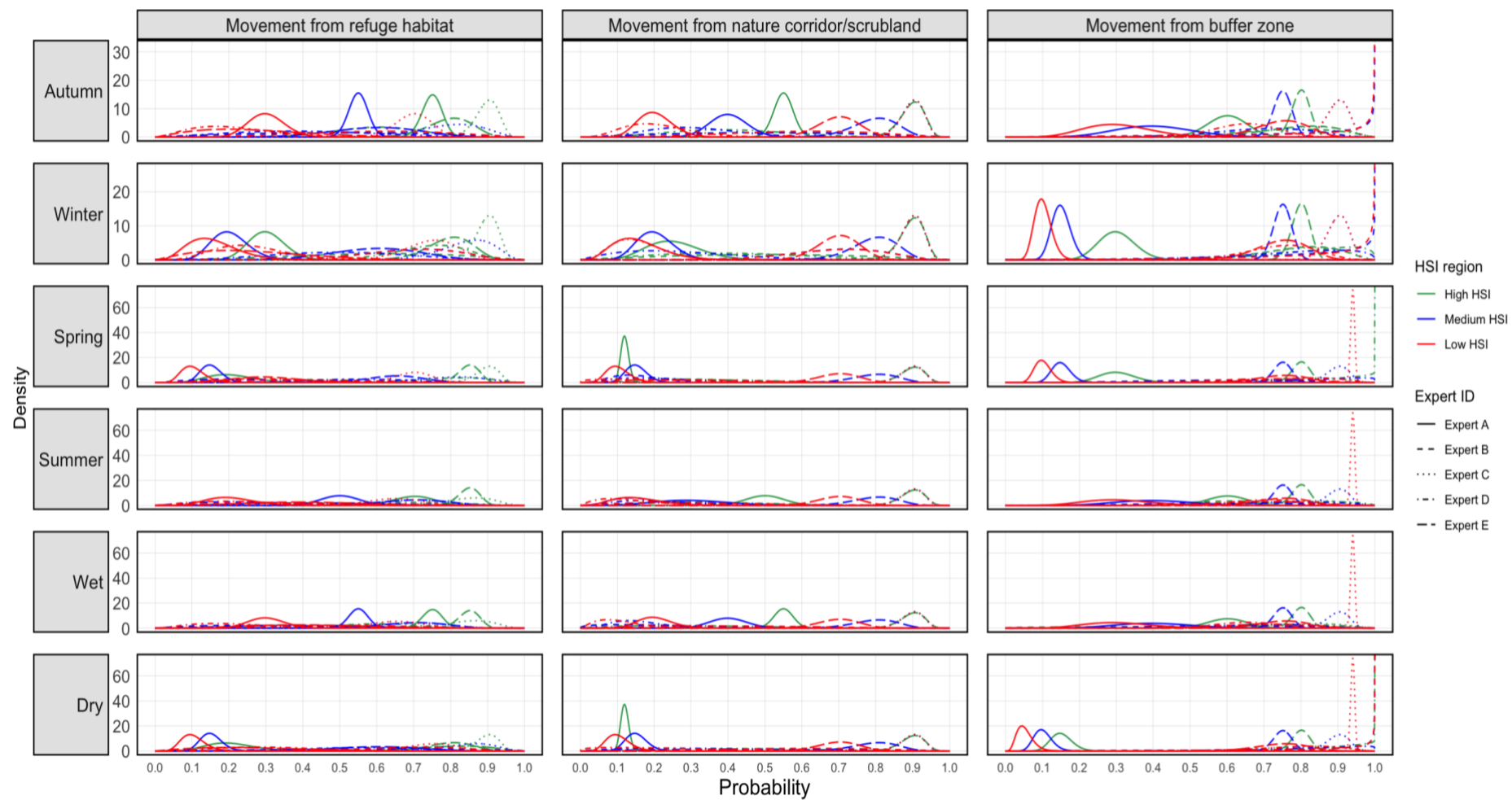


Figure D 1: Variation in beta distributions for the ‘Location’ based questions obtained from the expert elicitation to inform the risk assessment parameters.

Table D 4: The input parameters based on the most likely, minimum, and maximum bound probability estimates from the expert elicitation (nodes 1-3 are based on literature/maps).

Node 4 – Feral pig will move from refuge habitat to a nearby nature corridor or scrubland:									
	Low HSI region			Medium HSI region			High HSI region		
Season	Median	Min	Max	Median	Min	Max	Median	Min	Max
Autumn	0.34	0.10	0.77	0.57	0.21	0.86	0.75	0.32	0.92
Winter	0.34	0.09	0.83	0.61	0.17	0.90	0.75	0.26	0.92
Spring	0.32	0.07	0.83	0.54	0.12	0.86	0.79	0.15	0.92
Summer	0.34	0.11	0.72	0.54	0.15	0.80	0.74	0.24	0.90
Wet	0.37	0.12	0.73	0.56	0.16	0.80	0.75	0.18	0.90
Dry	0.37	0.07	0.83	0.58	0.13	0.90	0.80	0.16	0.93
Node 5 – Feral pig will move from nature corridor or scrubland into the buffer zone:									
	Low HSI region			Medium HSI region			High HSI region		
Season	Median	Min	Max	Median	Min	Max	Median	Min	Max
Autumn	0.59	0.13	0.92	0.53	0.19	0.92	0.60	0.23	0.93
Winter	0.65	0.08	0.92	0.69	0.13	0.92	0.60	0.16	0.93
Spring	0.39	0.06	0.92	0.24	0.08	0.92	0.65	0.11	0.93
Summer	0.32	0.06	0.92	0.32	0.09	0.92	0.53	0.16	0.93
Wet	0.41	0.06	0.92	0.42	0.07	0.92	0.56	0.08	0.92
Dry	0.60	0.07	0.92	0.57	0.12	0.92	0.65	0.11	0.93
Node 6 – Feral pig will move from buffer zone and interact with the piggery boundary nearby									
	Low HSI region			Medium HSI region			High HSI region		
Season	Median	Min	Max	Median	Min	Max	Median	Min	Max
Autumn	0.73	0.23	0.98	0.75	0.31	0.96	0.77	0.53	0.92
Winter	0.77	0.09	0.98	0.76	0.13	0.97	0.78	0.27	0.94
Spring	0.75	0.08	0.94	0.75	0.13	0.94	0.77	0.26	0.96
Summer	0.72	0.24	0.94	0.74	0.30	0.93	0.73	0.49	0.92
Wet	0.70	0.24	0.94	0.73	0.30	0.92	0.73	0.29	0.92
Dry	0.79	0.04	0.97	0.78	0.08	0.99	0.80	0.13	0.99
Non-specific application of control - Percentage of feral pig activity reduction that can be achieved by conducting control measures around the surrounding nature corridors/scrubland near the piggery									
	Low HSI region			Medium HSI region			High HSI region		
Location of control	Median	Min	Max	Median	Min	Max	Median	Min	Max
<i>nature corridors/scrubland near the piggery</i>	0.76	0.40	0.98	0.68	0.36	0.85	0.62	0.32	0.85
<i>Within the buffer zone of the piggery</i>	0.76	0.47	0.89	0.66	0.37	0.82	0.61	0.21	0.82
Specific application of control - Estimated percentage of reduction that can be achieved depending on how frequently it is conducted									
	Low HSI region			Medium HSI region			High HSI region		
Frequency of control	Median	Min	Max	Median	Min	Max	Median	Min	Max

Trapping									
<i>Daily</i>	0.79	0.31	0.92	0.73	0.38	0.91	0.64	0.35	0.84
<i>Weekly</i>	0.77	0.52	0.90	0.72	0.47	0.90	0.62	0.43	0.84
<i>Monthly</i>	0.64	0.27	0.86	0.61	0.25	0.86	0.61	0.25	0.86
<i>Seasonally</i>	0.34	0.13	0.77	0.32	0.12	0.75	0.25	0.08	0.68
<i>Yearly</i>	0.12	0.01	0.53	0.10	0.01	0.49	0.06	0.01	0.47
Ground shooting									
<i>Daily</i>	0.50	0.18	0.78	0.40	0.17	0.66	0.32	0.14	0.61
<i>Weekly</i>	0.29	0.13	0.62	0.26	0.13	0.51	0.22	0.07	0.57
<i>Monthly</i>	0.20	0.07	0.44	0.16	0.07	0.39	0.13	0.02	0.34
<i>Seasonally</i>	0.13	0.02	0.34	0.13	0.02	0.30	0.09	0.02	0.23
<i>Yearly</i>	0.07	0.02	0.23	0.07	0.02	0.15	0.05	0.01	0.12
Aerial Shooting									
<i>Daily</i>	0.95	0.81	1.00	0.95	0.81	1.00	0.92	0.81	1.00
<i>Weekly</i>	0.84	0.68	0.96	0.83	0.67	0.97	0.84	0.66	0.97
<i>Monthly</i>	0.73	0.55	0.90	0.78	0.53	0.90	0.81	0.55	0.90
<i>Seasonally</i>	0.59	0.13	0.89	0.61	0.17	0.87	0.63	0.21	0.88
<i>Yearly</i>	0.42	0.07	0.72	0.46	0.11	0.70	0.46	0.05	0.74
Poison Baiting (1080/Sodium Nitrite)									
<i>Daily</i>	0.78	0.56	0.88	0.81	0.55	0.89	0.81	0.55	0.90
<i>Weekly</i>	0.83	0.58	0.94	0.84	0.61	0.94	0.86	0.60	0.93
<i>Monthly</i>	0.68	0.25	0.88	0.70	0.25	0.86	0.71	0.27	0.87
<i>Seasonally</i>	0.52	0.18	0.88	0.53	0.18	0.86	0.55	0.18	0.86
<i>Yearly</i>	0.29	0.12	0.84	0.30	0.01	0.81	0.34	0.01	0.82

**The certainty for all estimates is 90%*

Table D 5: Case study results using the risk assessment and allocated estimates per node.

Node	Outcome of node	Result/value (Median (min, max))
1. Is the piggery in a region that has feral pig occurrences? *.		
	Located in South-east QLD within the 'Medium HSI' region based on Table 1 and maps of estimated feral pig distribution and abundance ^{242,382} .	YES
2. Is the piggery within <10km of a feral pig refuge habitat? *		
	Closest potential feral pig refuge habitat is within 300m of the piggery (determined by site visit and confirmed by satellite map)	YES
3. Is the piggery located within <4.3km to a water source?		
	It is bordering a river which is approximately within 50m of the piggery fence (determined by site visit and confirmed by satellite map).	YES
4. The probability that a feral pig will travel from their refuge habitat into nearby nature corridors/scrubland.		
(i) what HSI region is the piggery in?	Med HSI	0.61 (0.17, 0.90)
(ii) What is the seasonal condition?	Winter	
5. The probability that a feral pig will travel from the nature corridors into the buffer zone.		
(i) what HSI region is the piggery in?	Med HSI	0.69 (0.13, 0.92)
(ii) What is the seasonal condition?	Winter	
(iii) What control method is being used in surrounding nature corridors/scrubland and how frequent?	NA: no control	
6. The probability that a feral pig within the buffer zone (that is <1km long) will interact with the piggery boundary fence.		
(i) what HSI region is the piggery in?	Med HSI	0.76 (0.13, 0.97)
(ii) What is the seasonal condition?	Winter	
(iii) What control method is being used in the buffer zone and how frequent?	Specific control ⇒ Trapping - yearly ⇒ Ground shooting - yearly ⇒ Poison baiting – yearly	0.10 (0.01, 0.53) 0.07 (0.02, 0.15) 0.30 (0.01, 0.81)
NA: Not applicable		

Table D 6: Probability of encounter calculations and outcomes of various scenarios based on the application of control.

