

Improving disease surveillance
in Australia's sheep industries:
Investigations of syndromic surveillance,
farmer behaviour and sheep trade networks

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ABSTRACT

Designing and delivering effective, useful livestock health surveillance is a challenge for many countries. The observations of people in frequent contact with livestock, captured through passive surveillance, play an important role in many national surveillance systems. In Australia, the effectiveness of passive surveillance on sheep and beef farms has been limited by infrequent veterinary contact. Farm workers frequently observe signs of disease in livestock, but these observations are not captured by existing surveillance systems. This thesis therefore posed the question: can farmers' observations be collected to generate useful surveillance information?

Syndromic surveillance of farmers' observations is one approach to increase data capture from extensive livestock farms. Chapter 3 describes the operation of a syndromic surveillance system collecting farmers' observations of livestock health in Victoria, Australia, over its first two years of operation from 2014 to 2016. Survival analysis and classification and regression tree analysis were used to identify farm level factors associated with reliable participation, to inform future recruitment aimed at farmers who were willing and able to provide regular, timely reports. Farmers keeping only sheep were the most reliable and timely respondents, while farmers aged under 43 years or working full time on-farm had lower response rates than older farmers or part-time farmers. This chapter demonstrates that recording farmers' observations of signs of disease using syndromes is a feasible and effective method to gather disease occurrence data.

The utility of syndromic data is further investigated in Chapter 4, using the observations collected by the surveillance system to quantify ewe mortality on sheep farms in southern Australia. Ewe deaths were reported in 540 of 612 reports, describing 2106 individual deaths, with a median of 4 deaths per positive monthly report. Median mortality rates ranged between individual farms from 1 to 5 deaths/1000 ewes/month. The incidence rate ratio of mortality in the five months preceding and following lambing was 2.8 (95% CI 2.0 to 4.1) compared to the remaining seven months of the year. Overall ewe mortality could therefore be reduced through strategies targeted to improving peri-parturient ewe survival. In a subset of reports where veterinary contact was recorded, just 15% of reported deaths involved a veterinarian. Further investigation of how and why farmers respond to ewe deaths

without veterinary support is needed, to determine the best farm management strategies to reduce mortality.

Chapter 5 investigates Australian sheep farmers' low rates of veterinary contact. The study aimed to understand why Australian sheep farmers chose not to contact veterinarians when their animals showed signs of disease, and what alternative approaches they took to managing unwell animals. Data were collected during three focus group discussions with sheep farmers in Victoria, Australia. Transcripts of those discussions were analysed using a modified grounded theory approach to develop a preliminary theory of Australian sheep farmers' disease response behaviour. Critical steps in the decision-making process included the farmer recognising that action is needed, and then deciding what that action would be. The farmers reported having to decide whether they would act independently based on their previous experiences, or alternatively to seek advice. Veterinarians played a small but important role as potential advisors, alongside others including trusted farming friends and farmer discussion groups. Self-reliance and confidence in their knowledge and skills was highlighted as the main reason the farmers often chose not to seek veterinary advice. Rather than being seen as a barrier to effective passive surveillance, the actions that arise from farmers' self-reliance when facing disease should be taken into account when designing novel surveillance approaches.

A final consideration for observational disease surveillance is the selection of individuals to contribute data to the system. While characteristics associated with participation may guide recruitment as described in Chapter 3, it is also useful to target surveillance to farms that have increased risk of acquiring or disseminating disease. The movement of animals between farms contributes to infectious disease spread, and can be investigated through network analysis methods. Australia's National Livestock Identification Scheme sheep movement records are suitable for such analyses, but are known to be a targeted subset of all sheep movement in the country. However, knowledge of the effect of sampling or incomplete network data on these studies is limited. In Chapter 6, a simulation algorithm is presented that provides an estimate of required sampling proportions based on predicted network size, density and degree value distribution. The algorithm may be applied *a priori* to ensure network analyses based on sampled or incomplete data provide population estimates of known precision. Results demonstrate that, for network degree metrics, sample size requirements vary with sampling method. Where simulated networks can be constructed to closely mimic

the true network in a target population, this algorithm provides a straightforward approach to determining sample size under a given sampling procedure for a network metric of interest.

Chapter 7 then presents analysis of National Livestock Identification Scheme sheep movement data for Victoria, Australia. The sheep movement network in Victoria shows typical livestock movement network characteristics including scale-free and small-world topology, small diameter and short average path lengths, supporting the assumption that disease could spread rapidly in the state through sheep movements if it were not detected rapidly. Victoria's position as a net importer of sheep and sheep flow is confirmed, driven substantially by the activity of saleyards (livestock markets) and abattoirs. Little variation within or between years in overall movement patterns were detected. While most farms are connected to a very small number of properties in the network, small subsets of farms demonstrate high degree values (being directly connected to many other properties through incoming out outgoing animal movements) or high frequency of sheep purchases or sales. These farms may be useful targets for emerging surveillance methods that can be implemented on-farm.

Together, these studies provide new information about the Australian sheep industry and the feasibility of new surveillance approaches to improve the effectiveness of surveillance. By describing farmer behaviour, livestock movements patterns and the feasibility of syndromic surveillance approaches to capture farmers' observations of signs of disease, these studies justify further development and implementation of novel surveillance approaches in Australia and serve as an example for other countries facing similar surveillance challenges. While there is no ideal surveillance system, integrating new approaches into wider surveillance strategies can improve the quality of information generated by surveillance, to better describe true disease states in the population and drive appropriate response activities.

DECLARATION

This is to certify that:

- i. the thesis comprises only my original work towards the PhD except where indicated in the Preface,
- ii. due acknowledgement has been made in the text to all other material used,
- iii. the thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Signed by the candidate



Dr Caitlin Pfeiffer

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18th December, 2018

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This thesis is dedicated to the late Brian and Lorraine Pfeiffer, dearly loved and missed.

PUBLICATIONS

Parts of this thesis have been published in peer-reviewed journals or presented at conferences and symposia, as follows:

PEER-REVIEWED PUBLICATIONS

1. Pfeiffer, C. N., Firestone, S. M., Campbell, A. J., Larsen, J. W., Stevenson, M. A., 2015. Sample size considerations for livestock movement network data. *Preventive Veterinary Medicine* 122, 399-405.
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2. Pfeiffer, C.N., Firestone, S.M., Campbell, A.J.D., Larsen, J.W.A., Stevenson, M.A., 2015. The impact of sample size on understanding disease dynamics in livestock movement networks. *Proceedings of the FVAS Postgraduate Symposium*, University of Melbourne, Werribee, Australia, 27.
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23. Pfeiffer, C.N., Campbell, A.J.D., Firestone, S.M., Stevenson, M.A., Larsen, J.W.A., 2015. Assessing engagement of sentinel farmers in syndromic surveillance reporting. Presented at the 14th Symposium of the International Society for Veterinary Epidemiology and Economics (ISVEE14), Yucatan, Mexico.
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PREFACE

Except where detailed here, all sections of this thesis comprise my original work toward the PhD. The studies presented were funded as part of the Local Area Network for Disease Information (LANDI) project by the Victorian Sheep and Goat Compensation Fund and the Victorian Cattle Compensation Fund, administered by Agriculture Victoria. Additional funding for the study reported in Chapter 5 was provided by a MLA Postgraduate Scholarship from Meat and Livestock Australia.

A modified version of Chapter 3 has been submitted for peer-reviewed publication to Preventive Veterinary Medicine under the title, “Using farmers’ observations for animal health syndromic surveillance: Identification and importance of timely and reliable respondents.” I was the lead investigator and first author, responsible for all major areas of the surveillance system design, study design, data collection and analysis, and preparation of the manuscript. Mark Stevenson, Simon Firestone, John Larsen and Angus Campbell were the supervisory authors and were involved in conceptual design, data analysis, manuscript composition and editing.

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LIST OF ABBREVIATIONS

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
AIC	Akaike information criterion
ASPREN	Australian Sentinel Practices Research Network (National GP Disease Surveillance Network)
AUSVETPLAN	Australian Veterinary Emergency Plan
BSE	Bovine spongiform encephalopathy
BTEC	Brucellosis and tuberculosis eradication campaign
BVD	Bovine viral diarrhoea
CART	Classification and regression tree
CI	Confidence interval
CV	Coefficient of variation
DEDJTR	Department of Economic Development, Jobs, Transport and Resources (Victorian Government)
DSE	Dry Sheep Equivalents
EM	Expectation-maximisation
FIFA	International Federation of Association Football
FMD	Foot-and-mouth disease
GEE	Generalised estimating equation
GSCC	Giant strongly connected component
GWCC	Giant weakly connected component
ICC	Incoming contact chain
LANDI	Local Area Network for Disease Information surveillance system
MCMC	Markov chain Monte Carlo
NLIS	National Livestock Identification System
NSW	New South Wales
OCC	Outgoing contact chain
OIE	World Organisation for Animal Health
OJD	Ovine Johne's disease

PDR	Probability of disease ratio
PIC	Property identification code
PTIC	Pregnancy tested in-calf
QAP	Quadratic assignment procedure
QLD	Queensland
R_0	Basic reproductive number
RE-EM	Random effect expectation-maximisation
RFID	Radio frequency identification
SA	South Australia
SBS	Syndrome-based surveillance
SD	Standard deviation
SDI	Significant disease investigation
SE	Standard error
SNA	Social network analysis
SNS	Syndrome-non-specific surveillance
SPPV	Surveillance positive predictive value
SPS	Sanitary-phytosanitary agreement
SSe	Surveillance sensitivity
SSp	Surveillance specificity
SY	Saleyard
SyS	Syndromic surveillance
TAFE	Technical and further education
TAS	Tasmania
TPB	Theory of Planned Behaviour
TSE	Transmissible spongiform encephalopathy
VIC	Victoria
WA	Western Australia

GLOSSARY

The terms in this glossary are presented under four subheadings: surveillance terminology, general network analysis terminology, global network measures for network analysis, and node-level network measures for network analysis.

Surveillance terminology

Active surveillance	A surveillance system where the exact type and frequency of data collected for surveillance are specified in the design of the system, with data collection usually co-ordinated by veterinary authorities. (Salman, 2008; Hoinville et al., 2013)
Animal health surveillance	The actions needed to detect, monitor, and provide information to facilitate responses to threats to animal health, encompassing both diseases in animals, as well as other hazards such as drought, flood, or antimicrobial resistance.
Early warning surveillance	A sub-type of general surveillance, where the scope focusses specifically on detecting unexpected or emerging hazards, also referred to as 'scanning surveillance'. (Hoinville et al., 2013)
Enhanced passive surveillance	A surveillance system where a passive surveillance approach has been modified to increase the frequency or relevance of the data collected. Examples include actively soliciting regular reports from animal observers, or specifying particular types of data to be included in observational reports.
General surveillance	A surveillance system with broad scope, with objectives to detect and respond to many health concerns or hazards. (Hoinville et al., 2013)
Hazard-specific surveillance	A surveillance system with narrow scope to detect or monitor a single hazard such as a disease or infectious agent, also referred to by other authors as 'targeted surveillance'. (Hoinville et al., 2013)
Participatory surveillance	Surveillance activities that engage the general population (or a subset of it e.g. animal owners) in recording and reporting health data, often with regular structured reporting using technology such as websites or mobile apps.