<i>Scenario values</i>	<i>Control outcome</i>	<i>Calculation</i>	<i>Probability of encounter</i>
<i>Most likely outcome</i> ⇒ <i>using the median values for each node</i>	No control applied	$= 0.61 \times 0.69 \times 0.76$ $= 0.32$	32%
	Including control	$= 0.61 \times 0.69 \times ((0.76(1-(1-0.1) \times (1-0.07) \times (1-0.30))))$ $= 0.13$	13%
<i>Lower bounds</i> ⇒ <i>using the minimum values for each node</i>	No control applied	$= 0.17 \times 0.13 \times 0.13$ $= 0.002$	0%
	Including control	$= 0.17 \times 0.13 \times ((0.13 \times (1-(1-0.01) \times (1-0.02) \times (1-0.01))))$ $= 0.0001$	0%
<i>Upper bounds</i> ⇒ <i>using the maximum values for each node</i>	No control applied	$= 0.90 \times 0.92 \times 0.97$ $= 0.80$	80%
	Including control	$= 0.90 \times 0.92 \times ((0.97 \times (1-(1-0.53 \times (1-0.15) \times (1-0.81))))$ $= 0.07$	7%
<i>Worst case scenario</i> ⇒ <i>using max likelihood travel with lower values for control estimates</i>	No control applied	$= 0.90 \times 0.92 \times 0.97$ $= 0.80$	80%
	Including control	$= 0.90 \times 0.92 \times ((0.97 \times (1-(1-0.01 \times (1-0.02) \times (1-0.01))))$ $= 0.008$	0%
<i>Best case scenario</i> ⇒ <i>using min likelihood travel with upper values for control estimates</i>	No control applied	$= 0.17 \times 0.13 \times 0.13$ $= 0.002$	0%
	Including control	$= 0.17 \times 0.13 \times ((0.13 \times (1-(1-0.53 \times (1-0.15) \times (1-0.81))))$ $= 0.002$	0%

Questionnaire D 1: Background information, and examples of the question context and format provided to the experts involved in the elicitations. The location-based questions were repeated for each climatic season (autumn, winter, spring, summer, wet and dry season) and the additional control-based intensity questions were repeated for each different control measure type (trapping, ground shooting, aerial shooting, and poison baiting).

Elicitation Protocol & Question Format		
Background		
We are currently collecting information on feral pigs in Australia to help inform the domestic pig industry of feral-domestic pig interaction risks, and the potential disease spread such as African swine fever. Australia is currently free from African swine fever, and protecting the domestic pig industry from the disease is important for continued trade in the face of an outbreak. We will be asking you questions in regard to feral pig movement towards piggeries in Queensland, and the influence of control measures may have on feral pig encounters. The responses you give will be combined with the responses of other people we have interviewed to develop an overall picture of the risk of feral pig encounters at piggeries. This information will then be used to develop a risk assessment tool that can be used by commercial producers for African swine fever disease preparedness. Your response is confidential and you will be given the opportunity to adjust your answers before the elicitation is concluded. You will also be updated on any official reporting (i.e peer review journal submission) that your responses are a part of in the future. Thank you for your participation, it is greatly appreciated.		
QUESTIONS		
All questions will be about quantities surrounded by uncertainty and measured on a continuous scale.		
Consider the example		
<i>In an experiment to determine if seasonality has an influence on feral pigs interacting with domestic piggeries, consider the location of the study to be in an ecoregion containing high habitat suitability factors (i.e, water source, foliage protection). What would be the probability of detecting a feral pig within 300m of the piggery during Spring?</i>		
5% percentile (lower bound)	95% percentile (upper bound)	Median (best estimate)
Suppose you respond as shown below:		
5 5% percentile (lower bound)	50 95% percentile (upper bound)	15 Median (best estimate)
We will consider your:		
best estimate to correspond to the median of the subjective (personal) distribution you assign to the variable in question. lower bound to correspond to the 5% percentile of the subjective (personal) distribution you assign to the variable in question. upper bound to correspond to the 95% percentile of the subjective (personal) distribution you assign to the variable in question.		
This means that, <i>according to your belief</i> :		
- the true value is equally likely to be above or below 15% - there is only a 1 in 20 chance that the true value is below 5% - there is only a 1 in 20 chance that the true value is above 50% - there are 18 in 20 chances (90%) that the true value lies between 5% and 50%		
In the comment sections, if you could also provide your personal level of confidence in your response by stating 'low, medium, or high', would be appreciated.		

Topic: Location factors														
QUESTIONS										DEFINITIONS				
Piggeries are assumed to be at greatest risk of feral pig encounters if they are within 10km to the feral pig refuge habitat, <4.3km of a water source, and surrounded by nature corridors or scrubland for the feral pigs to travel through to get to the boundary of the piggery. The distances and pathways feral pigs travel, and the likelihood of them approaching a piggery may also vary depending on the time of the year and seasonal influences such as temperature and feed/water availability. As a result, the following questions are being asked per season (Autumn, Spring, Summer, Winter, Dry or Wet). Australia (especially QLD) is a diverse landscape and feral pig numbers will vary with surrounding habitats and ecoregions of interest. Piggeries are dispersed amongst the feral pig population in QLD, hence the following questions have also been broken down into 3 levels of habitat suitability index (HSI) regions on the assumed abundance of feral pigs. For each response provided, could you please state your level of confidence in the given estimate: High (>95% confident), Medium (65-95% confident), Low (<65% confident)										Refuge habitat: location that provides feral pigs with reliable and adequate supply of food, water, cover from thermal shelter via shade, and protection of direct sources of mortality or debilitation from predators and environmental disturbances. Buffer zone: is the open space between the piggery boundary fence and the nearby nature corridor or scrubland (which act as shelter to feral pigs) Assumed level of feral pig abundance in various habitat suitability index (HSI) regions: High - 4-6 pigs per km²; Eco-region TRS: Tropical and subtropical grasslands, savannas and shrublands (Far north QLD) Medium - 2-3 pigs per km²; Eco-regions TRS: Tropical and subtropical grasslands, savannas and shrublands, TEF: Temperate Broadleaf and Mixed Forest (South-east QLD) Low - 0-1 pigs per km²; Eco-region: TRS: Tropical and subtropical grasslands, savannas and shrublands, DES: Deserts and Xeric shrublands (West QLD)				
In the following scenarios, what is the expected probability a feral pig will travel towards a piggery in each of the following scenarios?														
		Low HSI region (0-1 pigs/km)				Medium HSI region (2-3 pigs/km)				High HSI region (4-6 pigs/km)				
Question ID	Location based questions	Median (best estimate)	5% percentile (lower bound)	95% percentile (upper bound)	Level of confidence in your response	Median (best estimate)	5% percentile (lower bound)	95% percentile (upper bound)	Level of confidence in your response	Median (best estimate)	5% percentile (lower bound)	95% percentile (upper bound)	Level of confidence in your response	Any additional comments
AUTUMN														
A1.1	Assuming the piggery is within <10km of a feral pig refuge habitat. What is the probability that a feral pig will move from a refuge habitat to a nearby nature corridor or scrubland?													
A1.2	What is the probability that a feral pig would move from the scrubland/nature corridors, to the buffer zone?													
A1.3	What is the probability that a feral pig in the buffer zone would interact with boundary fence of a nearby commercial piggery?													

Topic: Feral pig control measures														
QUESTIONS										DEFINITIONS				
The risk of feral pigs encounters at piggeries may also vary with the level of preventative measures taken per farm or within the area due to decline in population numbers. Acknowledging there are numerous type of control measures available to reduce/eliminate feral pigs within the area , and depending on the frequency being used to determine how they can impact the probability of detecting feral pigs. We understand the efficacy of control will vary depending on the abundance of feral pigs within the region, and their ability to repopulate and return to the area of concern. As a result in the following question we are asking for estimates per different regions depending on the habitat suitability index. Also acknowledging that mating behaviours of feral pigs may fluctuate throughout different seasons of the year which may influence how effective control methods are, although for this question we are considering the average estimate of population reduction caused by the specific methods around the property. For each response provided, could you please state your level of confidence in the given estimate: High (>95% confident), Medium (65-95% confident), Low (<65% confident)										Assumed level of feral pig abundance in various habitat suitability index (HSI) regions: High - 4-6 pigs per km2; Eco-region TRS: Tropical and subtropical grasslands, savannas and shrublands (Far north QLD) Medium - 2-3 pigs per km2; Eco-regions TRS: Tropical and subtropical grasslands, savannas and shrublands, TEF: Temperate Broadleaf and Mixed Forest (South-east QLD) Low - 0-1 pigs per km2; Eco-region: TRS: Tropical and subtropical grasslands, savannas and shrublands, DES: Deserts and Xeric shrublands (West QLD)				
What is the expected percentage reduction in feral pig population in low, medium, and high HSI region in the following scenarios?														
		Low HSI region (0-1 pigs/km)				Medium HSI region(2-3 pigs/km)				High HSI region (4-6 pigs/km)				
Question ID	Control based questions	Median (best estimate)	5% percentile (lower bound)	95% percentile (upper bound)	Level of confidence in your response	Median (best estimate)	5% percentile (lower bound)	95% percentile (upper bound)	Level of confidence in your response	Median (best estimate)	5% percentile (lower bound)	95% percentile (upper bound)	Level of confidence in your response	Any additional comments
A2.1	what is the percentage feral pig activity reduction that can be achieved by conducting control measures around the surrounding nature corridors/scrubland near the piggery? (i.e., 30%, 40%, 50%...)													
A2.2	what is the percentage feral pig activity reduction that can be achieved by conducting control measures within the buffer zone of the piggery? (i.e., 30%, 40%, 50%...)													
Additional control based questions														
A2.3	Out of the following control measures listed below, please allocate the estimated percentage of reduction that can be achieved depending on how frequently it is conducted: (some intensities may be deemed not applicable, please write 'NA' if necessary)													
	trapping													
	daily													
	weekly													
	monthly													
	seasonally													
	yearly													

7 Investigating the influence of disease spillover between feral and domestic pigs in ASF outbreaks using AADIS

7.1 Introduction

ASF is a major global biosecurity concern for the pork industry^{14,402}. This highly contagious and often fatal viral disease affects both domestic and wild pigs, causing severe economic and social disruption due to high mortality rates and the current lack of an effective vaccine^{8,78}. ASF outbreaks around the world have led to significant losses in pig populations, trade restrictions, and long-term impacts on pork producers^{84,123,149}. In countries with large feral pig populations such as Australia, the risk is heightened by the potential interactions between feral and domestic pigs, which increases the need for strict biosecurity and surveillance planning. The African swine fever virus (ASFV) can be transmitted directly (e.g., nose-to-nose contact) or indirectly via contaminated environments, water sources, or mechanical vectors such as rodents and foxes^{7,36,403,404}. As a result, both direct and indirect interactions between feral and domestic pigs pose a significant threat to pork production and trade.

In Australia, understanding the behaviour and ecology of feral pigs is essential for anticipating ASF transmission risks. Feral pigs typically form groups called sounders consisting of females and offspring, while adult males often roam alone as solitary boars⁴⁰⁵. The home ranges of both sounders and solitary boars vary depending on habitat suitability, resource availability, and population density^{143,355,406}. Seasonality further influences ASF transmission by affecting feral pig movement patterns, carcass decay rates, and the environmental persistence of the virus^{251,387,407}. Seasonal factors can affect the behaviours of feral pigs due to their thermoregulation needs and the availability of resources, leading to influence the likelihood of contact with domestic pigs^{354–356}. For instance, during dry or drought conditions, feral pigs may extend their ranges in search of water, increasing the chances of contact with domestic pigs and creates opportunities for indirect transmission through environmental contamination^{408–410}. ASFV can remain viable for extended periods in infected carcasses, especially in cool, moist environments, thus maintaining infectivity and posing a risk to scavenging feral pigs or domestic herds exposed directly or indirectly to contaminated areas^{411,412}. In contrast, higher temperatures and increased microbial activity during warmer periods can accelerate carrion decomposition, potentially reducing the duration of carcass-based transmission^{5,413,414}. These shifts in behaviour, combined with the seasonal persistence of the virus in carcasses, create multifaceted transmission dynamics that can be accounted for in simulation models such as AADIS.

Disease models are useful epidemiological tools designed to simulate the dynamics of infectious disease outbreaks under a variety of scenarios⁴¹⁵. The Australian Animal Disease Spread (AADIS) model is a prime example, integrating ecological, behavioural, and epidemiological data to model complex transmission pathways and inform outbreak response policy and decision-making^{17,416}. The flexible structure of AADIS allows for adaptation to different diseases and outbreak conditions, enabling users to simulate scenarios involving control effectiveness and cost, transmission and contact rates, and diverse surveillance strategies¹⁷. Its adaptability to include interactions between feral and domestic pigs makes it a valuable tool for preparing for diseases like African swine fever (ASF), particularly in ASF-free countries like Australia.

The spread and control of ASF in domestic pigs, sounders, and between sounders and domestic pig herds has been previously simulated in the AADIS-ASF Queensland (QLD) model^{17,188}. Key findings from the simulations found that without the application of feral pig control (implemented by population thinning/removal), maintenance of infection in feral pigs and spillover back to domestic pigs can increase the size and duration of an outbreak in domestic pigs. However, the degree of spillover between feral and domestic pigs, as well as the size of the outbreak will depend on several factors such as the region, time of year (season), density of feral pig population, and the intensity of on-farm biosecurity measures. A key gap has been that the epidemiological interface between sounders and domestic pig herds was difficult to parameterise and requires local empirical data on contacts between the two pig populations^{17,188}. Several studies across states in the United States of America, as well as one in Queensland Australia, have emphasised the importance of characterising the spatial variation of contact rates in structuring the transmission process between wildlife and livestock^{409,417–419}. A lack of empirical data on wild pig-domestic pig interactions makes it difficult to determine the best network structures and parameters for simulation modelling. Thus, a previous chapter included in this thesis (Chapter 4), intended to aid understanding in this knowledge gap by conducting camera trap surveillance to detect feral pig (or sounder) activity at the boundary of a commercial piggery and at hotspot locations around the piggery and in doing so provide some basis to parameterising inter-sounder contact rates around piggeries and rates of interactions that could lead to spillover events.

In epidemiological modelling, the contact rate refers to the number of interactions between susceptible and infectious individuals (or populations) per unit time that could potentially lead to pathogen transmission^{420,421}. This parameter is critical, as it influences the dynamics and outcomes of an outbreak. The effectiveness of contact is an additional parameter that specified the probability that each contact results in transmission of infection. Specific interventions may target reducing contact rates *per se* (i.e., restricting animal movement, implementing fencing or buffer zones, or reducing

population density), or reducing the effectiveness of the contacts that are occurring (i.e., improving biosecurity, disinfecting equipment and vehicles, using personal protective equipment, or vaccination). A *feral pig/sounder contact* may be defined as any instance where a feral pig or a group of feral pigs are detected in proximity with a domestic piggery, either directly or indirectly, creating a potential risk for disease transmission. Direct contact includes physical interactions, such as nose-to-nose contact through a fence. Whereas, indirect contact occurs when the virus spreads through shared environmental spaces, vehicles or transmission on fomites, for example from contaminated surfaces, water sources, or via scavenging pests. As not all contacts result in ASF transmission, the likelihood of an *effective contact* being made (one that leads to pathogen transmission) is required to be considered. The likelihood of a contact being effective is influenced by multiple factors, such as the prevalence of infection, the type of production system (e.g., indoor vs. free-range farming), the level of on-farm biosecurity measures, and climatic conditions that affect virus survival in the environment. These factors are all incorporated into the AADIS framework when estimating the probability of transmission.

The aim of this chapter was to conduct a sensitivity analysis using the AADIS model to demonstrate how varying the spillover contact rates between feral pig-to-domestic pig herds, and inter-sounder contact rates affects disease spread outcomes, with the rates themselves informed by empirical ecological data from earlier chapters. This approach highlights the capacity of the AADIS model to address the complexities of wildlife-livestock interactions and the potential for targeted interventions, with the goal of supporting evidence-based decision-making for ASF preparedness and response planning in the Australian context.

7.2 Methodology

7.2.1 Estimating feral/domestic contact rates from field data

This study analysed distinct **sounder groups** of feral pigs approaching a piggery using camera trap data in the southeast QLD region (Chapter 3). Novel criteria were developed and applied to classify and quantify contact rates based on detection patterns to demonstrate how these field data can be used in epidemiological models.

The criteria outlined below were used to group each feral pig detection into distinct contact events. This methodology ensured a consistent approach in estimating the presence of sounders or solitary boars within a defined period, which allowed the analysis of feral pig movement and activity in the study area to be incorporated into a disease model. The criteria include:

Best-case scenario: Assumed the minimum number of detection events, considering *each detection within a 24-hour period as the same sounder* (for counts >1) or solitary boar (for counts =1) revisiting the piggery. However, additional detections within the same day were counted as separate events if animals were visibly identifiable as different from those previously detected, based on features such as size, body structure, or markings.

So Worst-case scenario: Assumed the maximum number of detection events within each 24-hour period, treating *each detection as a unique sounder* (for counts >1) or a solitary boar (for counts =1) visiting the piggery within the 24-hour period.

Using the available empirical data, in each scenario, the total counts of solitary boars and sounders was used to determine the mean, minimum and maximum number of contacts daily per month and season:

- ⇒ **Daily contact rate per month:** total sounders and boars detected per day, divided by the number of days in the specific month
- ⇒ **Daily contact rate per season:** total sounders and boars detected per day within the months of specific season divided the number of days in the months of the specific season.
i.e., For Autumn: 45 detections across March, April and May, were divided by 92 days (total days in March (n=31), April (n=30) and May (n=31)). The resulting contact rate for Autumn = 0.49 contacts per day.

7.2.2 Sensitivity analysis

The effect of sounder-to-farm spillover transmission and contact rates between sounders in ASF outbreaks was investigated in case studies that focused on specific parameter settings in AADIS to evaluate the influence of these parameters.

7.2.2.1 Case studies background

Using the generated contact rates, the sensitivity analysis was conducted in AADIS by running two separate case studies, (a) investigating the influence of various contact rates between feral pigs and domestic pig farms, and then (b) investigating the influence of inter-sounder contact at points of interest, (i.e. a piggery) using different contact rate values. For each case study, best- and worst-case scenarios were investigated with adjusting contact rate values. Four simulations were run with 500 iterations per scenario, each seeded in a different season. All runs included feral pig spillover and feral pig control, as outlined in Table 7.1.

Table 7.1: Simulation settings in AADIS for each case study

Simulation	Start date	Season	Feral pig spillover	Feral pig control
1	1 st Jan	Summer	Enabled	Enabled
2	1 st March	Autumn	Enabled	Enabled
3	1 st June	Winter	Enabled	Enabled
4	1 st Sept	Spring	Enabled	Enabled

In all simulation runs, ASF outbreaks were initiated in the same grid cell in the Western Downs region of southeast Queensland where camera traps were previously deployed in Chapter 4. This grid cell contained both feral pigs (3.3 pigs/km²) and a small commercial piggery with 300 sows. Detection was configured to occur 21 days after seeding, triggering movement restrictions, stamping out, tracing, and surveillance. Outbreaks continued until disease control or fade-out, with a maximum duration of 365 days.

For both case studies, linear regression models were fitted to evaluate the effects of scenario and season on four key disease outcomes: the number of infected feral pig groups (sounders), the number of infected premises (num IPs), the number of animals culled, and the infection area (km²). These four outcome variables were all log-transformed (to base 10, adding 1 for any zero values) for linear regression as initial exploratory analyses (inspection of histograms and skew statistics) showed all were right-skewed, this also helped to stabilise and normalise variance in residuals of the regression

models, as assessed by plots of residuals versus fitted values, Scale–Location plots (for assessing heteroscedasticity) and Q–Q plots to assess symmetry. Reference categories for categorical predictors were set as winter for season and the quarter of the midpoint scenario, enabling interpretation of model coefficients compared to the least extreme conditions. For each outcome, models were fitted separately, and coefficients, standard errors, and 95% confidence intervals were estimated. Model fitting and parameter estimation were performed using the ‘*lm*’ function in R (version 4.3.1)⁶⁵. The proportion of spillover events and the likelihood of the outbreak being resolved within a year (365 days) was also assessed for each case study.

7.2.2.2 Case study 1: Sensitivity of simulated outbreaks to feral/domestic contact rates

To assess the influence of feral-to-domestic pig transmission (spillover) on ASF outbreak dynamics, the five different contact rate scenarios were simulated. The AADIS model was run using default disease, control, and resourcing parameters, with the feral pig-to-domestic pig herd contact rate being the only parameter varied. Additional detail can be found in Bradhurst et al. (2021) on the development of the AADIS-ASF model, including its configuration for simulating the spread and control of ASF within and between feral pig populations and domestic pigs⁴²².

7.2.2.3 Case study 2: Sensitivity of simulated outbreaks to inter-sounder contact rates

To investigate the impact of feral pig social structure on disease spread, five further scenarios were also tested based on different inter-sounder contact rates. For this case study, the empirical data collected at the piggery was used to symbolise a point of interest where sounders gather/interact with each other, which could lead to disease transmission. Other examples of places where sounders may encounter each other either directly or indirectly are water sources such as dams and rivers and food sources such as crops and feedlots. In this analysis, the inter-sounder contact rate was the only parameter varied. This allowed the effect of varying social contact intensity among feral pigs to be isolated and quantified in terms of outbreak size, spatial extent, and impact.

7.3 Results

7.3.1 Estimating feral/domestic contact rates from field data

The minimum and maximum feral pig detections in the camera trap data were aggregated into best- and worst-case scenarios using the established criteria to distinguish individual contacts in the images. The monthly crude counts are shown in Table 7.2, with the highest contacts occurring in April across both scenarios, and the least number of contacts in August and September as found in Chapter 4. The daily contact rates per day for each month and per season are presented in Table 7.3. The highest daily contact rate was in autumn (2.59; range 1.37, 3.91), and the lowest was in spring (0.45; range 0.41, 0.49). Table 7.4 displays the input values that were used across the scenarios in both case studies.

Table 7.2: Crude count of feral pig contacts at the piggery when applying the best-case and worst-case scenario criteria

	Best case (minimum contacts)			Worst case (maximum contacts)		
	<i>sounders</i>	<i>boars</i>	<i>total</i>	<i>sounders</i>	<i>boars</i>	<i>total</i>
Jan	8	8	16	8	10	18
Feb	10	20	30	18	45	63
March	17	18	35	31	35	66
April	25	23	48	114	67	181
May	20	24	44	44	63	107
June	19	16	35	49	27	76
July	11	11	22	20	17	37
Aug	3	7	10	3	9	12
Sept	3	7	10	4	8	12
Oct	9	2	11	11	3	14
Nov	15	1	16	18	1	19
Dec	4	8	12	7	8	15
Total	144	145	289	327	293	620

Table 7.3: Daily feral pig contact rates per month and season, generated from the empirical data

	<i>min</i>	<i>midpoint</i>	<i>max</i>	<i>Contact rate per month midpoint [range]</i>	<i>Contact rate per season midpoint [range]</i>
Dec	12	13.5	15	0.44 [0.39 – 0.48]	Summer 0.86 [0.64 – 1.07]
Jan	16	17	18	0.57 [0.52 – 0.58]	
Feb	30	46.5	63	1.50 [1.03 – 2.17]	
March	35	50.5	66	1.68 [1.13 – 2.13]	Autumn 2.59 [1.37 – 3.91]
April	48	114	181	3.68 [1.6 – 6.03]	
May	44	76	107	2.45 [1.42 – 3.45]	
June	35	55.5	76	1.85 [1.17 – 2.53]	Winter 1.04 [0.73 – 1.36]
July	22	29.5	37	0.95 [0.71 – 1.19]	
Aug	10	11	12	0.37 [0.33 – 0.39]	
Sept	10	11	12	0.35 [0.33 – 0.40]	Spring 0.45 [0.41 – 0.49]
Oct	11	12.5	14	0.40 [0.35 – 0.45]	
Nov	16	17.5	19	0.60 [0.53 – 0.63]	
Total	289	454.5	620		

Table 7.4: Generated contact rate estimates used for each of the scenarios in the case studies.