Passive surveillance	A surveillance system where voluntary reports about observations of signs of disease are used as surveillance data, collected by people who regularly observe animals, with the frequency of reporting dependent on the observer rather than the surveillance system. (Dufour and Hendriks, 2009; Hoinville et al., 2013)
Risk-based surveillance	A surveillance system with scope to detect or monitor one or more hazards that are identified through a process of prioritisation based on risk (probability and consequences of infection). (Stärk et al., 2006)
Scanning surveillance	See early warning surveillance.
Scope (of surveillance)	An indicator of the number of health conditions or hazards encompassed by the objectives of a surveillance system. The scope of a surveillance system can be general, hazard-specific, or risk-based.
Syndromic surveillance	A surveillance system that uses clinical signs grouped into syndrome categories, rather than specific diagnoses, to monitor disease trends. (Vourc'h et al., 2006)
Targeted sampling	When the population under surveillance is a specifically chosen subset of the population of interest, that are at increased risk of the disease of interest. (Hadorn and Stärk, 2008; Blickenstorfer et al., 2011)
Targeted surveillance	A surveillance system that utilises targeted sampling to select the population under surveillance. (Hadorn and Stärk, 2008; Blickenstorfer et al., 2011)

Network analysis terminology: General

Centrality measures	Measures that describe how well connected the individual nodes in the network are, for example degree and betweenness. Typically given for each node in the network, but can also be summarised into network measures (i.e. 'degree centralisation index', 'betweenness centralisation index'). Centralisation indices express what percentage of the theoretical maximum value that could exist in the network that is actually present, allowing the relative 'connectedness' of multiple networks to be compared. (Martínez-López et al., 2009)
Cohesion measures (also termed cohesiveness)	Measures that describe how well connected the network is overall, for example density, fragmentation, average path length and reciprocity. (Dubé et al., 2009)

Directed network	A network where each edge indicates a unidirectional connection, from one node i to another node j . Reciprocal edges are possible but not necessary in a directed network, in contrast to an undirected network, and are represented in a directed network as two edges, one in each direction between the node pair. For example, the network created by livestock movements (edges) between farms (nodes) is a directed network, as a livestock movement from one farm to another does not imply that a reciprocal movement between that farm pair in the opposite direction has or will occur. (Dubé et al., 2011b)
Edge	One of the two fundamental types of network information, representing the connections that exist between individual nodes in the network. (Wasserman and Faust, 1994)
Geodesic	A property of node pairs, the geodesic is the length of the shortest path (path with fewest edges) between two nodes. In practical terms, the geodesic indicates the smallest number of 'steps' to get from a given node to another specific other node in the network, including respecting the direction of edges for a directed network. (Dubé et al., 2009)
Hub	A node with both high in-centrality and high out-centrality, usually defined by high in- and out-degree. Hub nodes tend to substantially increase the cohesiveness of the network, by connecting otherwise distant nodes in the network to one another (Dubé et al., 2011b). In the context of infectious disease spread on a network, hubs are also sometimes referred to as 'superspreader' nodes. (Lloyd-Smith et al., 2005)
Neighbour	Considering a single node of interest, that node's neighbours are the other nodes connected to it by a path with length $\leq k$. First-order neighbours ($k = 1$) are the nodes directly connected to a node of interest by an edge, while second-order neighbours ($k = 2$) are connected to the node of interest by a path of length two. Neighbours of third- and greater order can also be considered. (Ortiz-Pelaez et al., 2006)
Node	One of the two fundamental types of network information, representing the individuals units in the network that can be connected to one another by edges, for example farms in a livestock movement network. (Wasserman and Faust, 1994)
Path	A set of edges in the network that connect a specific pair of nodes together, respecting the direction of edges in a directed network. Path length is the number of edges in the path between a pair of nodes. A pair of nodes may be connected by zero, one, or more paths. Where multiple paths exist between a pair of nodes, each path may have a different path length, where the length of the shortest path is the geodesic of that node pair. (Wasserman and Faust, 1994)

Scale-free	A network where most nodes have low degree values, but a very small number of nodes have very high degree values, with the distribution of degree values in the network following a power-law distribution (strongly positively skewed with no peak). (Dubé et al., 2011b)
Small-world	A network where most nodes are connected in separate small groups, but a small number of high-betweenness nodes act as bridges between those groups, giving an overall network that is highly connected. (Dubé et al., 2011b)
Temporal network	A network where edges have a temporal property, representing time-bound links between nodes rather than persistent static connections. Such networks may also be termed dynamic networks or time-varying networks. (Holme and Saramäki, 2012)
Time-respecting path	A path between a pair of nodes in a temporal network, where the path from node i to node j occurs in the correct temporal order to truly connect the nodes. For example, a path can potentially carry an infectious disease from farm A to farm D, on a path via farms B and C, if the edges occur in the appropriate temporal order, where edge 'A to B' precedes edge 'B to C', both of which precede edge 'C to D'. (Holme and Saramäki, 2012)
Topology	A description of the overall structure of the network. Common topology measures include network size, diameter, and specific topological properties including small-world and scale-free. (Dubé et al., 2009)
Undirected network	A network where edges indicate connection bidirectional connections between node pairs (linking both node i to node j , and node j back to node i). For example, the network created by farms (nodes) with shared fencelines (edges) is an undirected network, as a shared fenceline by definition connects both neighbouring farms to one another. (Dubé et al., 2011b)
Network analysis terminology: Network measures	
Average path length	The average geodesic value across all node pairs in the network. In practical terms, this describes the average length of the shortest path between any two nodes in the network. (Martínez-López et al., 2009)
Density	The proportion of edges that actually exist in the network, compared to the theoretical maximum number of edges that are possible. (Martínez-López et al., 2009)
Diameter	The length of the largest geodesic in the network. In practical terms, the maximum number of edges ('steps') taken to follow a path from any node to any other node, for all node pairs linked by one or more paths in the network. (Wasserman and Faust, 1994)
Fragmentation	The proportion of all node pairs in the network that have no path connecting them. (Martínez-López et al., 2009)

Global clustering coefficient	The mean value of all local (node-level) clustering coefficients in the network. This indicates how commonly the first order neighbours of nodes are also connected to one-another, in the network overall. (Watts and Strogatz, 1998) <i>Note that an alternative definition, the amount of clustering present in the network expressed as a proportion of the theoretical maximum value that could exist (Wasserman and Faust, 1994), is not used in this thesis.</i>
Reciprocity	The proportion of all node pairs in a directed network, that are directly connected by a reciprocal pair of edges i.e. a path of length one in both directions. (Garlaschelli and Loffredo, 2004)
Network analysis terminology: Node measures	
Betweenness	The frequency with which the node of interest lies on a geodesic (shortest) path between two other nodes in the network. In practical terms, because nodes with high betweenness lie on the shortest paths connecting other pairs of nodes in the network, they act as ‘bridging’ nodes that increase the overall connectedness of the network. (Dubé et al., 2009)
Closeness	A summary measure indicating the path length (how many ‘steps’) are required to reach every other node in the network, from the node of interest. Mathematically, a node’s closeness is the reciprocal of the mean of all its geodesic values. (Dubé et al., 2011b)
Degree	The number of other nodes that are directly connected by an edge to the node of interest. Degree is analogous to the size of the first-order neighbourhood of the node of interest. In a directed network, the term total degree is used to differentiate this measure from in- and out-degree. (Wasserman and Faust, 1994)
In-degree	The number of other nodes directly connected to the node of interest by incoming edges (edges that terminate at the node of interest) in a directed network. In a livestock movement network, in-degree is the number of other nodes that move animals directly to the node of interest. (Wasserman and Faust, 1994)
Ingoing contact chain	The number of other nodes in the network that are connected to the node of interest by an ingoing, time-respecting path terminating at that node of interest. A time-respecting measure equivalent to ingoing reach on a static network. The term ingoing infection chain is also used, but is avoided in this thesis as not all contacts result in infection. (Nöremark and Widgren, 2014)
Local clustering coefficient	The proportion of first-order neighbours of a node that are also directly connected to each another by a single edge. When many first order neighbours are connected to one another, small highly connected clusters tend to emerge in the network; the local clustering coefficient is used to describe the extent of this behaviour for individual nodes. (Watts and Strogatz, 1998)

Neighbourhood size	The number of nodes connected to the node of interest by a path with length $\leq k$, with k being the ‘order’ of the neighbourhood. For example, the size of a node’s ‘second-order’ neighbourhood is the number of nodes that are connected to that node of interest by paths of length two or less. Incoming and outgoing neighbourhood sizes for individual nodes can also be determined in a directed network, analogous to how in- and out-degree are related to total degree.
Out-degree	The number of other nodes directly connected to the node of interest by outgoing edges (edges that originate at the node of interest) in a directed network. In a livestock movement network, out-degree is the number of other nodes that receive animals directly from the node of interest. (Wasserman and Faust, 1994)
Outgoing contact chain	The number of other nodes in the network that are connected to the node of interest by an outgoing, time-respecting path originating at that node of interest. A time-respecting measure equivalent to outgoing reach on a static network. The term outgoing infection chain is also used, but is avoided in this thesis as not all contacts result in infection. (Nöremark and Widgren, 2014)
Probability of disease ratio (PDR)	A summary measure specific to livestock movement networks, extending the concept of ingoing contact chain. The ratio of the probability of infectious disease being acquired by a node (herd) that has incoming livestock movements, compared to the baseline probability of disease in that herd if no movements had taken place. The PDR considers only time-respecting ingoing paths to the node of interest, with ingoing paths weighted by the number of animals moved on each contributing edge, and the option to specify farm-level disease prevalence for different nodes (or groups of nodes) in the network. Rather than being interpreted as an absolute value, it is intended for the relative PDR values of different nodes to be compared, allowing nodes with increased potential risk of acquiring disease to be identified. (Frössling et al., 2014)
Reach	The number of other nodes in the network that can be reached along a path of any length in the network, to or from the node of interest. Expressed either as an absolute number, or as a proportion of all nodes in the network. Incoming and outgoing reach for individual nodes can also be determined in a directed network, analogous to how in- and out-degree are related to total degree.
Weighted degree	The sum of weighted edge values for all edges connected to the node of interest. Common edge weightings for livestock movement networks include the number of animals moved on that edge or the frequency with which movements occurred on that edge in a defined time period. Weighted in- and out-degree for individual nodes can also be determined in a directed network, analogous to how in- and out-degree are related to total degree. (Volkova et al., 2010)

Chapter 1.

GENERAL INTRODUCTION AND OBJECTIVES

1.1 INTRODUCTION

In a perfect world, animal health surveillance would have an unlimited budget, with no restriction to the resources available for a surveillance system. Every disease of interest for surveillance would have a perfect diagnostic test, which would be universally available and provide instant results. The disease status of every animal in every place would be transparent and universally accessible to all. Unfortunately, this is not the world in which we live. Animal health surveillance is constrained by many factors, including the availability of resources and whether data describing the diseases or hazards of interest exists and is accessible. Surveillance data are always imperfect; the art of surveillance design is to determine exactly how, where, and to what extent compromises can be made, while still achieving the objectives of a surveillance system. This thesis explores common challenges faced when designing and implementing surveillance, and potential ways to overcome those challenges.

This thesis centres on the description of a pilot syndromic surveillance system, that collected observations of clinical syndromes from sheep and beef farmers from Victoria, Australia. Previously, information about the prevalence of endemic diseases on these farms was scarce, primarily because of the resources required to conduct endemic disease surveys. Furthermore, low rates of veterinary contact and limited descriptions of the patterns of sheep movement between farms in the industry meant that the frequency and spread of endemic diseases was rarely described in detail. Farmer's observations have previously been overlooked as a data source, perhaps because of they are not expected to be experts on animal health. However, this thesis will argue that farmers' knowledge is both substantial and valuable, and that finding a way to access this knowledge can provide a useful new direction for disease detection.

1.2 OBJECTIVES

The original objective of the project that formed the basis of this thesis was to increase the volume of surveillance information collected about the occurrence of diseases of ruminant livestock on sheep and beef cattle farms in southern Australia. Previous approaches to quantify disease frequency on these farms have relied on veterinarians to collect these data through passive surveillance, or on limited-duration, small-scale active surveillance programs. However, low rates of veterinary contact with sheep and beef cattle farms have limited the effectiveness of these approaches to quantify disease longitudinally. An alternative surveillance method, to directly engage farmers and collect their observations of clinical syndromes, was therefore devised as outlined in Chapter 3. This thesis sought to address the challenge of improving the usefulness of disease surveillance in the Australian sheep industry, through a farm-based observational approach to collecting surveillance data. The underpinning research questions were:

- Are Australian sheep and beef farmers willing and able to provide data that is useful for disease surveillance?
- How do Australian sheep farmers respond to signs of disease occurring in their livestock, and what implications does this behaviour have for surveillance?
- How can farmer-reported data can be effectively and efficiently used to improve surveillance?