	Summer			Autumn			Winter			Spring		
Scenario	<i>Dec</i>	<i>Jan</i>	<i>Feb</i>	<i>Mar</i>	<i>Apr</i>	<i>May</i>	<i>Jun</i>	<i>Jul</i>	<i>Aug</i>	<i>Sep</i>	<i>Oct</i>	<i>Nov</i>
Contact rate												
Max	1.07			3.91			1.36			0.49		
Midpoint	0.86			2.59			1.04			0.45		
Min	0.64			1.37			0.73			0.41		
Half of the midpoint	0.43			1.26			0.52			0.23		
Quarter of the midpoint	0.22			0.65			0.26			0.11		

7.3.2 Sensitivity analysis

7.3.2.1 Case study 1: Sensitivity of simulated outbreaks to feral/domestic contact rates

Outbreak simulations for the domestic/feral spillover scenarios demonstrated clear and consistent effects of both seasonal timing and contact rate intensity on outbreak magnitude. The outcomes varied markedly by season and scenario (Figure 7.1), with detailed outputs presented in Appendix E, Table 1.

Linear regression modelling further confirmed the influence of seasonal and contact rate effects in shaping outbreak severity (Table 7.5). Under the reference scenario of quarter midpoint contact during winter, the model predicted a mean of 44 infected wild sounders (95% CI: 41–48). Compared to this reference, outbreaks seeded in spring produced substantially fewer infections, with 4% as many feral pig infections (95% CI: 4.1% to 4.8%) relative to winter, while summer also showed a reduction to 7% (95% CI: 6.5% to 7.5%). In contrast, autumn scenarios led to a substantial increase in transmission, with four times as many infected sounders as winter (95% CI: 3.7 to 4.3 times higher). This seasonal pattern was consistent across all outbreak metrics. For example, the number of infected domestic pig (infected premises) in autumn was 2.5 (95% CI: 2.4–2.6), and animals culled were estimated at 1.3 (95% CI: 1.2–1.4) times more than the baseline in winter. The infected area in autumn also increased, reaching 1.2 times the winter value (95% CI: 1.1–1.4).

Scenario contact rate effects also played a critical role in outbreak extent. Compared to the quarter midpoint reference scenario (in winter), the maximum contact scenario resulted in 5.6 times more infected wild sounders (95% CI: 5.2–6.1), 3.4 times more infected premises (95% CI: 3.2–3.5), and 5.1 times the infected area (95% CI: 4.4–5.9). The number of animals culled under the maximum scenario was 4.78 times higher than under the baseline (95% CI: 4.31–5.29), highlighting the substantial increase in control efforts required under elevated contact conditions.

These findings reinforce the influence of seasonal dynamics and feral/domestic contact rates on outbreak outcomes. The consistent patterns observed across all outbreak metrics suggest that both the timing of spillover events and the intensity of spillover are critical considerations when assessing outbreak risk and planning for effective response strategies.

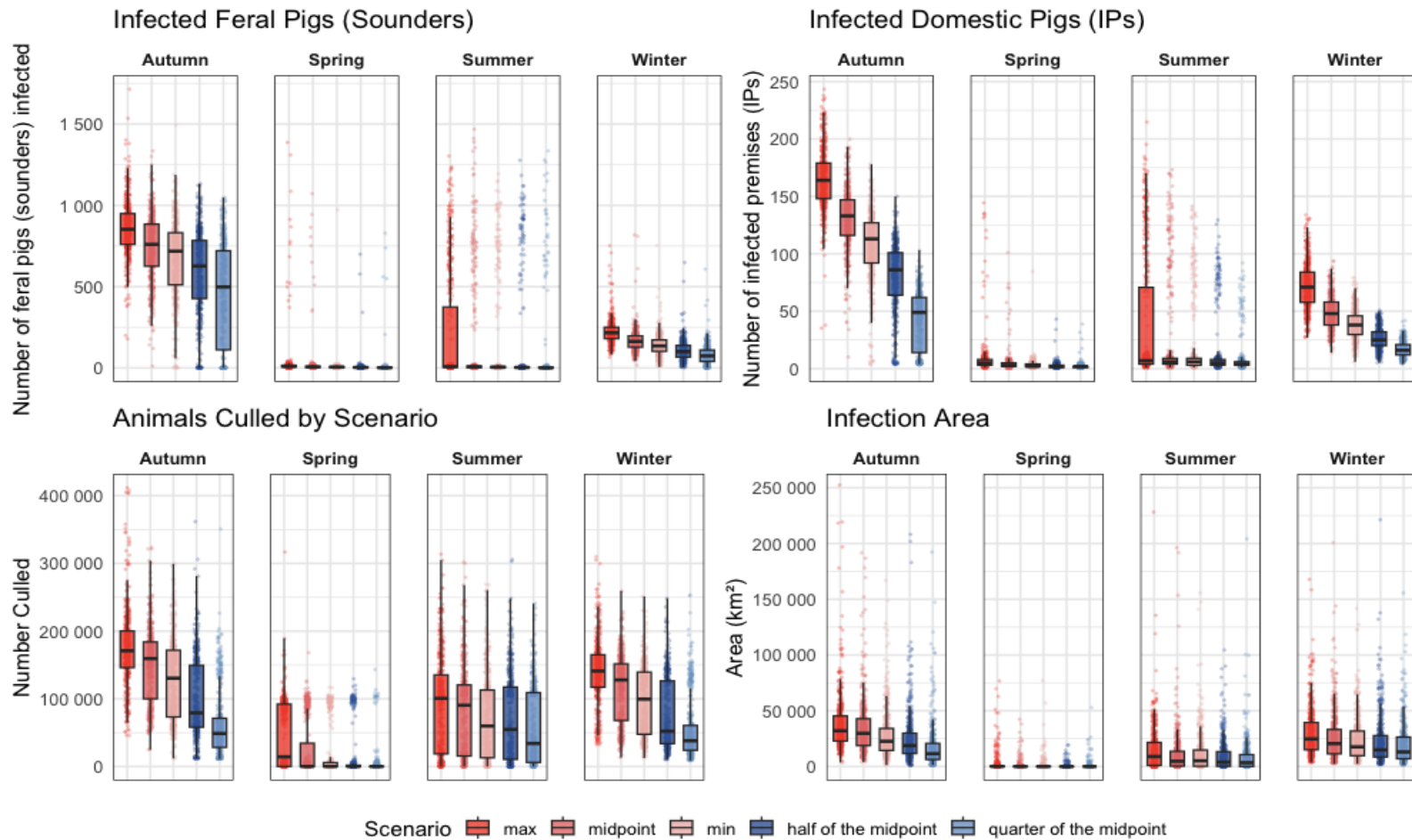


Figure 7.1: Sensitivity analysis of key outcome metrics from ASF outbreak simulations using AADIS, summarised by each scenario. The scenarios represent a different assumed contact rate between feral pigs and domestic pigs. The results show the final infected feral pig sounders, infected domestic pig properties (IPs), number of animals culled and the infection area (km²) at the end of the simulation, grouped by the season in which the outbreak was seeded. These values represent final totals, not seasonal rates of infection.

Table 7.5: Linear regression model outputs showing the estimated effects of season and various sounder-farm transmission scenarios on four key disease outcomes.

Outcome	Season/Contact rate	Coef	Std Error	Exponentiated Coef, i.e., original scale (95% CI)	
<i>log₁₀(Number of infected sounders)</i>	(Intercept)*	1.647	0.016	44.385	(41.21, 47.80)
	Autumn	0.602	0.016	3.998	(3.712, 4.306)
	Spring	-1.356	0.016	0.044	(0.041, 0.048)
	Summer	-1.156	0.016	0.07	(0.065, 0.075)
	Min	0.448	0.018	2.803	(2.58, 3.046)
	Midpoint half	0.304	0.018	2.015	(1.855, 2.189)
	Midpoint	0.559	0.018	3.626	(3.337, 3.94)
	Max	0.748	0.018	5.596	(5.15, 6.08)
<i>log₁₀(Number of IPs)</i>	(Intercept)*	1.267	0.009	18.491	(17.782, 19.227)
	Autumn	0.392	0.009	2.467	(2.372, 2.565)
	Summer	-0.956	0.009	0.111	(0.106, 0.115)
	Winter	-0.606	0.009	0.248	(0.238, 0.257)
	Min	0.292	0.01	1.958	(1.874, 2.045)
	Midpoint half	0.177	0.01	1.503	(1.439, 1.57)
	Midpoint	0.375	0.01	2.37	(2.269, 2.476)
	Max	0.53	0.01	3.385	(3.241, 3.536)
<i>log₁₀(Number of animals culled)</i>	(Intercept)*	4.551	0.02	35531.91	(32416.99, 38946.14)
	Autumn	0.115	0.02	1.303	(1.189, 1.428)
	Summer	-1.844	0.02	0.014	(0.013, 0.016)
	Winter	-0.417	0.02	0.383	(0.349, 0.419)
	Min	0.333	0.023	2.152	(1.942, 2.385)
	Midpoint half	0.195	0.023	1.568	(1.416, 1.738)
	Midpoint	0.449	0.023	2.81	(2.536, 3.113)
	Max	0.679	0.023	4.776	(4.311, 5.292)
<i>log₁₀(Infected area, km²)</i>	(Intercept)*	3.913	0.029	8180.593	(7185.092, 9314.021)
	Autumn	0.085	0.029	1.216	(1.068, 1.385)
	Summer	-3.239	0.029	0.001	(0.001, 0.001)
	Winter	-1.177	0.029	0.066	(0.058, 0.076)
	Min	0.319	0.032	2.082	(1.801, 2.407)
	Midpoint half	0.187	0.032	1.539	(1.331, 1.779)
	Midpoint	0.429	0.032	2.687	(2.324, 3.107)
	Max	0.71	0.032	5.132	(4.439, 5.933)

Coef – Coefficient, *Std Error* – Standard Error, *IPs* – Infected Premises, *CI* – Confidence Interval.
 * The intercept corresponds to the reference levels of **winter** season and **quarter of the midpoint** contact rate scenario.

7.3.2.2 Case study 2: Sensitivity of simulated outbreaks to inter-sounder contact rates

Inter-sounder relationships are also key drivers of disease outbreaks in the model. Results showed similar outcomes to Case Study 1, as both contact rate and seasonality strongly influenced outbreak dynamics (Figure 7.2). The numeric values of the outputs shown in Appendix E, Table 2.

Linear regression modelling demonstrated the influence of seasonal patterns on outbreak severity (Table 7.6). Using winter under the quarter midpoint contact scenario as the reference, outbreaks seeded in spring produced just 10% as many wild sounder infections (95% CI: 9.6–10.9%). Summer scenarios were similarly low, with infections reaching only 12.7% of winter levels (95% CI: 11.9%–13.5%). By contrast, autumn outbreaks produced over 4.4 times as many infections (95% CI: 4.2–4.7), indicating a strong seasonal amplification of transmission. A similar trend was observed in the number of domestic pigs (infected premises). Scenarios seeded in Spring produced only 14.6% as many infected premises as winter (95% CI: 14.1%–15.2%), and summer generated 17.4% (95% CI: 16.8%–18.1%), while autumn was associated with a 52% increase in the number of infected premises compared to scenarios seeded in winter (95% CI: 1.46–1.58). For the number of animals culled, seeding in spring reduced the outcome to 3.2% of the winter baseline (95% CI: 2.8%–3.5%), and seeding in summer to 21.8% (95% CI: 19.6%–24.3%). Autumn, however, had no substantial effect, remaining similar to winter (97.6%, 95% CI: 87.8%–108.5%). Scenarios seeded in spring were associated with a large reduction in infected area, 0.2% of the winter reference (95% CI: 0.2% to 0.3%), and summer to 3.3% (95% CI: 2.9%–3.9%). Scenarios seeded in autumn only has a slight reduction to 14% of winter levels (95% CI: 1%–25% lower than infected areas in winter).

Inter-sounder contact scenarios were also key drivers of outbreak severity. Compared to the quarter midpoint baseline, the mean contact scenario produced 7.79 times more wild infections (95% CI: 7.26–8.36), 2.21 times more infected premises (95% CI: 2.12–2.31), 1.76 times more animals culled (95% CI: 1.57 to 1.98), and nearly 1.89 times the infected area (95% CI: 1.61–2.22). The maximum contact scenario increased these effects further, producing nearly 12 times more wild infections (95% CI: 11.15–12.84), 2.87 times more infected premises (95% CI: 2.75–2.99), 2.59 times more animals culled (95% CI: 2.30–2.91), and a 3.62-fold increase in infected area (95% CI: 3.08–4.25).

These findings highlight the importance of incorporating both seasonal context and inter-sounder connectivity into outbreak preparedness and management planning. Seasonal timing and contact intensity are not only consistent predictors of outbreak magnitude but also critical levers for potential intervention.

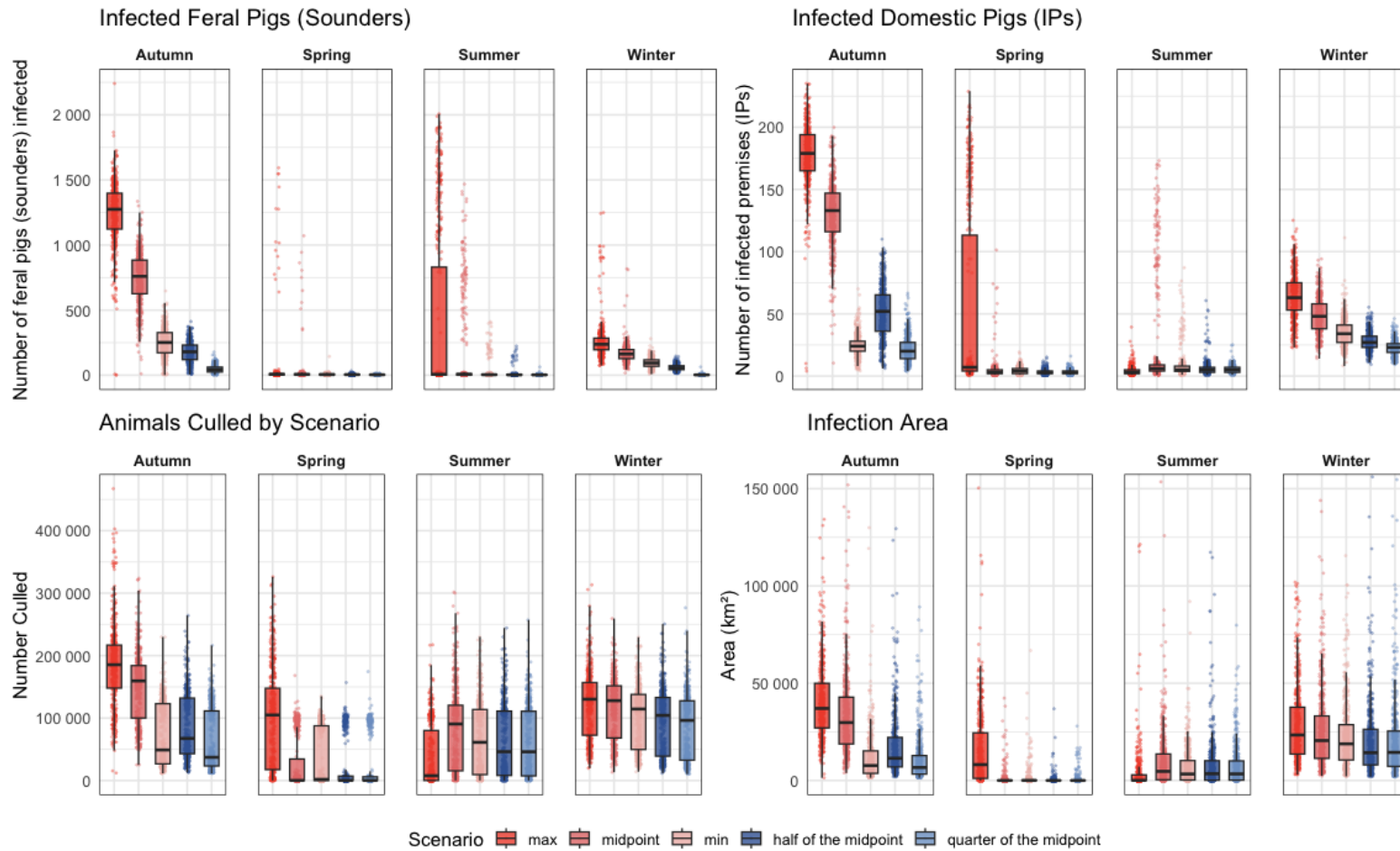


Figure 7.2: Sensitivity analysis of key outcome metrics from ASF outbreak simulations using AADIS, summarised by each scenario. The scenarios represent a different inter-sounder contact rate. The results show the final number of infected feral pig sounders, infected domestic pig properties (IPs), number of animals culled and the infection area (km²) at the end of the simulation, grouped by the season in which the outbreak was seeded. These values represent final totals, not seasonal rates of infection

Table 7.6: Linear regression model outputs showing the estimated effects of season and various sounder-sounder transmission scenarios on four key disease outcomes.

Outcome	Season/Contact rate	Coef	Std Error	Exponentiated Coef, i.e., original scale (95% CI)	
<i>log₁₀(Number of infected sounders)</i>	(Intercept)*	1.148	0.014	14.06	(13.2, 15.0)
	Autumn	0.647	0.014	4.43	(4.16, 4.72)
	Spring	-0.992	0.014	0.102	(0.096, 0.109)
	Summer	-0.897	0.014	0.127	(0.119, 0.135)
	Min	0.616	0.016	4.13	(3.85, 4.44)
	Midpoint half	0.490	0.016	3.09	(2.88, 3.32)
	Midpoint	0.892	0.016	7.79	(7.26, 8.36)
	Max	1.078	0.016	12.0	(11.1, 12.8)
<i>log₁₀(Number of IPs)</i>	(Intercept)*	1.357	0.009	22.8	(21.9, 23.7)
	Autumn	0.181	0.009	1.52	(1.46, 1.58)
	Spring	-0.835	0.009	0.146	(0.141, 0.152)
	Summer	-0.758	0.009	0.174	(0.168, 0.181)
	Min	0.100	0.01	1.26	(1.21, 1.32)
	Midpoint half	0.123	0.01	1.33	(1.27, 1.39)
	Midpoint	0.345	0.01	2.21	(2.12, 2.31)
	Max	0.458	0.01	2.87	(2.75, 3.00)
<i>log₁₀(Number of animals culled)</i>	(Intercept)*	4.760	0.023	57497	(51721, 63918)
	Autumn	-0.010	0.023	0.976	(0.878, 1.09)
	Spring	-1.501	0.023	0.032	(0.028, 0.035)
	Summer	-0.661	0.023	0.218	(0.196, 0.243)
	Min	0.151	0.026	1.42	(1.26, 1.59)
	Midpoint half	0.069	0.026	1.17	(1.04, 1.32)
	Midpoint	0.246	0.026	1.76	(1.57, 1.98)
	Max	0.413	0.026	2.59	(2.30, 2.91)
<i>log₁₀(Infected area, km²)</i>	(Intercept)*	4.028	0.032	10660	(9233, 12308)
	Autumn	-0.065	0.032	0.862	(0.747, 0.995)
	Spring	-2.644	0.032	0.002	(0.002, 0.003)
	Summer	-1.475	0.032	0.033	(0.029, 0.039)
	Min	0.149	0.036	1.41	(1.20, 1.66)
	Midpoint half	0.062	0.036	1.15	(0.983, 1.36)
	Midpoint	0.277	0.036	1.89	(1.62, 2.22)
	Max	0.558	0.036	3.62	(3.08, 4.25)

Coef – Coefficient, *Std Error* – Standard Error, *IPs* – Infected Premises, *CI* – Confidence Interval.

* The intercept corresponds to the reference levels of **winter** season and **quarter of the midpoint** contact rate scenario.

7.4 Discussion

This study demonstrates the influence of varying rates of feral to domestic pig and inter-sounder contact on simulated ASF outbreak dynamics in Australia. The AADIS model was parameterised using empirical contact rate data across seasons, enabling a structured assessment of how these parameters affect modelled outbreak outcomes. The modelling quantified the relative impact of these contact pathways and their seasonal variation on outbreak size, extent, and severity within the AADIS framework. Across all scenarios, it was found that increased feral to domestic and inter-sounder contact rates were associated with larger simulated outbreaks, with seasonal variation in these rates further amplifying or reducing simulated transmission dynamics. These findings illustrate how integrating empirical data into the AADIS framework allows for quantification of key transmission pathways and their seasonal influence, supporting scenario-based assessments relevant to risk-based preparedness planning.

The sensitivity analysis confirmed that the rate of feral-domestic contact is a key driver of outbreak size across all outcome metrics, including the number of infected premises (IPs), infected feral pig sounders, infection area, and animals culled in the simulated outbreaks. Even in scenarios with relatively low feral-domestic spillover, outbreaks could still escalate significantly depending on seasonal timing within the model. Notably, increases in this parameter across all seasons led to increases in outbreak scale, highlighting its influence on model outputs. These findings align with previous modelling studies suggesting that wild-domestic transmission pathways are crucial for outbreak initiation and spread, particularly in landscapes where domestic pigs and feral pigs share overlapping ranges^{355,417,421}.

While feral-domestic incursions present as an imminent concern for disease emergence to livestock, the potential for direct or indirect inter-sounder contact contributes to the extent to which ASF persists and spreads throughout the feral pig population at communal points of interest^{417,421}. The AADIS model also exhibited high sensitivity to changes in this parameter, as increased inter-sounder contact rates resulted in larger outbreaks and a corresponding increase in the likelihood of domestic farm incursions within the model. Inter-sounder contact, particularly when amplified by seasonal movement patterns, has been identified as a key mechanism in the potential spread of infectious diseases among feral pig populations^{418,419,423}. These effects are particularly concerning in combination with seasonal constraints such as reduced water availability or food scarcity, which may force sounders to overlap at shared resource points of interest, such as a piggery or feedlot where resources are available^{303,409,423}. A recent study quantified inter-sounder interactions in eastern Australia by using GPS tracking data from 146 feral pigs and found that seasonal variations also further impacted contact dynamics between sounders (especially intra-sounder contact) in summer⁴¹⁹. This was also found in

both case studies (within the maximum scenarios), demonstrating high infections among the feral pigs during summer and autumn compared to the other seasons.