These research questions were explored through the review presented in Chapter 2, which synthesised existing relevant work and identified research gaps in several key areas. Consequently, five studies were undertaken to add to the contribution made by describing the surveillance system. The specific objectives of the studies in this thesis included:

- To measure the participation of recruited farmers in the surveillance system, including analysis of several factors hypothesized to influence participation rates and compliance.
- To estimate the prevalence of common diseases of sheep using farmer observational data, and to compare these estimates to limited existing data collected using other approaches.

- To gain insight into the farmers' responses when disease occurs on their property, specifically their behaviours and the attitude that drives those behaviours. This particularly aims to better understand the barriers to current systems, both as a supportive argument for a new approach and to update our understanding of the veterinarian's role in passive surveillance.
- To detect missing data in network analysis and to estimate the effect of this missing data on network analysis findings.
- To understand present patterns of sheep movement in Victoria and to detect patterns that are either of high risk for disease transmission or of strong benefit for surveillance targeting.

This thesis combines knowledge of high-risk premises for infectious disease, based on network analyses, with an understanding of Australian sheep farmers' behavioural motivators for reporting. In combination, these factors have the potential to inform future policy and surveillance system design. A syndrome-based reporting system has potential to improve livestock health surveillance in Australia, by using syndromic information to monitor disease trends across geographic areas or identify unusual animal health events that require further investigation. Alongside other existing, more traditional surveillance approaches, an integrated approach to surveillance using multiple activities can better address the challenges of maintaining human and animal health at a local, national and international level (Vourc'h et al., 2006). Through a syndromic approach to facilitate non-veterinary stakeholders in livestock production to report signs of disease, surveillance of farmers' observations can fill an important gap in broader surveillance strategy. This is illustrated using the Australian sheep industry as an example, but is also relevant to other countries facing similar constraints to effective surveillance. The key outcome is optimising the efficiency and effectiveness of surveillance for all stakeholders in livestock health.

Chapter 2.

PRACTICAL LIVESTOCK HEALTH SURVEILLANCE:
DESIGNING SURVEILLANCE SYSTEMS
TO OVERCOME COMMON CHALLENGES

PREFACE TO CHAPTER 2

This chapter presents a review of literature relevant to the objectives outlined in Chapter 1. Specifically, it examines the principles of surveillance design before introducing the sheep industry in Australia, which will be used as an example to illustrate several common surveillance challenges. It then examines literature relevant to those challenges in three areas: the behaviour of farmers, the potential applications of syndromic surveillance, and the role of network analysis of livestock movement data in designing targeted surveillance. Together, these sections provide the relevant background to the research presented in Chapters 3 to 7 of this thesis.

2.1 ABSTRACT

Designing and delivering effective, useful livestock health surveillance is a challenge for many countries. Although the objectives of surveillance might be clear, practical issues including resource constraints and the availability of appropriate data often make it hard to realise these objectives. This review uses surveillance in the Australian sheep industry as an example to explore common challenges and potential solutions, in three areas: farmer behaviour, syndromic surveillance, and the role of network analysis in targeted surveillance. Australia's sheep industries do not presently benefit from the full potential value of surveillance, in part due to low rates of veterinary contact. Because farmers are key stakeholders in livestock health surveillance, understanding how they make decisions and respond to disease can inform new approaches to increase both data capture and the relevance of surveillance information. One potential approach is syndromic surveillance, which can have several forms including capturing the observations of farmers in a way that is potentially useful as surveillance data. Additionally, by targeting surveillance to farmers that are at increased disease risk due to their livestock trading activities, the efficiency of newly developed surveillance approaches can be increased. Through synthesis of literature from these disparate areas, potential solutions to the practical challenges of surveillance emerge, which can subsequently be tested and refined. Surveillance solutions should aim to produce useful information for stakeholders in livestock health including farmers, livestock industries and government.

2.2 INTRODUCTION

In Australia, a typical sheep farm consists of a thousand or more animals, grazing pasture in fenced paddocks year-round. Australian sheep farmers are self-sufficient in their farming approach, accustomed to managing endemic disease problems with little outside assistance. These farmers make up an industry that contributes substantially to Australia's economy, selling wool and meat products to valuable domestic and international markets. However, access to these markets relies on Australia's freedom from many diseases of trade significance. Therefore, evidence of the diseases that are prevalent in Australia's sheep population, as well as proof of freedom from significant diseases such as foot-and-mouth disease, underpins the success of the country's sheep industries. Animal health surveillance is the means of providing that evidence.

However, in a country where individual self-sufficient farmers are responsible for thousands of animals, effective surveillance is no simple task. This review will use the Australian sheep industry as an example to explore how challenges faced in the real world can be overcome through thoughtful design of animal health surveillance systems.

Animal health surveillance describes the actions needed to detect, monitor, and provide information that facilitates responses to threats to animal health. In addition to a primary focus on the occurrence of diseases in animals, animal health surveillance can also encompass other hazards, such as drought, flood, or antimicrobial resistance. The World Organisation for Animal Health (OIE, 2013a) define animal health surveillance as "the systematic ongoing collection, collation, and analysis of information related to animal health and the timely dissemination of information so that action can be taken". Morgan et al. (2015) go one step further to define an animal health surveillance system as "a set of interacting and interdependent components i.e. inputs and outputs" that function to create information from animal health data and to communicate that information to those who can respond appropriately. Accordingly, describing a surveillance system actually means describing the process that takes relevant raw data and converts it into information that can drive action. This process involves the collection of data describing events, its analysis to produce information, and then the effective communication of that information. This basic process is common to all surveillance systems, although exactly what data are collected and how the information generated by the system is used varies widely. Effective animal health

surveillance is a continuous, iterative process of data collection, analysis and informing of response activities, as shown schematically in Figure 2-1. The specific response activities that arise from surveillance information can be considered complementary, but separate, to the surveillance system itself (Häsler et al., 2011). Nonetheless, if action cannot arise from the information generated, then the system is simply monitoring animal health rather than delivering animal health surveillance.

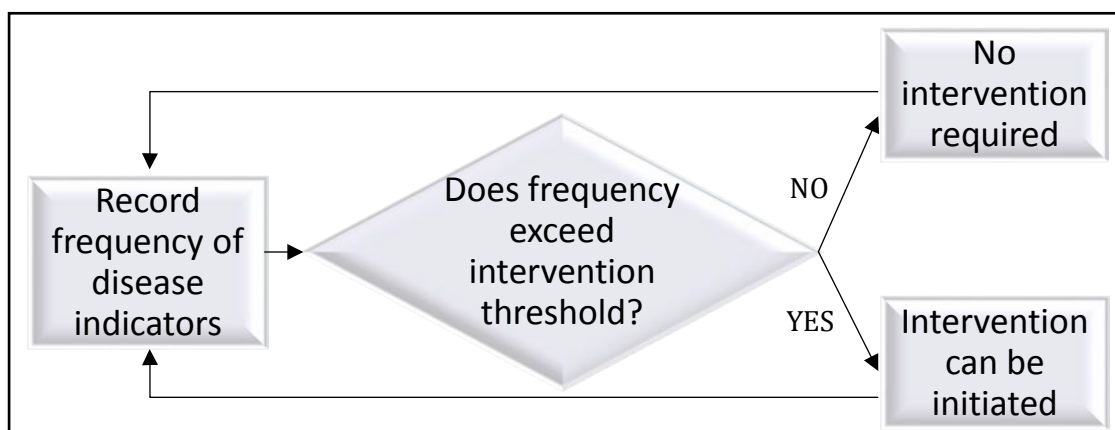


FIGURE 2-1. SCHEMATIC DIAGRAM OF KEY STEPS IN THE ITERATIVE PROCESS OF SURVEILLANCE. ADAPTED FROM CHRISTENSEN ET AL. (2001).

The purpose of animal health surveillance can include demonstrating freedom from infection, assessing the distribution of a disease, and early detection of exotic or emerging diseases (OIE, 2013a). The information generated by surveillance is used in many ways, including for outbreak response, measuring the consequences of a particular disease, identifying new diseases, monitoring disease patterns, designing and implementing control and prevention programs, detecting changes in health behaviours, and providing a basis for ongoing epidemiological research (German et al., 2001). As in many areas of veterinary epidemiology, real-world challenges shape the way animal health surveillance is conducted. There is no ideal surveillance system that can achieve all objectives perfectly, particularly because of the finite resources typically available for animal health surveillance. Therefore, careful design is needed to achieve the highest priority surveillance objectives in light of the resources available.

The first part of this review (Section 2.3) will explore the principles of surveillance design including clarifying key terminology. The relationship between surveillance objectives and attributes of system design and operation will be explored, with

specific attention to the compromises necessary for effective surveillance in the real world. Australian sheep industries will then be introduced in Section 2.4, with Section 2.5 focussing on present challenges and constraints to effective surveillance within those industries. These challenges include low rates of veterinary contact and a large industry dispersed over a broad geographic region where continuous intensive surveillance is unfeasible. Approaches that might help address these challenges will then be discussed, including how surveillance design can be designed to accommodate the behaviour of farmers and livestock workers (Section 2.6), the potential relevance of participatory and syndromic surveillance approaches (Section 2.7), and the role livestock movement data can play to prioritise surveillance resource allocation (Section 2.8). The review will conclude by identifying major gaps in the literature surveyed, including areas that will be addressed by the studies reported in the subsequent chapters of this thesis. Overall, this review chapter argues that objective-focussed design and a combination of surveillance methods can be used to deliver surveillance that better achieves its objectives in the face of challenges, both in Australia specifically and more broadly.

2.3 PRINCIPLES OF SURVEILLANCE DESIGN

Because every surveillance system has its own objectives and context, the design and delivery of animal health surveillance systems varies widely. As a starting point to discuss the principles of surveillance design, it is useful to describe surveillance activities in terms of structure, process and output (World Health Organization, 1997). In this section, each of these categories will be examined in turn, while also clarifying surveillance terminology. As in many sub-disciplines of epidemiology, some terms are used inconsistently (Lysons et al., 2007; Hoinville et al., 2013), so this section will also address these inconsistencies, defining common terms in the manner they will be used throughout this thesis (consistent with the Glossary provided in the front matter on page xxii).

2.3.1 STRUCTURE: SURVEILLANCE OBJECTIVES AND AVAILABLE RESOURCES

The structure of a surveillance system is defined by the system's objectives and resources (World Health Organization, 1997). No surveillance system can achieve every possible or desired objective, so specific objectives should be used to ensure the system can do what it has been intended for. Using the system's objectives as a starting point is arguably the best way to determine the process by which it will operate; this is objective-driven surveillance design.

Ideally, surveillance objectives should be clearly established before the system is designed. If the objective is unclear, the surveillance system could consume vast resources without providing the information and initiating the actions required by stakeholders. By contrast, a system with a clearly defined objective can transform limited resources into useful and valuable information and action. A surveillance system's objectives should be determined through collaboration between stakeholders and surveillance experts. Potential objectives may include detection of outbreaks, evidence to support trade assurance, monitoring endemic disease, or providing information to facilitate disease control or eradication campaigns (Hoinville et al., 2013). When defining the objectives of a surveillance system, it is useful to identify both what the system is designed to do, as well as acknowledging what it is *not* designed to do. This helps avoid policymakers and other stakeholders expecting more from the system than it has been designed to deliver.