The identification of periods of heightened risk, such as autumn, suggests that modelled outbreak outcomes are particularly sensitive to seasonal timing and reflect when disease prevention efforts should be intensified^{104,355,387}. In the context of the AADIS-ASF simulations, enhanced farm surveillance, buffer-zone monitoring, and movement restrictions may be more effective during times when feral pigs are likely to interact with farms or overlap with other sounders. Additionally, proximity to communal use of water bodies, crops, or farm-adjacent attractants creates zones of increased aggregation points for potential contact, resulting in the disease to be sustained and transmitted among multiple sounders in the model¹⁶⁰. Such conditions can increase contact rates between sounders and farms, acting as a bridge between isolated outbreaks and increased risk of spreading to livestock production systems under the simulated scenarios. These results reinforce that both feral-to-domestic and inter-sounder contact rates are influential parameters in the AADIS-ASF model and that their effects are modulated by seasonal variation in contact behaviour. Accordingly, the implications of these findings should be interpreted as conditional on the assumptions and structure of the AADIS-ASF model rather than as direct predictions of field outcomes. Specifically, the findings demonstrate that small increases in key contact rates, whether seasonal or due to specific settings such as farms near attractants, can scale up simulated outbreak impacts. As such, these results provide scenario-based evidence that may help inform preparedness planning and guide enhanced control deployment in high-risk periods and locations, where empirical data suggest contact rates are elevated.

An important aspect of this study was the use of empirical camera trap data to demonstrate and inform the model's parameterisation, particularly in estimating contact rates across different seasonal contexts. By drawing on field data collected at a commercial piggery, the model reflects realistic patterns of feral pig activity and habitat use at a point of interest between sounders (being the piggery in this case), providing context-specific inputs to the simulation of disease transmission dynamics. This approach demonstrates how locally derived surveillance data can be used to tailor epidemiological models to real-world settings, offering producers and policymakers a more grounded understanding of potential risk. However, while this location-specific focus enhances the relevance of the findings for the immediate study region, it also denotes a limitation that broader-scale and standardised datasets are needed to extend the model's applicability to other geographic regions and production systems. To improve the external validity and predictive value of such models, future work should prioritise the collection and utilisation of long-term surveillance data across diverse ecological and farming contexts.

Doing so would facilitate greater model validation and enable the development of robust, nationally scalable tools for disease preparedness and response.

This study confirms that feral–domestic pig spillover contact rates and inter-southern contact rates are sensitive and influential parameters in the AADIS model for simulating potential ASF outbreaks in Australia. Through scenario testing and sensitivity analysis, the model demonstrated that variation in these parameters considerably affects simulated outbreak size and impacts. Importantly, these parameters were informed by empirical data on seasonal contact rates, enabling the simulations to reflect realistic conditions observed in the field in a specific region. By quantifying the scale of these effects under different parameter values, this chapter contributes to ASF preparedness by highlighting modelled scenarios where and when disease risk may be most pronounced under current ecological conditions. While all findings remain conditional on the validity of AADIS-ASF framework, the integration of further empirical contact data into a national-scale disease model can help strengthen a valuable tool for guiding targeted planning and response strategies.

Appendix E: Chapter 7 supplementary material

Table E 1: Outputs of AADIS simulations, summarised by contact rate scenario and season of outbreak seeding. Scenarios reflect varying estimated contact rates between feral and domestic pigs. For each scenario-season combination, the table shows the final median [5th–95th percentile] of infected domestic pig properties (IPs), infected feral pig sounders, infection area (km²), and animals culled. Values represent cumulative outcomes by the end of each simulation.

Scenario (contact rate)	Season	Domestic pigs (IPs) median [5 th - 95 th]	Feral pigs (Infected sounders) median [5 th – 95 th]	Infection area (km ²) median [5 th - 95 th]	Animals culled median [5 th - 95 th]
Midpoint contact rate					
0.86	Summer	6 [2 – 125]	6 [0 – 845]	4,703 [0 – 37,612]	90,575 [252 - 189,728]
2.59	Autumn	133 [85 – 170]	760 [388 – 1017]	29,755 [9,997 – 86,971]	159,441 [63,892-234,596]
1.04	Winter	48 [26 – 75]	163 [83 – 252]	20,543 [4,693 – 65,345]	127,894 [36,613 – 182,743]
0.45	Spring	3 [1 – 8]	6 [0 – 22]	3 [0 -4,706]	171 [140 – 102, 600]
Minimum contact rate					
0.64	Summer	6 [2 – 100]	4 [0 – 847]	5,107 [0 – 4,2691]	59,908 [147 -174,028]
1.37	Autumn	113 [56 – 147]	718 [280 – 992]	22,594 [7,553– 69,172]	130,566 [50,672–223,158]
0.73	Winter	38 [19 - 62]	135 [47 – 229]	17,615 [4,517– 64,516]	99,573 [28,051 – 171,991]
0.41	Spring	2 [1 – 7]	5 [0 – 15]	0 [0 – 5,245]	157 [141 – 99,784]
Maximum contact rate					
1.04	Summer	7 [2 – 152]	8 [1 – 971]	8,937 [0 – 46,419]	100,650 [266 – 208,880]
3.91	Autumn	164 [126 – 213]	852 [597 – 1146]	32,061 [14,002– 85,642]	171,017 [83,323–265,808]
1.36	Winter	71 [41 – 109]	216 [123 – 325]	32,061 [7,135– 69,759]	141,080 [49,715–216,948]
0.49	Spring	5 [2 – 15]	10 [2 – 29]	64 [0 – 14,724]	14,349 [141 – 105,274]
Half of the midpoint contact rate					
0.43	Summer	5 [1 – 83]	3 [0 – 877]	3,952 [0 – 36,121]	54,871 [141 – 170,008]
1.26	Autumn	86 [8 – 117]	626 [4 – 957]	18,710 [5,034 – 64,296]	79,266 [21,943 – 195,115]
0.52	Winter	25 [11 – 44]	100 [26 – 190]	14,899 [3,339 – 66,326]	52,301 [19,572 – 160,375]
0.23	Spring	2 [1 – 6]	3 [0 – 12]	0 [0 – 2,107]	147 [141 – 100,420]
Quarter of the midpoint contact rate					
0.22	Summer	4 [1 – 46]	0 [0 – 661]	3,426 [0 – 27,789]	34,095 [141 – 149,056]

0.65	Autumn	2 [1 – 4]	498 [0 – 915]	11,467 [1,361 – 48,852]	48,844 [12,060 – 162,165]
0.26	Winter	16 [7 – 29]	74 [2 – 174]	13,049 [2,619 – 58,619]	38,080 [13,381 – 145,887]
0.11	Spring	2 [1 – 4]	1 [0 – 9]	0 [0 – 3,345]	147 [141 – 100,420]

Table E 2: Outputs of AADIS simulations, summarised by contact rate scenario and season of outbreak seeding.

Scenarios reflect varying estimated inter-sounder contact rates. For each scenario-season combination, the table shows the final median [5th–95th percentile] of: infected domestic pig properties (IPs), infected feral pig sounders, infection area (km²), and animals culled. Values represent cumulative outcomes by the end of each simulation.

Scenario (contact rate)	Season	Domestic pigs (IPS) median [5 th - 95 th]	Feral pigs (Infected sounders) median [5 th – 95 th]	Infection area (km ²) median [range]	Animals culled median [5 th - 95 th]
Midpoint contact rate					
0.86	Summer	6 [2 – 125]	6 [0 – 845]	4,703 [0 – 37,612]	90,575 [252 - 189,728]
2.59	Autumn	133 [85 – 170]	760 [388 – 1017]	29,755 [9,997 – 86,971]	159,441 [63,892- 234,596]
1.04	Winter	48 [26 – 75]	163 [83 – 252]	20,543 [4,693 – 65,345]	127,894 [36,613 – 182,743]
0.45	Spring	3 [1 – 8]	6 [0 -22]	3 [0 -4,706]	171 [140 – 102, 600]
Minimum contact rate					
0.64	Summer	5 [2 – 32]	4 [0 – 174]	3,313 [0 – 21,873]	61,142 [148 -165,059]
1.37	Autumn	24 [11 – 41]	251 [86 – 427]	7,668 [2,127 – 33,195]	48,949 [17,899 – 146,921]
0.73	Winter	34 [19 – 52]	94 [37 – 157]	18,843 [4,546 – 59182]	114487 [27614 – 174329]
0.41	Spring	4 [1 – 8]	5 [1 -17]	24 [0 – 5,913]	1,802 [120 – 103,195]
Maximum contact rate					
1.04	Summer	3 [1- 10]	7 [0 – 1719]	60 [0 – 16,916]	7,743 [122 – 125,081]
3.91	Autumn	179 [139 – 214]	1274 [806 – 1543]	37,025 [16,130 – 90,559]	185,406 [81,621 – 295,472]
1.36	Winter	63 [33 – 95]	238 [124 – 391]	23,380 [6,503 – 69,114]	130,229 [40,460 – 201,096]
0.49	Spring	7 [2 – 188]	7 [1 – 24]	8,166 [0 – 49,832]	104,888 [171 – 236,485]
Half of the midpoint contact rate					
0.43	Summer	5 [2 -12]	3 [0 – 12]	3,452 [0 – 28,036]	46,161 [146 -165,125]
1.26	Autumn	52 [16 – 89]	180 [40 – 308]	11,438 [3,644 – 48,092]	67,407 [239,63 – 170,530]
0.52	Winter	27 [17 – 42]	56 [27 – 98]	14,249 [3,386 - 57,649]	104,254[23,363 – 167,861]
0.23	Spring	3 [1 – 7]	5 [1 – 13]	2 [0 -1,748]	164 [112 – 102,610]

Quarter of the midpoint contact rate					
0.22	Summer	5 [2 -10]	3 [0 – 8]	3,364 [0 – 28,643]	46,021 [157 -150,967]
0.65	Autumn	20 [7 – 41]	44[10 – 102]	6,691 [1,831 - 35,039]	37,207 [13,158 – 142,763]
0.26	Winter	23 [13 – 33]	3 [0 -8]	14,429 [2,920 – 59,565]	96,336 [18,123 - 159,243]
0.11	Spring	3 [1 – 6]	3 [1 – 9]	1 [0 – 3,064]	160 [133 – 101,272]

8 General Discussion

This thesis aimed to undertake epidemiological studies to improve the understanding of the dynamics between feral and commercial pigs and thus inform Australia's preparedness for potential ASF outbreaks. This began with an investigation into the potential role of wild pigs in ASF outbreaks in Asia and the Pacific to gather insights into what has occurred in locations where ASF is already present or a growing concern. The studies that followed involved the development of a protocol for the deployment of camera trap surveillance around piggeries, investigation into the detection probability of camera traps of various coverages, the development of a risk assessment tool for assessing feral pig risk around commercial piggeries, and finally, a sensitivity analysis to assess the importance of feral-domestic pig contact rates in ASF outbreaks using the Australian Animal Disease Spread (AADIS) model. This discussion overviews the key findings of each research chapter, critically evaluates the methodologies used and thereby the strength of the key findings, and discusses important areas for future investigation in relation to feral-domestic pig interactions and the broader implications of this work for infectious disease management whilst reflecting on my personal experience and skills gained throughout this research journey.