Once the objectives of the surveillance system have been determined, the resources available to conduct surveillance should be assessed. This includes the financial cost associated with the system, as well as the availability of suitably experienced people, and practical constraints including technological capability and infrastructure. The opportunity cost of surveillance should also be considered: conducting surveillance takes time and resources that could be used for other animal health or community activities. Technology considerations include what kind of connectivity and communication will be needed, including mobile phone reception and internet access, and whether computing resources and available expertise are sufficient to analyse the kinds of data that will be collected. The surveillance system's objectives may need to be adjusted to reflect the available resources. The most suitable approach should

accommodate the practical constraints of what data it is feasible to collect, analyse, and report, to achieve the desired objective.

The scope of surveillance should be clearly identified in the objectives of a surveillance system, and may be influenced by the practical constraints discussed above. In this thesis, the term surveillance scope will be used to describe the number of health conditions included in a system, defined as either hazard-specific, general, or risk-based. When a surveillance system aims to detect or monitor a single disease or agent, this is hazard-specific surveillance (Hoinville et al., 2013). The pathophysiology and epidemiology of the disease or agent of interest (the hazard) drives what data are collected and used by hazard-specific systems. Their objective is usually to answer a specific epidemiological question, such as determining disease prevalence or confirming absence of disease. A common application of hazard-specific surveillance is to confirm the absence of spongiform encephalopathies in animal populations (Doherr et al., 2001; Animal Health Australia, 2017). An alternative term, targeted surveillance, has also been used to describe systems focussed on a defined disease or condition (Lysons et al., 2007); this is an example of the inconsistencies that occur commonly in surveillance terminology (Hoinville et al., 2013). In this thesis, the term targeted surveillance will be reserved to describe the population under surveillance rather than the scope of a surveillance system (as discussed in Section 2.3.2). Because hazard-specific surveillance can require vast resources to be focussed on a single disease, it is only suitable for a small number of priority hazards. An alternative approach is required to capture relevant information on other diseases.

That alternative approach is often general surveillance, where data are collected about many hazards over time (Hoinville et al., 2013). General surveillance usually comprises a variety of activities commonly focussed on early detection of changes in disease frequency (Martin et al., 2015). These activities might include monitoring laboratory submissions and diagnoses, abattoir inspection, and collecting data from those in direct contact with animals. For example, wildlife health surveillance in Australia encompasses data collection on OIE-listed diseases, viral diseases of bats, unusual mortality events, cases of salmonellosis and arboviral infections, and other unusual cases of disease in wildlife (Animal Health Australia, 2017). These cases are reported to the system by a network of surveillance co-ordinators based primarily in zoo wildlife hospitals, sentinel wildlife clinics and universities. General surveillance

activities usually cannot provide prevalence estimates for specific diseases, but are useful for giving an overview of disease presence or absence. Early warning surveillance (or scanning surveillance) is a sub-type of general surveillance, where the scope focusses specifically on detecting unexpected or emerging hazards (Hoinville et al., 2013). A major advantage of general surveillance is its resource-efficiency, able to collect data on a variety of hazards with fewer resources than hazard-specific surveillance.

Between the two extremes of hazard-specific and general surveillance sits risk-based surveillance, where the hazards to be detected or monitored by the system are actively prioritised when setting the system's objectives. In a risk-based approach, each hazard included in the system is justified explicitly using a risk assessment approach that considers both the probability and the consequences of each hazard (Stärk et al., 2006). Hazard prioritisation can be either a qualitative process or be informed by a formal quantitative risk analysis (Hoinville et al., 2013). For example, McKenzie et al. (2007) developed a risk-based approach for prioritisation of surveillance of diseases in New Zealand wildlife. However, to conduct a risk analysis, the potential cost of the consequences of each hazard must be estimated. This requires knowledge of the relative cost of endemic diseases, cost of potential disease outbreaks (including endemic and exotic diseases) and some knowledge of baseline disease frequency (Scott et al., 2012). Thus, the availability of relevant data is crucial for a compelling risk-based prioritisation of surveillance activities, which sometimes limits the rigor of a risk-based surveillance approach. Once the highest risk hazards are identified, final hazard selection may also be influenced by the available resources, including available diagnostic or confirmatory laboratory capacity, response capacity and funding (Kloeze et al., 2010). Hazards that are not selected for hazard-specific surveillance may still be monitored through general surveillance. Because resources for surveillance are finite, risk-based surveillance helps ensure that the most important hazards are being monitored by the system. Risk-based surveillance can be more cost-effective and feasible than conducting hazard-specific surveillance for every disease of interest, and more reliable than general surveillance to provide specific information about important hazards.

The scope of surveillance, whether hazard-specific, general or risk-based, is a crucial detail of a system's objectives that should be clearly specified when determining the

structure of the surveillance system. Each potential scope has strengths and weaknesses. General surveillance has the potential to detect any hazard but no guarantee of doing so. Hazard-specific surveillance has good capacity to achieve its very narrow objective at substantial cost. Risk-based surveillance allows prioritisation of the surveillance effort for multiple hazards, to improve resource efficiency, but relies on high quality information to determine the highest priorities. The desired objective, and resources available, will determine which scope is most appropriate for a specific surveillance system.

Once system objectives and scope are chosen and assessed against the resources available, the surveillance process can be designed accordingly. This design must encompass the entire surveillance process: data collection, transformation into information, and appropriate dissemination of that information. The result is objective-driven surveillance design, increasing the likelihood the system will generate useful information and enable effective response activities to occur.

2.3.2 PROCESS: COLLECTING, INTERPRETING AND COMMUNICATING INFORMATION

The surveillance process includes all the steps needed to take raw data, convert it into information and then interpret and communicate what that information means. Important considerations include where data might come from, what types of data are collected, what kinds of analysis are appropriate and how they should be conducted, and how the resulting information should be presented so it is easily understood by stakeholders of the system, who can respond with action as necessary. This section will briefly discuss each of these steps that cumulatively describe the surveillance process.

Data for surveillance can be obtained from almost any point of animal production or diagnostic processes. Potential data types include farm production data, the observations of people in direct contact with animals along the production chain, clinical case records, requests for and results of diagnostic tests, carcass production measures and meat inspection results. Traditionally, most surveillance systems have focused on diagnostic test results as a major source of data, because they indicate clearly whether individuals or groups of animals are positive or negative for a given disease. However, more diverse data types, including pre-diagnostic data, are

becoming more commonly integrated into surveillance systems, and will be discussed further in Section 2.7.

Once desirable data types are chosen, sources who can provide that data must be identified. Data sources for surveillance are the people or organisations who can provide relevant data for the system to analyse. Potential data sources can include environmental organisations, veterinarians, slaughter inspectors, saleyard employees, and farmers or other animal owners, as well as the structured diagnostic testing of traditional surveillance activities (Doherr and Audige, 2001; Gates et al., 2015). The relevance, availability and quality of data available will usually determine which data sources are selected. Ideally, relationships between surveillance system staff and those providing data should be established collaboratively as 'data partners' wherever possible, rather than being framed as unilateral 'data providers'.

It is rarely feasible to conduct surveillance on all animals in the population of interest, so the population of animals represented in the data (the population under surveillance) should also be considered. The population under surveillance can be a random sample of the whole population of interest selected using probability sampling methods to minimise bias and maximise validity (Cameron et al., 2008). Alternatively, the sample may be a specifically chosen subset of the population that are at increased risk of the disease of interest (Hadorn and Stärk, 2008; Blickenstorfer et al., 2011). This will be termed targeted sampling throughout this thesis, although it is also referred to as risk-based sampling (Alban et al., 2008; Salman, 2008; Hoinville et al.). The term targeted surveillance will therefore be used to describe surveillance systems where targeted sampling has been used to select the population under surveillance. Targeted surveillance is particularly useful when the system's objective prioritises the detection of new cases more highly than accurately estimating the exact prevalence of disease in the population of interest. The population under surveillance may also be determined by the availability of existing data. Where data created for other purposes is incorporated into a surveillance system, information may only be available about a restricted population, which is neither probability sampled nor targeted based on disease risk. The population under surveillance must therefore be assessed for every data source, to ensure it can provide the information needed to achieve the surveillance objective. Non-representative data can still be useful for

surveillance, but the associated biases should be kept in mind during analysis and interpretation of the results from these data.

Once the type of data needed and the available data sources are identified, data must actually be collected. Data collection for surveillance can be broadly categorised into active, passive and enhanced passive approaches. In active surveillance, the exact data required for surveillance is specified and data collection is usually co-ordinated by veterinary authorities (Salman, 2008; Hoinville et al., 2013). Often (but not in all cases), active surveillance is also hazard-specific, for example serological testing for diseases of interest. Active surveillance can also encompass multiple hazards, such as in Australia's arbovirus monitoring program which monitors the distribution of vectors for important viral diseases including bluetongue, Akabane and bovine ephemeral fever (Animal Health Australia, 2017). Active surveillance systems are best suited to high-priority diseases that are biologically well understood and where appropriate diagnostic tests are available (Dufour and Hendrikx, 2009). However, they offer minimal value for the detection of the unexpected, such as previously unknown emerging diseases (Scott et al., 2012). Alternative complementary data collection activities, such as passive surveillance programs, are often needed alongside active surveillance to achieve real-world surveillance objectives such as demonstrating proof of disease freedom.

In passive surveillance, observations of signs of disease (cases or suspect cases) are reported voluntarily to the surveillance system by people who regularly observe animals (Dufour and Hendrikx, 2009; Hoinville et al., 2013). The main defining feature of passive surveillance is that it relies on the observer to initiate the report. These reports can include compulsory disease notifications, as well as veterinarians or farmers providing voluntary field reports of unusual clinical signs. Passive surveillance is therefore flexible, able to detect both anticipated and unexpected cases and hazards, including early cases of emergency or emerging diseases (Dufour and Hendrikx, 2009). Where important hazards are detected by passive surveillance, follow-up investigation or active surveillance activities are usually needed, to more accurately determine the extent and significance of the disease (Hadorn and Stärk, 2008; Salman, 2008). Passive surveillance is cost-effective because it can cast a wide net for disease problems with limited direct input from veterinary authorities, and is

an efficient and feasible method to increase the likelihood of early detection of emergency diseases, such as foot-and-mouth disease in Australia (Garner et al., 2016).

However, passive surveillance relies on those observing animals being able to identify cases, and willing to report them. The requirement for disease awareness and whether individuals are inclined to report observations are two commonly recognised limitations of passive surveillance (Hadorn et al., 2008; Welby et al., 2017). Because reporting is voluntary, passive surveillance on its own is less representative than active surveillance to describe the occurrence of a specific hazard. However, the information generated by passive surveillance remains valuable, especially for general surveillance disease objectives such as detection and early warning. Not all general surveillance objectives are achieved through passive surveillance data collection, although the two terms are often used interchangeably (for example, in Martin et al., 2015). To clarify, general surveillance describes a surveillance system where the objective is to monitor multiple hazards, including emerging diseases that were previously unknown. Passive surveillance describes opportunistic collection and use of the field observations of those in contact with animals as surveillance data. Appropriate methods for passive surveillance will be a major focus throughout this thesis.

A third, intermediate category of surveillance data collection, termed enhanced passive surveillance, has emerged in response to the limitations of traditional passive surveillance such as representativeness and reluctance to report disease (Harkess et al., 1988; Hernández-Jover et al., 2011; Hoinville et al., 2013). Exact definitions of enhanced passive surveillance are still emerging, but these programs usually bear resemblance to passive surveillance with additional active oversight from veterinary authorities. Reports for enhanced passive surveillance are usually requested from those in contact with animals in a prescribed format, such as indicating the presence or absence of particular syndromes of interest (Thompson et al., 2016). This type of surveillance is 'enhanced' because reporting is actively encouraged, such as through regular engagement with animal observers (Ouagal et al., 2010) or a predetermined reporting frequency. When considering objective-driven surveillance design, multiple surveillance data types or approaches to data collection may be used. The combination of active surveillance together with passive or enhanced passive

approaches is often be the most effective and resource-efficient way to achieve the overall objectives of the system (Hadorn and Stärk, 2008; Bertolini et al., 2011).

In the analysis of any type of surveillance data, data processing protocols and data verification procedures should be explicitly documented (Drewe et al., 2015), to avoid errors that give rise to misleading surveillance information. The statistical and analytical techniques used in the surveillance process may be specifically established for animal health data, or may be adapted from human health surveillance. Any adapted analyses must be appropriately validated for use in an animal health surveillance system before they are implemented (Rodríguez-Prieto et al., 2015). Once data analysis is completed, the resulting information needs to be presented in a form that can be effectively communicated.

2.3.3 OUTPUT: EFFECTIVE COMMUNICATION TO ENABLE ACTION

The output of a surveillance system is how the information generated by the system is communicated, allowing action to be undertaken in response (World Health Organization, 1997). This is what distinguishes animal health surveillance from simply monitoring animal health. As noted by Vial and Berezowski (2015), “within disease control organizations, the fundamental purpose of all surveillance, regardless of type, is to provide accurate and timely information upon which to make decisions about how to control disease.” The type of surveillance information provided, how the information is presented, and the timeliness of communication are all crucial to drive action in response.

A surveillance system’s output can include both written material as well as effective data visualisation, and may be communicated or publicised by many channels, including online or via social media. Communication materials need to provide an appropriate amount of technical detail, as well as relevant or interesting insights suited to the intended audience of stakeholders (Wuijckhuise et al., 2011). There are likely to be multiple audiences for surveillance data, and so tailoring communication to each group increases the likelihood that useful action will result from surveillance information. The work of surveillance is not done until the results are communicated and converted into action, so the technicalities of communicating the results of surveillance effectively should not be overlooked.

The action that should arise from surveillance information will vary depending on the hazard(s) under surveillance and the objectives of the system. Detection of an exotic or emerging disease may trigger a substantial field response, such as in the 2007 equine influenza outbreak in Australia (Kirkland et al., 2011). However, not all signals generated by surveillance system require immediate field responses—some may simply initiate further surveillance activities (Buehler et al., 2004). For example, following outbreaks of theileriosis detected by passive surveillance in Victoria, Australia, active surveillance in the form of a disease survey was conducted to confirm this disease was re-emerging in the state (Perera et al., 2013). In the case of surveillance of endemic diseases, an increase in prevalence may trigger extension activities targeting owners of susceptible species and development of industry guidelines for managing disease. This would usually occur over a longer timeframe than that required for rapid eradication of an exotic disease incursion.

The actions arising from surveillance should be recorded and monitored, as the agreement of these outputs with the objectives of surveillance define the overall usefulness and therefore success of the surveillance system. Where outputs do not match the system's objectives, the design of the surveillance system should be reviewed and evaluated. A useful approach to evaluating surveillance, whether during conceptual design or as part of the review of an implemented system, is to consider the attributes of the system. The next section will discuss what the attributes of a surveillance system are, and how they can be used to frame objective-based surveillance design.

2.3.4 ATTRIBUTES OF SURVEILLANCE: UNDERSTANDING A SYSTEM'S STRENGTHS AND WEAKNESSES

Operational surveillance systems should be periodically evaluated, to ensure they are achieving their objectives and to improve their performance or cost-effectiveness. There are a variety of attributes that have been suggested for surveillance evaluation that summarise the many strengths and weaknesses a system can have, as reviewed by Drewe et al. (2012). Surveillance attributes are defined broadly as “the many quantifiable characteristics of surveillance systems” (Drewe et al., 2015). These attributes are also relevant as a starting point to consider how surveillance challenges can be overcome, because prioritising certain attributes during system design often

means other attributes may have to be compromised. Balancing the prioritisation of attributes is the key to addressing surveillance challenges – recognising where compromises are appropriate, and promoting the uptake of a surveillance approach despite those compromises. Detailed discussion of the many attributes of surveillance that have been identified are available elsewhere (Hendrikx et al., 2011; Drewe et al., 2012; Calba et al., 2015; Drewe et al., 2015). This section provides a summary of the most important considerations for crucial attributes, as well as the interactions between them, as the basis for discussing how surveillance approaches can be improved in the face of common challenges. These attributes include timeliness, simplicity, acceptability, stability, sensitivity and specificity, representativeness, coverage, flexibility, cost-effectiveness and usefulness.

Timeliness describes the surveillance system's overall ability to detect disease events and initiate appropriate responses in a suitable time frame (Thacker et al., 1987; Buehler et al., 2004). It is also used to describe the time that elapses between specific steps in the surveillance process, such as between a disease occurring and the first report being received by the surveillance system (Martin et al., 2015). Timeliness should be sufficient to achieve the system's objective (Thacker et al., 1987; World Health Organization, 1997). A timely surveillance system may mean rapid detection and response to an emergency disease situation, or simply detecting endemic disease cases to provide periodically updated prevalence estimates.

Simplicity means a system that collects the minimum amount of data required, at the minimal frequency needed to achieve its objectives (Thacker et al., 1987). Historically, simple surveillance design has made systems easier to understand, easier to implement, with lower costs and more flexibility. More recently, there is a temptation to disregard the importance of simplicity, as technology makes it more feasible to store and analyse large volumes of data. This can lead to systems that collect any and all available data, rather than focussing only on that which is absolutely needed. However, simplicity remains important despite these capabilities, to ensure the system's objectives remain the focus of the surveillance process, as well as to reduce the volume of confidential information needed. This second consideration helps address data partners' often substantial concerns about privacy and data security, simultaneously increasing acceptability (Kloeze et al., 2010; Vial and Berezowski, 2015).

Acceptability assesses whether individuals at each step in the system are willing to play their specified role (Thacker et al., 1987). Participation, the extent to which individuals and groups are willing to enrol and to maintain participation over time, is one indicator of acceptability (Elbers et al., 2010a; Zurbrigg and Van den Borre, 2013; Struchen et al., 2016). An ideal system should be managed in a way that makes it readily accepted by all involved, including data partners, those driving the analysis and interpretation of information, and the people who are responsible to act on the information generated. Acceptability must be maintained over time for a system to be sustainable. New systems may generate user excitement that will overshadow initial difficulties with system operation. However, issues affecting acceptability must be identified and addressed to maintain participation once the novelty of the systems wears off (Vourc'h et al., 2006). These issues include how intuitive and convenient the system is to access and work with, as well as the value of incentives or benefits to data providers (Amezcuca et al., 2010; Sawford et al., 2013; Zurbrigg and Van den Borre, 2013). The system should operate smoothly and in a sensible way, incorporating appropriate technology as needed (Meynard et al., 2008). Data security can also affect acceptability, as real or perceived problems with the collection and storage of confidential, potentially sensitive or valuable data can be major concerns for potential data partners (Struchen et al., 2016).

Stability is also crucial for the long-term operation of a surveillance system. Features of stable systems were described by Drewe et al. (2015) to include reliability (function without failure), availability (operational when needed) and sustainability (operate consistently long-term). Stability relies on having sufficient resources to operate and maintain the system, including funding and technical staff availability (German et al., 2001). These resources must be maintained over time for the system to remain stable, although changes to funding sources may be negotiated over time. Sufficient data partners are also needed to maintain stability, remembering that some attrition is always expected (Fielding et al., 2005). This usually requires active recruitment of additional participants over time, as well as consideration of any acceptability issues that may be driving attrition.

Case detection accuracy indicates how closely records in the system truly represent the disease status of the population under surveillance, and is typically expressed through the concepts of sensitivity and specificity. These accuracy measures have

been adapted from the epidemiological principles of accuracy in diagnostic testing, and can be interpreted in an analogous way, including the consequences of incorrect detection (Grosbois et al., 2015).

Surveillance system sensitivity (SSe) is the proportion of true cases in the population under surveillance, that are detected by the system (Table 2-1 is a contingency table to demonstrate this concept, where $SSe = A/[A+C]$). For exotic disease surveillance, SSe also indicates a system's ability to detect new outbreaks of exotic diseases (Sosin, 2003; Drewe et al., 2015). SSe can be calculated by comparing data from the surveillance system to an alternative data source for the same population (Del Rio Vilas et al., 2005; Drewe et al., 2012), or can be estimated for a system overall based on the probability of individual steps in the surveillance process using scenario tree modelling (Hutchison and Martin, 2006; Welby et al., 2011; Martin et al., 2015). A sensitive system detects a high percentage of true cases in the population.

TABLE 2-1. CONTINGENCY TABLE VISUALISATION OF POSSIBLE OUTCOMES OF EVENT DETECTION, TO CALCULATE CASE DETECTION ACCURACY FOR SURVEILLANCE, ADAPTED FROM THACKER ET AL. (1987).

	<i>System detects event</i>	<i>System does not detect event</i>	
<i>Event occurs in population under surveillance</i>	True event detected A	Event missed C	All events in population A+C
<i>Event does not occur in population under surveillance</i>	False event detected B	No event to detect D	All non-events in population B+D
	All events in system A+B	All non-events in system C+D	Population at risk A+B+C+D=N

Surveillance system Sensitivity = $A/[A+C]$. Surveillance system specificity = $D/[B+D]$.

surveillance system positive predictive value = $A/[A+B]$.

Surveillance system specificity (SSp) is the proportion of true absences of disease that are correctly classified by the system (Table 2-1, where $SSp = D/[B+D]$). For outbreaks of exotic disease, its complement ($1-SSp$) is the rate of false alarms generated by the system (World Health Organization, 1997; Drewe et al., 2015). SSp can be difficult to determine directly, because any surveillance systems collect only case data without directly measuring how many non-cases occur in the population. The true size of the

population at risk may not be accurately known, resulting in difficulty determining either the number of true absences of disease detected by the system (D in Table 2-1) or the total number of true absences of disease in the population (B+D in Table 2-1), to provide a denominator to calculate SSp (Thacker et al., 1987; Christensen, 2001). Surveillance system positive predictive value (SPPV) is a useful alternative measure when SSp cannot be determined (Thacker et al., 1987), being the proportion of all cases reported that are truly positive (Table 2-1, $SPPV = A/[A+B]$). This can be determined by validating surveillance data with an alternate data source (ideally with 'gold standard' diagnostic accuracy or using a Bayesian approach in the absence of a gold standard) to determine the proportion of false positives being detected by the system. A highly specific system (or one with high SPPV) generates very few false positive disease signals, meaning that disease cases recorded by the system will reflect true occurrence of disease. The sensitivity and specificity of the surveillance system are influenced by the accuracy of how individual cases are identified, including the diagnostic accuracy of any laboratory testing performed. Diagnostic misclassification results in surveillance misclassification of cases.

Representativeness describes how well the characteristics of the population under surveillance reflect the wider population of interest (Drewe et al., 2012). Because surveillance data are usually collected from a sample of the population of interest, representativeness determines how appropriate it is to infer the information generated by surveillance applies to the broader population. A representative sample mirrors the temporal, spatial and animal-level risk-factors of the wider population (Thacker et al., 1987; Drewe et al., 2012). Representativeness can be reduced by bias or incomplete data. Surveillance bias is the extent to which disease occurrence estimates generated by system (i.e. about the population under surveillance) differ from the true disease state of the population of interest (Drewe et al., 2015). If biases in the system are quantified, analytical methods can attempt to correct for them in disease occurrence measures. The precision of estimates produced by the surveillance system are determined by the system's coverage, also called the surveillance fraction and analogous to sample size. A larger surveillance fraction offers more precision and less uncertainty around disease occurrence measures, although it cannot overcome biases in the population under surveillance. There are often practical and resource limitations that influence the coverage achievable by a surveillance system.