The first research chapter examined the role of wild pigs in the Asia and Pacific region, focusing on their ecological behaviour, population dynamics, and their capacity to spread ASF. The contribution made by wild pigs is currently not well understood; as their distribution, density and susceptibility to the virus has raised concerns that their role in the epidemiology of ASF in the region might be underestimated^{28,424}. The aim of this chapter was to assess the potential role of wild pigs in ASF outbreaks in the region and to provide recommendations regarding what control and management strategies could be used (or further enhanced) to reduce the risk of wild pigs becoming a major driver of ASF spread. It was important to conduct a literature review initially to understand the dynamics of wild and endemic suid species present within the region, and which of these have been infected with ASF. Formal meetings with representatives from the Food and Agriculture Organisation of the United Nations (FAO) Global Framework for the progressive control of Transboundary Animal Diseases (GF-TADs) provided a rare opportunity to further develop conceptual thinking about this topic, beyond that of the literature review. By reviewing surveillance data from international databases (e.g., the World Animal Health Information System WAHIS, FAO, and IUCN), quantitative information on disease spread, reported outbreaks, and the distribution and conservation status of wild suid species across the study area was collated. This was then compared with findings from the published literature to assess alignment and highlight inconsistencies. This method allowed several sources of information to

be consolidated to provide a broad overview of ASF outbreaks and the populations affected. A meta-analysis would have been an alternative approach, providing a more robust statistical evaluation of reporting trends and disease transmission risks but was considered infeasible due to a lack of quantitative data of documented accuracy and precision. Given these limitations, a descriptive approach was reasoned to be more appropriate to establish a clear background understanding of ASF spread and reporting patterns. The survey was distributed by email to WOAHP country delegates within Asia and the Pacific via the WOAHP regional representative network. In instances in which multiple delegates from the same country provided a response to the survey, their results were merged to provide a single country level response. If contradictory answers were provided by multiple respondents from the same country, preference was given to 'yes' answers. While this approach simplified aggregation, it may have introduced a form of information bias, which could slightly overestimate the presence of transmission, or implementation of surveillance measures and control activities. Also, assuming that control measures are in place when they are not, can give a false sense of security. This may lead to underestimating the risk of disease spread, causing insufficient responses and allowing outbreaks to worsen. I note that the overall focus of the chapter was to explore the potential for wild pig populations to contribute to ASF spread across the Asia-Pacific region, rather than provide precise country-level estimates. Given the chapter's broader focus on ecological patterns and risk potential, the impact of this bias is considered to be minor and does not meaningfully alter the key findings or the overall interpretation of the thesis. To improve this method in the future, the survey could include a wider range of participants beyond WOAHP country delegates (such as herd managers or pork industry representatives) and use different methods to reach respondents, such as phone calls or in-person meetings, if feasible. When aggregating responses from the same country, an improved systematic approach could be used, such as considering the expertise of respondents or using consensus techniques such as the Delphi method.

This research highlighted gaps in ASF surveillance and reporting in wild suid populations across Asia and the Pacific. Areas for important further research include strengthening ASF surveillance in wild suid populations, particularly through targeted active surveillance in high-risk regions and expanding monitoring efforts using remote sensing and GPS tracking to refine ASF risk assessments. Improving knowledge of wild suid distribution and population densities remains critical to better understand their role in ASF transmission. Additional studies are also needed to examine ecological factors influencing ASFV persistence, such as carcass decomposition rates across different climates. Evaluating the effectiveness of various control strategies would support the development of practical mitigation measures, such as population management tools for *Sus scrofa* and region-specific biosecurity improvements for small-scale and free-range pig farming systems. Proactive measures in

ASF-free areas, including enhanced border quarantine and early detection systems, also warrant further investigation. Conservation-focused research could assess ASF's impact on endemic wild suid species, contributing to the design of tailored protection programs. Lastly, enhancing international collaboration and working toward standardised ASF surveillance protocols across WOA member countries will be key to improving data consistency, outbreak reporting, and coordinated disease management.

Importantly to note, the relevance and relative importance of these surveillance and control priorities differ across regions, reflecting variation in production systems, biosecurity practices, and surveillance capacity. For example, in Europe domestic pig holdings are often considered epidemiological dead ends under high biosecurity and reporting standards, whereas findings from East and Southeast Asia suggest more frequent bidirectional transmission between domestic pigs and wild suids, as reflected in the WOA survey results presented in this thesis^{28,360,425}. In Australia, ASF dynamics are expected to differ again due to the prohibition of swill feeding, generally high on-farm biosecurity, and reliance on passive surveillance systems, alongside the presence of widespread feral pig populations. Accordingly, the findings of this thesis are interpreted within an Australian ecological and regulatory context rather than assuming uniform ASF epidemiology across regions.

The second chapter focused on developing a camera trap surveillance protocol to monitor feral pig activity around commercial piggeries as the disease risks posed by interactions between feral and domestic pigs remain a concern^{64,162,303–305}. There is currently limited data or evidence in Australia confirming: (a) if these interactions are occurring; and (b) if they are occurring, their frequency³². As a result, effective surveillance is crucial for capturing these pig interactions and enhancing biosecurity measures. This chapter outlined the development and application of a protocol using camera trap technology around commercial piggeries, which can be replicated and utilised by the pork industry to assess farm-level risk of feral pig encounters. The findings from this study guide the implementation of a comprehensive feral pig surveillance system for commercial piggeries.

For this camera trap surveillance system to be readily implemented by pig herd managers, it was important that it was practical, scalable, and tailored to varying farm conditions. This required a clear, easy-to-follow deployment protocol, using cost-effective technology, and minimal maintenance demands. While the Reconyx™ cameras that we used for this study proved to be fit for purpose, future approaches could explore the use of solar-powered, cellular-connected alternatives that can send real-time alerts. This would reduce labour requirements for checking devices and enable herd managers to respond quickly to incursions, strengthening biosecurity at the farm boundary.

The protocol involved two phases of camera deployment: an initial pilot period followed by the full monitoring setup. The pilot period played a critical role in confirming the presence of feral pigs before committing additional resources to full-scale surveillance. This step was essential for ensuring efficient use of time, labour, and equipment, avoiding unnecessary deployment in areas that were likely to have no pig activity. By identifying high-activity zones early, the pilot phase allowed for targeted camera placement during the main monitoring period, improving data quality while conserving resources. Incorporating a pilot phase into standard surveillance protocols can help herd managers implement monitoring systems more strategically and cost-effectively. Future studies could improve recommendations around the pilot period by testing different pilot durations and deployment strategies across various sites and seasons. This would help determine the optimal length and timing needed to confirm feral pig presence efficiently. Incorporating complementary detection methods, such as ground surveys or baited sites, could enhance detection during this phase. Additionally, evaluating the cost–benefit of different pilot designs and trialling camera rotation may offer more targeted and resource-efficient surveillance protocols.

For herd managers to move beyond the pilot phase and adopt a full monitoring system, the systematic grid layout provided a practical and adaptable framework for camera placement. Rather than recommending that a camera be placed in every grid cell, the grid was intended to provide a guide for camera placement, driven by the required level of coverage. This allowed flexibility while still maintaining consistency in layout, which was critical for data quality and comparison of findings across different sites. Importantly, the grid system formed the foundation for the next research chapter, investigating the detection probability (Chapter 5) under different camera coverage scenarios. The results from this protocol and the detection probability work allow herd managers to make informed decisions about how many cameras may be required to effectively monitor their property, depending on their risk level, property size, and resource availability. As a result, the grid layout not only contributed to a more systematic monitoring design but also played a key role in shaping evidence-based recommendations on surveillance efficiency, helping producers strike a balance between cost, effort, and detection reliability.

The artificial intelligence software packages eVorta and Wildlife Insights were evaluated to complete the image analysis processes. Both packages use an automatic image recognition algorithm that identifies and tags animal species using camera trap data. The algorithms use previously uploaded images to train their current models, resulting in high specificity and sensitivity for both programs. The Wildlife Insights package was somewhat inefficient as the user had to provide confirmation before uploaded data could be added to the ‘catalogue’ folder (i.e., data transfer was not automatic). Additionally, due to the large number of images being uploaded after each camera service (ranging

from 0.24 to 1.28 million images) the process of uploading data became time consuming. As a result, manually identifying images was found to be more efficient for the purposes of this study. Improving the speed of file transfers and/or reducing the number of images to be processed to return the same outcomes is a profitable area of future investigation. Additionally, identifying individual feral pigs within the data was a challenge due to their physical similarities, so a 10-minute interval between encounters was implemented to help manage uncertainties in distinguishing individual pigs. This interval was intended to reduce the likelihood of counting the same animal multiple times within a short period, thereby providing a more conservative and standardised estimate of independent detection events

While automatic image recognition helped to standardise detections, it may have introduced bias. If different pigs were captured on camera within a timeframe, they may have been grouped as one, leading to underestimates in pig numbers. Conversely, if the same pig reappeared just outside of the 10-minute interval, it may have been counted more than once. These potential errors likely affected the accuracy of the encounter estimates, which were used to understand feral pig activity and detection probability in the following chapter (Chapter 5). As a result, this assumption introduced uncertainty around the number of unique encounters and may have reduced the internal validity of our findings. Since the data relied on assumptions, the findings should be interpreted with caution. Future research could improve the validity and reliability of similar models by incorporating GPS-collars on several pigs within different sounder groups to help track the movement of individual pigs and determine if they were the same or separate detections within the 24-hour period. The analysis of temporal patterns through regression models and non-linear splines provided valuable insights into pig activity patterns. Expanding the model to include environmental variables, such as temperature or habitat suitability index' of feral pigs, could further refine these analyses.

Overall, this study provided a valuable framework for monitoring feral pig activity around commercial piggeries, providing empirical data for the subsequent research chapters, and help inform surveillance planning and disease modelling. Further work could incorporate GPS collaring alongside camera traps to improve the precision of movement data by estimating encounters of individual pigs and providing clearer insights into contact rates. For surveillance data to be informative across an entire jurisdiction or national scale in disease models such as AADIS, it is required to be spatially representative, and capable of capturing patterns of pig activity across different seasons and landscapes. This includes reliable estimates of presence, movement pathways, and potential contact with domestic pigs. Achieving this level of data quality requires standardised deployment strategies, sufficient coverage, and long-term monitoring to account for temporal variation. Optimising camera placement, such as identifying the minimum level of coverage needed to retain accurate detection probabilities, is critical

not only for cost-effective implementation in commercial settings, but also for producing data robust enough to support disease modelling.

Parameters such as pig density, movement distance, and the frequency of feral–domestic pig interactions are essential for simulating disease transmission and assessing outbreak risk. Improved parameterisation, grounded by empirical data, would strengthen the predictive accuracy of the model and enhance its utility for emergency response planning and targeted biosecurity interventions. Recommendations for further work include trialling GPS-collar deployments with camera trap monitoring to validate detection-based assumptions and better understand the scale of pig movements. These steps would provide the pork industry with a stronger evidence base to inform surveillance strategies, improve biosecurity decision-making, and refine disease spread models used at state and national levels.

The detection probability chapter (Chapter 5) was an extension of the camera trap surveillance protocol by evaluating how different camera coverage intensities influenced the probability of detecting feral pig activity. The objective was not only to assess detection performance but to generate applied insights into how surveillance could be optimised for practical on-farm use. Understanding detection probability was critical for improving the cost-efficiency of biosecurity surveillance and aligning effort with risk.

The study design incorporated both random and purposive subsampling to simulate various levels of coverage (from 10% to 100%) under different layout configurations, including fence-only, hotspot-only, and combined strategies. As the analysis was limited to a single property, its internal validity (such as the confidence in the relationships observed between camera placement and detection) was strong. However, external validity to other farms or regions, remained constrained by the homogeneous context and limited spatial replication. The method used was novel as it integrated empirical camera trap data with probabilistic modelling to guide real-world surveillance decisions. By reconstructing lower coverage scenarios from a full dataset, the analysis approximated how producers might experience lower detection success as surveillance effort is reduced. This method offered a practical and scalable way to estimate performance trade-offs without requiring repeated field trials, creating an innovation with potential for broader application in wildlife monitoring and farm biosecurity.

One of the key findings was that hotspot-based camera placement consistently outperformed systematic fence layouts, particularly at lower coverage intensities. This affirmed that targeting surveillance in high-risk zones, such as nature corridors near water sources, shelter, or feeding areas offer greater detection returns than attempting perimeter-wide coverage. For the farm used, an

optimised layout would therefore prioritise dense coverage of known activity hotspots, especially during peak periods identified in prior analyses. Such a strategy could reduce costs without compromising surveillance integrity, an insight of high relevance to producers with limited resources.