Flexibility describes the ability of a system to be adapted for changing information needs or operating conditions (Sosin, 2003; Drewe et al., 2015). A flexible system takes little additional time, human effort and resources to be adjusted for a new situation, such as surveillance for a new disease, a changed case definition or shifts in reporting needs. Flexibility also encompasses the concepts of multiple utility and portability. A system with multiple utility can capture information on multiple diseases or health conditions (Thurmond, 2003), thanks to an appropriately designed surveillance process encompassing data management, analysis and communication. A portable (or generalisable) system can be readily used in another location or context, such as replicating an existing system in a new country (Sosin, 2003; Drewe et al., 2012). When applying an existing surveillance system design to a new country, interoperability is also advantageous: this means the new system can be integrated into other surveillance programs already established in that country (Drewe et al., 2012). Although surveillance systems are often developed specifically for each context (including country, hazard and population of interest), making a system flexible and interoperable can mean it can be shared between contexts to improve the quality of surveillance. Because good surveillance design takes careful consideration and therefore consumes resources, being able to share a well-designed system can improve international—even global—surveillance efforts.

Surveillance systems consume resources during effective operation, making cost-effectiveness and feasibility important attributes. Cost-effectiveness considers whether the expected outcomes of the system justify the cost of surveillance, including the time, human effort and financial requirements of system operation (Drewe et al., 2012). Benefits to be considered against these costs include the direct economic, political and social benefits of surveillance, as well as indirect benefits such as peace of mind and increased confidence from trading partners (Thurmond, 2003). Describing these more intangible benefits helps make the case for a truly cost-effective surveillance approach, rather than just preferring the least-cost option. Feasibility describes the extent to which the necessary resources (people, funding, technological capability, connectivity, etc.) are actually available for the system (Drewe et al., 2012). The most cost-effective approach may not be the one that is feasible, for example due to lack of expertise or suitable equipment, which will influence the design of the surveillance system.

Finally, the most important attribute of a surveillance system is its usefulness. Usefulness measures how successful overall the system is in generating the required action to meet its objectives. Usefulness is a combination of both impact and relevance, where impact is the change or action that occurs because of information generated by the system (Drewe et al., 2015), and relevance is how well the outputs meet the system's objectives (Drewe et al., 2012). Although compromises in other surveillance attributes may be necessary due to practical constraints, the usefulness of a system should not be willingly compromised. A system with excellent sensitivity and acceptability, but which does not demonstrate its usefulness by producing relevant information that drives action to achieve its objectives, has not reached its surveillance potential.

2.3.5 THE COMPROMISE OF SURVEILLANCE DESIGN

Having recognised the many attributes of a surveillance system, we can now consider how they come together in system design. There is no perfect surveillance system, and it is unlikely that a single system that can achieve every possible objective.

Accordingly, compromises between attributes are typically needed so that realistic objectives can be achieved with the resources available. Once the system's objectives are explicitly defined, the system attributes that will best achieve that objective can be identified and prioritised when designing the surveillance process. For example, surveillance for exotic diseases needs to have excellent diagnostic accuracy, while at the same time consuming modest resources due to the low probability of a disease incursion (Thurmond, 2003). In many cases, there is an association between attributes (Buehler et al., 2004), such that improving one attribute may result in reduction of another. This means that, rather than striving to maximise all attributes, the attributes that are most critical to achieve the system's objectives should be prioritised. Any resulting losses in other attributes should be recognised and minimised if possible, but are often unavoidable. Several examples are outlined here to illustrate the compromises that are often necessary.

One important compromise is between resource use and representativeness. Ideally, the population under surveillance should be representative of the population of interest in every way, using a probability sampling approach. However in the real world, the number of animals or farms contributing data to surveillance is constrained

by the practical resources available. For example, if a veterinarian must attend the farm to collect samples, there are limits to how many farms can be visited in a day, and how many animals can be sampled in a given amount of time. While an ideal surveillance system would select animals to be sampled for surveillance randomly independent of their farm or district, this is often unfeasible. Therefore cluster sampling of a given number of animals within each farm (or abattoir etc.) is typically used, to achieve the desired coverage within a reasonable timeframe. Furthermore, not all farms selected to participate in surveillance may be willing to have their animals sampled. This can result in selection bias if participating farms are systematically different from farms who decline to participate. Because it may not be feasible to use an ideal representative surveillance, analytical methods to account for biases, and caveats when interpreting information from the system, are often required.

Another common trade-off in surveillance attributes is between timeliness and specificity. When reviewing potential data sources for surveillance, Gates et al. (2015) identified the potential time delays to case detection for specific sources of data, such as diagnostic testing or meat inspection. These data sources have high specificity for many diseases compared to simple observation of live animals. However, for diagnostic testing, affected animals must be identified, sampled and the results of testing made available, before cases can be recorded by the surveillance system. Similarly, for meat inspection, diseases that occur on farm are not detected until affected animals are selected for slaughter, transported and processed by the abattoir. Therefore, substantial delay can occur between initial case occurrence, and detection by the system. Highly specific surveillance systems generate few false positive cases, usually because they have strict case definitions requiring diagnostic testing to verify the diagnosis before it is recorded by the system. These systems tend to be less timely than systems that rely on field observations alone, which have lower specificity owing to their broader case definitions (e.g. clinical signs alone). A highly specific approach is appropriate if the consequences of a false positive case are greater than the consequences of a short delay in system detection. However, if timeliness is a higher priority than specificity, then an approach using broader case definitions might be preferred. Reducing the specificity of the case definition will increase the probability of a false positive detection, but reduce time delays in detecting true cases. Follow-up

verification testing can be used to minimise the impacts of these false positive detections.

Building on the importance of the case definitions in surveillance is the relationship between sensitivity and specificity. Surveillance system sensitivity is highest (i.e. the probability of a false negative detection, or missing a case, is lowest) when the case definition is broad, because the system can detect disease cases that present slightly different to the 'textbook' case, or where diagnostic testing is inconclusive or falsely negative (for example, if antibiotic treatment is undertaken prior to attempted bacterial culture). By contrast, surveillance system specificity is highest (i.e. the probability of a false positive detection, or designating an unaffected individual as a case, is lowest) with a very narrow case definition that will only include cases of disease that are unequivocally positive diagnoses. Therefore, the case definitions chosen for a surveillance system should reflect whether sensitivity or specificity is highest priority. It is difficult for a single surveillance activity to maximise both sensitivity and specificity simultaneously. One way to overcome this challenge is to designate multiple categories for cases using different case definitions, such as 'suspect' vs. 'laboratory confirmed' which were used in the 2001 UK outbreak of foot-and-mouth disease outbreak (Gibbens et al., 2001). However, having multiple case definitions decreases the simplicity of the surveillance system and may also reduce cost-effectiveness and feasibility. This is just one illustration of how compromises in surveillance design are difficult to avoid, especially given the resource-constraints that often occur in animal health surveillance.

Although the relationships between attributes are well-recognised, they have seldom been quantified. A rare example is the relationship between sensitivity, specificity and timeliness, investigated by Izadi et al. (2009) using a Bayesian network model to compare analytical algorithm performance on each of these attributes. That study showed that the exact quantitative relationship between attributes is influenced by the hazard of interest and what data are collected.

After the priority attributes of a surveillance system are identified, it may become clear that a single surveillance activity cannot achieve the desired objective. For example, abattoir surveillance may be suited for the samples needed to detect a disease, but provide information too late for it to be useful for on-farm disease control. Similarly, serological testing for a sporadic abortive agent in livestock with a strong

seasonal reproductive pattern may not be feasible, due to large numbers of animals requiring sampling in a short period. Therefore, surveillance systems commonly have a suite of related activities, each of which contributes strengths in different attributes. An example is Australia's arbovirus monitoring program, incorporating not only routine serological testing of cattle in sentinel herds, but also periodic serological surveys of cattle in other herds, and trapping of relevant insect vectors (Animal Health Australia, 2017). In this case, the sentinel herds contribute longitudinal information on virus circulation, while the serological surveys provide more geographically dispersed snapshots of disease occurrence, and vector monitoring increases the probability of early detection (timeliness) of substantial changes in disease distribution as vectors become established in new areas. By combining several surveillance activities, each with strengths in different surveillance attributes, surveillance systems are more likely to achieve their objectives within the bounds of available resources.

The details of how useful surveillance systems are designed vary widely, due to diverse objectives and the practicalities of the country where they are deployed. Clearly defining the system's objectives at the outset increases the likelihood that the outputs generated by the system will be useful and relevant. Traditional surveillance methods such as hazard-specific surveillance and active data collection are well-established and have well-known advantages (such as specificity and representativeness) and shortcomings (being expensive and having limited coverage) as discussed above. To improve the attributes not optimised by these more traditional surveillance methods, the addition of emerging surveillance approaches should also be considered when designing or improving a surveillance system. These approaches include enhanced passive surveillance, targeting surveillance to high-risk populations, and risk-based prioritisation of hazards. Using multiple, complementary surveillance activities can have the net effect of improving the usefulness of surveillance, to protect and improve animal health.

Because there is no perfect surveillance system, it is unsurprising that there are many common challenges faced when designing and implementing effective animal health surveillance. The next sections of this review will introduce the Australian sheep industry and consider it as an example to illustrate several of these common challenges.

2.4 OVERVIEW OF SHEEP PRODUCTION IN AUSTRALIA

Sheep production is one of Australia's major agricultural outputs, with a national sheep population estimated at 70.9 million animals in 2015 (Meat and Livestock Australia, 2016a). In 2013, Australia was the world's second largest producer of lamb and mutton, producing approximately 8% of the world's total lamb and mutton supply (Meat and Livestock Australia, 2016a). Australia is also a world leader in wool production, producing 25% of the world's greasy wool. In 2015-2016, sheep industries produced over 500,000 tonnes of lamb and over 190,000 tonnes of mutton (carcass weight), and 325,000 tonnes of wool (greasy weight) (Australian Wool Innovation Limited, 2016; Meat and Livestock Australia, 2016a). In 2015-2016 the total gross value of combined lamb and mutton meat production was A\$3.3 billion, alongside A\$3.0 billion in wool production. Of all Australian sheep products in 2015-2016, 91% of wool, 56% of lamb and 91% of mutton was exported. Protecting the productivity and quality of the sheep industries, including maintaining export market access, is therefore a high priority for Australia's economy.

Australia's major export markets for sheep products include the sale of lamb to countries in the Middle East, Greater China and the USA, mutton to the Middle East, South-East Asia, greater China and the USA, and live sheep exports to the Middle East (Meat and Livestock Australia, 2016a). Wool is primarily exported to China, with Italy, Czech Republic and India the next most common destinations (ABARES, 2017). Australia's success in international markets, especially in the Middle East, is driven by consistent quality and certified freedom from many OIE-listed diseases, including foot-and-mouth disease (FMD), spongiform encephalopathies (including BSE and scrapie) and sheep pox. Each of Australia's trading partners have their own requirements for disease status and evidence of disease freedom, in accordance with the World Trade Organisation's sanitary and phytosanitary ('SPS') agreement. Australia therefore has a strong imperative to ensure effective animal health surveillance is occurring to support access to these export markets, alongside domestic surveillance objectives. Continual improvement of surveillance methods are needed to keep pace with international expectations of the evidence base for proof-of-freedom claims and for early detection of emergency diseases in sheep.

In Australia, sheep production is concentrated in the more southern states, with the national distribution of sheep numbers by state shown in Figure 2-2. The main areas

of sheep production span a variety of agro-ecological zones ('climates'): semi-arid rangelands inland (200–300 mm average annual rainfall); Mediterranean environments (300–600 mm average annual rainfall) particularly in Western Australia and parts of South Australia; and temperate climates such as in Victoria and New South Wales with winter- or summer-dominant or uniform rainfall patterns that may receive up to 800 mm rainfall annually (Williams et al., 2002). The Victorian sheep industry is the focus of the studies reported in this thesis, both for practical reasons and because of the important role of sheep production in Victoria. The sheep industry is the third largest of Victoria's agricultural industries, largely driven by export opportunities for both sheepmeat and wool. Despite having only 21% of Australia's sheep population and 3% of the country's landmass, in 2015-16 Victoria's sheepmeat production was the largest in the country, with 41% of the country's total lamb and mutton by value (a state total value of \$1.3 billion) as well as being the second highest producer of wool (25% of national production, valued at \$751 million) (Australian Bureau of Statistics, 2017c). Victoria is also considered a higher risk area of Australia for the establishment and spread of foot-and-mouth disease, owing to its mild climate, higher stocking rates, relatively high human population density and proximity to airports and seaports (East et al., 2013).