However, this approach carried inherent limitations. Identifying hotspots was dependent on expert guided prior knowledge of pig movement patterns, which may not be available for all properties or may vary seasonally. The reliance on purposive placement could introduce selection bias if high-risk areas are misidentified, potentially leading to undetected incursions. As such, the findings reinforced the value of adaptive surveillance strategies, whereby systematic layouts are used initially to identify hotspots, which are then prioritised for ongoing monitoring. This blend of systematic and purposive placement offered a more resilient model for on-farm biosecurity.

The study also identified areas for methodological refinement. Although layout comparisons were useful, they were based on a single farm's topography and did not account for differences across various landscapes, which could affect pig movement and detection. Expanding the study to include multiple farms and terrain types would improve external validity and support broader industry recommendations. Moreover, incorporating spatial covariates such as vegetation cover, topography, and human activity into detection models would enhance predictive accuracy and support precision surveillance.

In summary, the study provided novel, empirically informed insights into how surveillance design affects detection probability and operational efficiency. The methods used allowed for flexible, data-driven optimisation of camera layout strategies and produced actionable evidence that producers can use to tailor surveillance to their specific biosecurity needs. While the approach demonstrated strong internal validity and practical relevance, further research is needed to test its reliability across diverse environments and seasons. Importantly, the findings underscored the potential for surveillance systems to move beyond uniform deployment toward risk-based, adaptive strategies that maximise efficiency without compromising detection capacity.

The previous chapters primarily focused on quantifying the role of feral pigs in the potential spread of ASF, and how to efficiently monitor their presence to assess the likelihood of interactions with domestic pig herds. Building on this, the objective of the risk assessment chapter (Chapter 6) was to develop a quantitative risk assessment tool that estimates the probability of feral pig encounters at the boundary of commercial piggeries in Queensland, Australia. This tool was designed to support evidence-based decision-making by pork producers, enabling them to assess their individual risk levels and determine the appropriate degree of surveillance and control efforts, such as trapping or ground shooting, without relying on blanket assumptions or generic protocols.

The tool integrated a combination of expert elicitation, peer-reviewed literature, and empirical data aggregation methods, offering a structured and transparent way to incorporate uncertainty, variability, and limited data, all challenges that are common in wildlife surveillance and emerging disease risk modelling. An important outcome of this work was the identification of high-risk seasonal periods and spatial nodes, providing an attempt at a spatially and temporally explicit model for predicting contact risk between feral and domestic pigs in the Australian context. This offers clear utility for targeted intervention, allowing producers and industry bodies to shift from reactive to proactive surveillance and control.

To evaluate the internal validity and practical relevance of the risk tool, a real-world case study was conducted using a piggery where feral pig presence had been documented through camera trapping (Chapter 3). The outputs of the model aligned well with observed detections, providing initial empirical support for its applicability. This form of informal validation demonstrated that the tool could reasonably capture the likelihood of feral pig activity at specific locations and times, lending credibility to its underlying assumptions and structure. However, external validity such as the generalisability of the tool across broader regions or diverse production systems, remains limited without further application across a variety of piggeries with differing environmental, operational, and biosecurity characteristics.

Several areas for further refinement emerged, such as expanding the tool to incorporate climatic variables, such as rainfall, water availability, and vegetation growth, would allow it to better reflect ecological drivers of feral pig movement and activity. Additionally, conducting a sensitivity analysis of the model would help clarify which input variables most influence the risk estimates, aiding in simplification, transparency, and the identification of future data collection priorities. Such analysis would also highlight the intervention points most likely to reduce encounter risk.

Crucially, while the underlying structure of the risk assessment was functional and technically possible at a single site, its utility could be enhanced through the development of a user-friendly digital platform. Such a tool would allow herd managers to input site-specific information, such as geographic location, landscape features, and biosecurity measures and receive tailored outputs with corresponding surveillance and control recommendations. This type of interactive, accessible system would greatly improve the likelihood of industry uptake and provide real-time, location-specific guidance for pork producers.

In its current form, the risk assessment tool presents a strong foundation for further development and is ready to be shared with Australian Pork Limited (APL) as a framework for risk quantification and targeted biosecurity planning. The identification of high-risk periods and locations can already be used

to inform strategic decisions regarding the timing and deployment of surveillance and control programs. The risk assessment alignment with empirical detection data demonstrates its immediate value in identifying locations where feral pig incursions are likely, which can guide resource allocation and policy development.

Nonetheless, further work is needed before the tool can be implemented at scale across the industry. This includes broader field validation, completion of sensitivity and uncertainty analyses, integration of dynamic environmental variables, and the creation of an accessible interface. Industry uptake will depend not only on the technical performance of the tool but also on the clarity and usability of its outputs. By working towards these next steps through collaboration with APL and stakeholders, this tool has the potential to become a central component of national biosecurity strategy for managing feral pig incursions and mitigating disease risks such as ASF.

The final research chapter used the Australian Animal Disease Spread (AADIS) model to conduct a sensitivity analysis, evaluating how different levels of feral pig-to-farm transmission and inter-sounder contact rates influence simulated African swine fever (ASF) outbreak dynamics. By simulating a range of scenarios across two case studies, the analysis demonstrated how seasonal conditions and wildlife contact parameters drive significant variation in simulated outbreak size, spread, and severity. Outbreaks seeded in autumn consistently produced the largest outbreaks, particularly under high transmission and contact rate assumptions, while outbreaks seeded in spring had markedly lower disease impacts.

The methodology was designed to isolate and test critical parameters based on a sample of empirical data. Uncertainty around feral pig-to-domestic pig contact is an important consideration, and the model demonstrated that changes in this parameter resulted in large differences in disease outcomes. Empirical camera trap data from a single commercial piggery (from chapter 3) was used to generate the contact rates used in this research. This provided a locally relevant foundation for the model and demonstrates how real-world surveillance data can be integrated to contextualise outbreak scenarios.

However, future improvements should include broader data collection across multiple piggeries and landscapes, or integration of outbreak data from ASF-affected regions overseas. Additionally, refining estimates with technologies such as GPS tracking, would enhance the model's validity.

Despite these limitations, the findings have contributed to the advancement of simulation modelling that is informing Australia's preparedness for ASF, and the approaches can be adapted for informing simulation of other wildlife-livestock interface diseases, such as foot and mouth disease or avian influenza. The research reinforces concerns over the role of feral pigs in disease spread and highlights the need for proactive risk assessment tools and surveillance strategies. The study also illustrates the

value of empirical data to support scenario modelling, while underscoring the need for more comprehensive datasets to reduce uncertainty and improve confidence in model-driven policy decisions.

Overall, a major contribution of this thesis is the development of a camera trap surveillance system tailored specifically for use by pork producers and industry stakeholders. The detailed protocol methodology and layout strategies have been provided to guide producers in deploying camera traps effectively, particularly in landscape features known to be hotspots for feral pig movement. By identifying optimal placement strategies and evaluating coverage intensity, this research offered practical tools to maximise detection probability while minimising resource expenditure, an essential consideration for industry adoption.

Furthermore, the thesis introduced a quantitative risk assessment tool that allows pork producers to assess the likelihood of feral pig encounters at individual properties. In doing so, it provided a decision-support mechanism for producers to evaluate control and surveillance options tailored to their specific operational and environmental context. Such a tool is vital not only for risk mitigation but also for resource prioritisation, especially in regions where biosecurity budgets and resources are limited. Finally, to tie everything together, the AADIS sensitivity analysis provides an example on how empirical data can be integrated into epidemiological models, whilst also highlighting the impact of sounder-farm transmission and inter-sounder contact rates on ASF outbreaks.

The broader implications of this research extend to national biosecurity policy and planning. It provided a model framework for evidence-based decision-making in ASF preparedness and response, supporting targeted surveillance strategies that can be adopted at both regional and industry levels. Importantly, this research delivered methods that are not hypothetical but grounded in real-world application, demonstrated through a case study where the risk assessment tool was applied and informally validated using empirical data from a feral pig incursion at a piggery site. This affirmed the tool's potential utility and relevance, though also alluded to the need for wider-scale testing and refinement across diverse geographic and production settings. Furthermore, the methodologies developed in this study are adaptable to other infectious diseases where wildlife contribute to transmission dynamics. For example, avian influenza, FMD, and leptospirosis all of which involve complex interfaces between wild and domestic animal populations^{426–428}. This underscores the broader applicability of the risk assessment framework beyond ASF, offering a valuable foundation for future preparedness and response efforts targeting a range of zoonotic and transboundary animal diseases.

To further enhance the utility of the risk assessment tool, the incorporation of GPS collaring data on feral pigs presents a valuable opportunity. Collaring studies can generate high-resolution data on individual movement patterns, habitat preferences, and contact patterns between feral pigs and domestic piggery zones. These insights can strengthen the accuracy of contact rate estimates by revealing how frequently and under what conditions pigs are likely to approach boundaries. When linked with camera trap images and timestamps, GPS data can help clarify the behavioural context of detections, whether pigs are simply passing through, engaging in repeated visits, or interacting with other animals. This added layer of behavioural insight would greatly refine the probability estimates and improve the ecological validity of the model.

In addition, the integration of artificial intelligence image recognition offers a promising avenue for improving the efficiency of camera trap surveillance. Currently, image review is a time-consuming, labour-intensive process requiring manual verification of each detection. Advances in AI technology, specifically in data processing could greatly reduce this burden. If AI systems can be developed to handle high-volume data without requiring user confirmation for each detection, the time between image capture and actionable information would be drastically shortened. This would allow researchers and producers to process and respond to surveillance data more rapidly, improving outbreak readiness and overall monitoring efficiency.

While the outputs of this thesis represent useful innovations, the full value of these tools to the pork industry depends on further steps to support real-world implementation. For the risk tool and surveillance system to achieve meaningful uptake and impact, several core actions are required. First, further validation across multiple sites with differing environmental conditions and piggery layouts will be essential to improve the external validity of the detection probability estimates and fine-tune predictive performance. Second, the development of a user-friendly, interactive digital platform is needed to operationalise the tool, enabling producers to input their own data and receive tailored risk assessments without requiring advanced technical expertise. Third, a formal sensitivity analysis of the risk assessment tool should be undertaken to identify which inputs most influence risk estimates, thereby guiding where future data collection and model refinement should be focused.

Thus, by incorporating GPS movement data and feral-domestic pig contact behaviour patterns, along with the improvement of AI-based image recognition, would greatly enhance the resolution and automation of these outputs. These developments would make the tool more dynamic and responsive to real-time risk conditions, as well as more feasible for adoption at scale across Australia's diverse pork production systems. Once these developments are undertaken, the surveillance system and risk assessment tool developed through this research will be ready for immediate adoption by APL and industry stakeholders. These steps will transition the model from a robust research output to a fully

operational, field-ready system capable of supporting producer-led decision-making and national ASF preparedness. Moreover, this integrated approach can be adapted for other livestock industries where wildlife-livestock interfaces pose a disease risk, offering a scalable model for future biosecurity resilience.

In conclusion, this thesis has provided critical insights into feral pig activity, surveillance strategies, and risk assessment in the context of ASF management. The research outputs, including the camera trap surveillance protocol and risk assessment tool, offer practical applications for the pork industry and biosecurity awareness. Future work should focus on refining these models with additional data and ensuring their integration into national biosecurity frameworks. The findings of this study not only advance scientific knowledge but also provide actionable insights for mitigating the risks associated with feral pig incursions in Australia. Importantly, the methodologies developed here are adaptable to other infectious diseases involving wildlife vectors, underscoring the broader utility of this work in supporting national preparedness and disease management across multiple sectors.

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