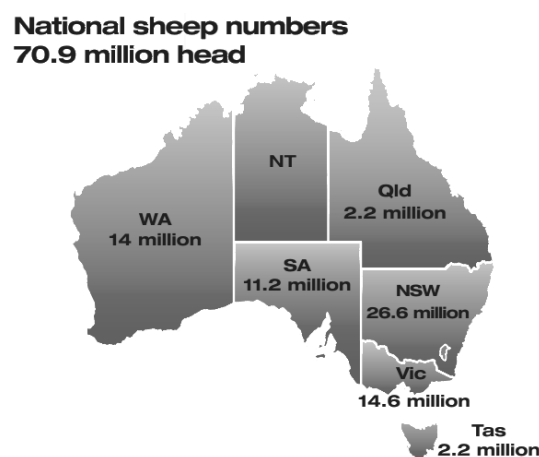


FIGURE 2-2. DISTRIBUTION OF THE AUSTRALIAN SHEEP FLOCK AS AT JUNE 2015. FIGURE FROM MEAT AND LIVESTOCK AUSTRALIA (2016A).

On almost every sheep farm in Australia, sheep are extensively managed, grazing outside year-round and never housed. The average Australian sheep farm has 2857 head of sheep on 700ha of land (Australian Bureau of Statistics, 2017a). However, this varies widely and farms with 10,000 or more sheep grazed over several thousand

hectares are also common. Australian sheep farms typically consist of privately owned, fully fenced paddocks, with no common land. The typical production calendar for most Australian sheep enterprises includes a discrete lambing time lasting 5 to 10 weeks at some time during autumn, winter or spring. This lambing period is known to be associated with increased mortality of both ewes and lambs (Suter, 2013), with disposal of sheep carcasses managed on-farm rather than via a carcass collection and centralised disposal service. The other major annual husbandry event is shearing, which can occur at various times of the year as no clearly advantageous time of shearing has been demonstrated (Campbell et al., 2011). Although many farms are family-operated and may not employ external staff, labour efficiency is a major driver of enterprise profitability (Martin, 2016). In summary, the typical Australian sheep farm consists of thousands of animals of different stock types (lambs, weaned sheep, ewes, etc.), grazing hundreds of hectares and supervised by only one or two people, with little external systematic data collection about animal health mandated. This presents a challenging context for conducting effective animal health surveillance. Nonetheless, effective surveillance activities are needed to meet the country's surveillance objectives, as will be discussed in the next section.

2.5 SURVEILLANCE REQUIREMENTS FOR EXTENSIVE LIVESTOCK INDUSTRIES IN AUSTRALIA

2.5.1 SURVEILLANCE OBJECTIVES

The need for innovative and improved surveillance methods in the Victorian and Australian sheep industries is driven by the objectives of surveillance. The primary focus of many of Australia's surveillance activities is to demonstrate ongoing proof-of-freedom for diseases of trade significance, as well as to facilitate early detection of disease incursions (de Witte, 2013). Economic risk is a substantial motivator for developing highly effective surveillance strategies, and an ABARES report in 2013 estimated the national loss of revenue due to a widespread incursion of FMD could reach \$50 billion over 10 years, primarily due to loss of export markets (Buetre et al., 2013). If FMD were introduced to Australia, early detection of the first cases and subsequent initiation of the AUSVETPLAN disease strategy for control of FMD (Animal Health Australia, 2014) should minimise this substantial economic cost (East et al., 2016). Early detection is largely dependent on an effective passive surveillance

system (Garner et al., 2016). However, animal health surveillance in Australia has the potential to do more than just protect export market access and minimise the cost of emergency disease incursions.

Sheep industries in Australia also need surveillance to demonstrate that their products do not pose a threat to human health or animal welfare, and to safeguard and improve farm productivity. Public health surveillance of food-borne diseases associated with animals is coordinated in Australia by the Communicable Diseases Network Australia, with several food-borne pathogens notifiable in either humans, animals or both (Animal Health Australia, 2017). Australian consumers are also increasingly concerned about the welfare of animals involved in agricultural production. These animal welfare concerns encompass both preventing the inappropriate management of livestock (such as malnutrition during drought or unnecessary husbandry procedures), as well as the control and prevention of endemic diseases that can cause suffering and unnecessary mortality. High standards of animal welfare are a high priority for Australian sheep industries. For example, priority endemic diseases for Australia's red meat industries have been identified (Lane et al., 2015), encompassing not only the productivity and economic impacts of disease in beef, sheep and goat industries, but also highlighting specific diseases that can compromise the welfare of livestock. Surveillance to support these nationally significant endemic diseases has recently been identified as one of the high level goals for Australia's animal health surveillance systems (Iglesias et al., 2017). However, in the construction of this list, it was noted that insufficient information was available about the prevalence of many endemic diseases. Therefore, an additional important outcome of improved disease surveillance would be to better quantify the 'normal' occurrence of endemic diseases across sheep industries. This would then allow diseases occurring at an unacceptable or increased frequency to be identified and prioritised for improved management and control measures.

The Australian sheep industry needs thoughtful surveillance design to achieve the objectives of early detection of emergency diseases, providing evidence to support claims of proof-of-freedom, safeguarding human health by detecting zoonoses, and promoting animal welfare and industry productivity. Systems to analyse surveillance data and facilitate effective responses are largely available in Australia, but a major challenge is the limited availability of suitable data entering surveillance systems to

achieve these objectives. The reasons why these data are difficult to collect will now be outlined.

2.5.2 HISTORICAL CONTEXT FOR DISEASE SURVEILLANCE AND CONTROL

Australia has benefited from disease freedom for many important diseases of livestock since domestic livestock were first introduced to the country by early British colonists. Prior to British colonisation, there were no ruminant animals in Australia. As an island nation, the ability to control importation through seaports and later airports mean that many diseases have been excluded from the country, either entirely or for many decades. However, some diseases were imported and became established in livestock, including footrot and lice in sheep. These diseases persist, causing substantial losses to sheep industries (Lane et al., 2015). Other diseases that were imported and became established in livestock populations have been the subject of successful eradication campaigns, after years of intensive surveillance and disease control activities. One of the most notable of these was the brucellosis and tuberculosis eradication campaign (BTEC), beginning in 1970 and achieving recognised disease freedom in the 1990s (Tweddle and Livingstone, 1994). The magnitude of BTEC meant that an increased number of veterinarians were employed by government, providing services to and developing relationships with farmers. However, following the success of the BTEC campaign, shifts in government funding have fundamentally altered the interaction between farmers and veterinarians.

The history of veterinary services for livestock in Australia influences the way farmers respond to livestock diseases. Agricultural extension, including the provision of animal health advice, was historically provided as a free service from government agriculture departments including veterinarians. These services provided support for sheep and cattle farmers to understand and apply scientific research on-farm to improve productivity (Marsh and Pannell, 1998). Trusting relationships formed between extension officers and their farming clients, which also encouraged a positive attitude toward government agriculture departments (Hunt et al., 2012). Regional government veterinary laboratories were also historically well-established in Australia, having been essential for the BTEC program (Tweddle and Livingstone, 1994).

However, from the late 1980s onwards, changes in policy and funding structures caused a dramatic reduction in government extension services (Hunt et al., 2012). The resulting gap in on-farm scientific advice was partially offset by a rise in private extension consultancy groups, but left many farms without direct advisors. It is unclear why private veterinarians largely failed to step in to fill these gaps in service provision to farmers, although some veterinarians may have seen the provision of broader farm management and extension advice as beyond their skill set. Around the same time, many regional veterinary laboratories were consolidated, making submission of diagnostic material from animal disease outbreaks less convenient with greater transport costs, as well as changing suddenly from fully subsidised to full-cost to the farmer. Previously strong relationships between farmers and government veterinary services were weakened, and the effectiveness of passive surveillance on pasture-based farms in Southern Australia has been compromised as a result.

Further strain to the relationship between farmers and veterinarians was caused by the management of ovine Johne's disease (OJD) following its recognition in the Australian sheep flock, particularly in Victoria. OJD was first detected in an Australian sheep in New South Wales in 1980 and in several areas of Victoria in 1996 (Sergeant, 2001). With a latent period that can last several years between infection and clinical disease, and imperfect diagnostic tests, disease control programs were initiated without certainty of whether the disease could be effectively eradicated or not. In the early years of the disease response program in Victoria, infected farms were identified and destocked, followed by re-stocking with replacement stock deemed to have low OJD risk (Sergeant, 2001). Appropriate financial compensation was provided, but the intangible costs associated with destocking proved too much for some farmers who left the industry entirely (Lade, 2002). As the OJD response progressed into the early 2000s, attempts at eradication ceased and were replaced with an effective vaccination campaign to manage the disease (Lane et al., 2015). However, substantial unease persisted across Victoria's sheep farmers for some time, with views that the attempted eradication had been ineffective and unnecessary. The campaign had been a blow to farmers' trust in government (Palmer et al., 2009a), and gave farmers recent experience of the potential negative consequences of disease reporting or having an important notifiable disease detected on their property. Understandably, in the years that followed, the effectiveness of passive surveillance started to be questioned. The Matthews review, an assessment of Australia's preparedness for a foot-and-mouth

disease (FMD) outbreak, highlighted the emerging disconnect between farmers, veterinarians and the government, and noted that FMD's notifiable status had little impact on farmers' reporting behaviour (Matthews, 2011). This review called for innovative surveillance to establish connections with farmers and their communities, highlighting the importance of awareness and communication programs with livestock workers to build trust and capacity for detection.

2.5.3 CURRENT SURVEILLANCE ACTIVITIES

Despite the challenges of recent decades, Australia presently has a range of surveillance activities to support the country's surveillance objectives of early detection of outbreaks, proof of freedom and understanding significant endemic diseases. Australia's state and territory governments are responsible for the delivery of animal health surveillance and emergency response activities within their jurisdictions (Animal Health Australia, 2017). These activities include both hazard-specific surveillance and support for passive surveillance and voluntary disease reporting. While government veterinarians support and deliver many of these activities, private veterinarians also play an important role, through the detection and reporting of notifiable diseases and unusual clinical cases. Compulsory reporting of suspect notifiable diseases is enforced by legislation in all states and territories, and encompasses the observations of animal owners as well as the diagnoses made by veterinarians and laboratories.

Australia's active surveillance programs relevant to domestic mammals include the national transmissible spongiform encephalopathy (TSE) surveillance program, the national sheep health monitoring project, the national arbovirus monitoring program (which encompasses hazard-specific activities for bluetongue, Akabane virus and bovine ephemeral fever), and the screw-worm fly surveillance and preparedness program (Animal Health Australia, 2017). Only the first two of these programs are relevant to the Victorian sheep industry, as the three arboviruses have been demonstrated to be absent from Victoria and the climatic conditions in southern Australia are unsuitable for the persistence of screw-worm fly (Fruean and East, 2014). In terms of TSE diseases, Australia is recognised by the OIE as a country of negligible risk for bovine spongiform encephalopathy (BSE), and has historical freedom from scrapie. The national hazard-specific TSE surveillance program occurs

across the country and focuses on risk-based sampling of sheep and cattle with clinical signs considered consistent with BSE or scrapie. Targeting these animals with the highest probability of infection gives the system high sensitivity to detect TSEs, and supports Australia's OIE status.

The national sheep health monitoring project is a general surveillance activity, using abattoir inspections to collect data about a number of endemic diseases of sheep (Animal Health Australia, 2017). In this program, operating across 18 domestic and export abattoirs, 16 conditions are monitored by qualified meat inspectors and company personnel. These include syndromes such as arthritis, cancer, dog bites, grass seed contamination, pleurisy and pneumonia, as well as specific diagnoses such as ovine Johne's disease and *Taenia ovis* infection. In addition to daily summaries reported to the abattoirs involved, results of monitoring are collated by Animal Health Australia in the Central Animal Health Database, with the state datasets available for state sheep health coordinators to report findings to individual farmers. However, the number of target diseases for this program is limited both by the small amount of time available for individual carcass examination, as well as by the appropriateness of visual diagnosis immediately after slaughter for any particular condition.

Alongside these active surveillance programs is Australia's substantial passive surveillance capacity. The observation and reporting of clinical syndromes by farmers, abattoir workers and others in contact with animals, alongside the pre-diagnostic and diagnostic observations of veterinarians, is a form of passive surveillance and is the most common method of animal disease detection in Australia (Animal Health Australia, 2017). These reports are supplied voluntarily, either to state government officers or via an emergency animal disease hotline.

To support passive surveillance, the national significant disease investigation program (SDI program) funds the investigation of significant disease events by government and non-government veterinarians (Animal Health Australia, 2017). Where a passive surveillance report is consistent with an emergency animal disease (encompassing exotic diseases e.g. FMD, emerging diseases e.g. Hendra virus, or nationally significant endemic diseases e.g. anthrax), investigations are led by state or territory government staff, with response costs being shared between government and industry (Animal Health Australia, 2017). Alongside these emergency disease investigations, the SDI program aims to increase the number of disease investigations undertaken for

unusual disease cases. This is achieved by providing subsidies for non-government veterinarians to perform post-mortem investigations and also covers associated laboratory costs, ideally to the point of diagnosis. Where a diagnosis is not reached, relevant testing is pursued to exclude nationally significant diseases. Bovine brucellosis testing is also undertaken opportunistically alongside passive surveillance investigations of abortion in cattle, as well as during cattle export certification. The SDI program is the primary system for surveillance of endemic diseases, giving a general impression of overall endemic disease but resulting in a scarcity of prevalence measures, with existing records either non-representative or out of date. Furthermore, the effectiveness of the SDI program is dependent on farmers recognising clinical syndromes and engaging a veterinarian to further investigate, and it is unclear how reliably this occurs. It could also be argued that the data captured through passive surveillance is a small and a biased picture of the total disease burden.

Additional surveillance activities have been undertaken in the Victorian sheep industry, under the Biosecurity Strategy for Victoria launched by the Victorian state government in 2009 (Bell, 2011). These included monitoring of all disease in eighteen sentinel sheep flocks, opportunistic investigations of ewe and lamb mortalities in the peri-parturient period, and examination and post-mortem investigation of unwell and deceased animals at saleyards and abattoirs (Suter, 2013). Throughout these projects, which completed their first phase of operation in 2012, no emergency animal diseases were detected. The results of these surveillance activities give a broad overview of the disease burden of the Victorian sheep population, but the results of these studies have only been made publicly available in highly aggregated forms (Suter et al., 2013a; Suter et al., 2013b). Further, despite being co-funded by both livestock industries and government, the high cost associated with conducting large numbers of post-mortems and diagnostic investigations to obtain these data may not be sustainable as a national or long-term surveillance activity.

2.5.4 GAPS IN CURRENT SURVEILLANCE

While Australia boasts a substantial and highly effective suite of surveillance activities, these are largely focussed on exotic disease exclusion and proof of freedom to support export market access. This leaves substantial gaps in the effectiveness of surveillance for changes in the prevalence of endemic diseases, and surveillance focussed on protecting animal welfare. Cost-effective, sustainable approaches to disease surveillance could be highly beneficial, to increase the volume of information generated to support these surveillance objectives.

The historical events reported above have led to erosion of the contact between veterinary services (government and private) and extensive livestock farmers. This led to lost opportunities for obtaining surveillance data describing the disease status of sheep and cattle industries through farmer-focussed passive surveillance activities. Governments cannot control whether a farmer will actually choose to report the clinical syndromes they have observed (Palmer et al., 2009a). Nonetheless, government-led passive surveillance programs rely on farmers and veterinarians to report unusual signs of disease. Farmer reporting of unusual clinical syndromes is particularly useful for industries with low rates of routine veterinary contact, such as sheep and beef farms in Australia. Data reported in 2003 suggested only 20-30% of all broad acre farmers in Australia engage veterinary services in a given year (Frawley, 2003). More recently, a postal survey of Australian beef farmers revealed less than 60% had contacted a veterinarian in the preceding 12 months (Hernández-Jover et al., 2016). Furthermore, non-response bias means this figure was likely an overestimate of the wider industry's veterinary contact.

Reviewing the existing surveillance activities occurring in Australia's sheep industries demonstrates a clear gap between farmers and animal health authorities. It would be desirable to increase the fraction of sheep health problems that can be detected by surveillance activities; this could feasibly occur in one of two ways. The first is to improve passive surveillance by increasing the proportion of clinical syndromes reported to veterinarians, as suggested by Garner et al (2016). The second is to establish alternative surveillance data collection, so that clinical syndromes can be detected even if they are not directly 'reported' to private or government veterinarians. The preferred approach is one that will be acceptable to all stakeholders in surveillance, and feasible with the resources available for surveillance.

Before either of these approaches is implemented, more information is required in three important areas. A better understanding of how farmers respond to disease in their livestock is needed by either approach. If they are not contacting veterinarians regularly, how are Australian farmers managing disease in their livestock? Studies focussed on the behaviour of both Australian farmers, as well as those with similar production systems in other countries, will be reviewed in Section 2.5. These studies, largely focussed on disease reporting behaviour or the uptake of biosecurity recommendations, provide the background for further investigation of Australian sheep farmers' behaviour specifically. A better understanding of farmers' approaches to disease management is important, as it can allow new programs to be designed with the farmers' needs in mind, creating an acceptable and sustainable approach to improved surveillance.

Furthermore, if a new approach is needed to overcome the existing limitations to surveillance in Australia's sheep industries, then existing work on appropriate surveillance methods should be considered. In particular, syndromic and participatory surveillance activities have potential relevance to improve surveillance data capture from farms, as they work around the assumptions of more traditional surveillance activities, such as reliance on the veterinarian to generate case data. It may be possible to implement a new system in parallel to existing surveillance activities to capture farmers' observations of signs of disease, for example using a reporting system based on clinical syndromes (hence 'syndromic' surveillance). The background and potential design approach of such a system are discussed in Section 2.6, along with examples of operational system and lessons learnt from their implementation.

As it is unfeasible to expect such a reporting system to include all farmers of interest, it may be desirable to target farmers whose farms have above-average disease risk to participate in new surveillance activities. Farm disease risk is associated with the livestock movements onto and off that farm; therefore understanding patterns of livestock movement can help identify high-risk farms for targeted surveillance. An overview and examples of the investigation of livestock movement data as a means to target novel surveillance activities is given in Section 2.7. The remaining sections of this chapter will thus explore the relevant background to designing improved surveillance activities for Australian sheep industries.

2.6 UNDERSTANDING THE DISEASE RESPONSE BEHAVIOUR OF LIVESTOCK OWNERS

2.6.1 TRADITIONAL PASSIVE SURVEILLANCE RELIES ON FARMER REPORTING

Passive surveillance, the voluntary reporting of observations of signs of disease by people who are in contact with animals (Hoinville et al., 2013), is only effective when sufficient cases of disease are reported to the surveillance system. Passive surveillance reports contribute to Australia's surveillance capacity, particularly for early detection of emerging or emergency diseases (Animal Health Australia, 2017). In Australia, farmers are the main observers of livestock for the majority of their animals' productive lives, so capturing information on what farmers are seeing is crucial to the usefulness of a passive surveillance system. Understanding when farmers actually report disease signs is therefore crucial for the design of effective passive surveillance, whether the report is provided by direct contact with government staff, or arises from a phone call or visit from a local private veterinarian who subsequently reports the case. Any missing observations can decrease the sensitivity of passive surveillance to detect changes in disease patterns. Further, if the kinds of disease problems that are reported are systematically different from those that go unreported, the overall view of disease provided by the system can become biased.

Traditional passive surveillance relies heavily on farmers having regular contact with veterinarians or other animal health officers. In Australia, governments employ non-veterinary staff with appropriate training and supervision as animal health officers alongside veterinarians. While they are not responsible for making diagnoses, these people may be the first point of contact for farmers with animal health concerns, and so have a similar role to veterinarians in the passive surveillance process. For simplicity, the term 'veterinarian' will be used throughout this section and in Chapter 5, but it should be interpreted to also include these non-veterinary animal health officers where appropriate. Individuals observing cases of disease and receiving information about animal health from farmers as part of their routine work can screen large numbers of disease cases for any unusual or potentially important disease signs. Veterinarians are relied on as the major group of observers who can differentiate the

normal occurrence of endemic disease from an unusual case that is of surveillance interest. Cases that fall outside normal disease occurrence can then be reported by the veterinarian to a passive surveillance system. This approach to surveillance depends on veterinarians having established relationships and regular contact with farmers. It is efficient and effective, as long as the veterinarian is exposed to sufficient numbers of cases on sufficient numbers of farms to detect unusual signs or prevalence of disease.

The success of this approach can be threatened where the connection between farmers and veterinarians is weak. While the proportion of disease events with direct veterinary involvement is difficult to estimate, for sheep and beef industries in countries like Australia, veterinary contact with farms tends to be infrequent and irregular. In a sentinel farms survey conducted in the early 2000s in New Zealand (Black et al., 2001), where sheep production is similar to Australian farms, a veterinarian was only contacted in 30% of significant animal health issues identified by the farmers. If farmers fail to identify every potentially significant health problem in their livestock, the percentage of all animal health problems reported could be even lower. In recognition of the implications of low rates of veterinary contact for passive surveillance, there have been calls to increase the frequency of veterinary visits, especially to extensive sheep and beef farms (Garner et al., 2016). Understanding the behaviour of farmers, and why present rates of veterinary contact remain low, would be helpful when devising strategies to increase the rate of veterinary visits. Alternatively, other ways to capture reports of disease events occurring on farms could be investigated, to overcome the low rate of veterinary contact.

A major challenge arising from low rates of veterinary contact is the timely detection and accurate diagnosis of exotic or emerging diseases. New diseases may be mistaken for endemic diseases that the farmer is used to dealing with, especially if clinical signs are similar. If misdiagnosis occurs, the farmer's normal routines for endemic disease management will likely be implemented, delaying appropriate action such as contacting a veterinarian or imposing quarantine of affected animals. The challenge here arises that while it is unfair to "expect producers to be vets" (Wright et al., 2016), farmers who do not regularly use veterinarians leave themselves responsible for distinguishing unusual diseases from common endemic issues. Although Australian farmers believe that they are capable of responding appropriately to disease without veterinary advice (Palmer et al., 2009a; Lanyon et al., 2015; Wright et al., 2016), they

have high thresholds for tolerating 'normal' disease occurrence, which limits the sensitivity of passive surveillance. Wider recognition of this tension, and the beliefs that underlie it, could drive an appetite to trial alternative methods to improve surveillance, such as collecting farmers' observations.

Before discussing disease reporting in relation to farmer behaviour, it is worth distinguishing farmer disease reporting from the voluntary use of private veterinary services. As alluded to above, disease reporting can occur in two ways: a farmer directly reporting observed signs of disease to a surveillance system, or a farmer contacting a veterinarian to seek advice about the observed problem, with the veterinarian subsequently reporting it to the surveillance system. In Australia, it is only mandatory to report notifiable diseases, most of which are OIE listed diseases (OIE, 2013b) along with some endemic diseases of state or national importance (Animal Health Australia, 2017). Cases or suspect cases of these diseases are required to be notified within a specified time period. For all other cases of disease, including unusual presentations of endemic diseases (other than those which may be suspect cases of notifiable diseases) or emerging diseases, there is no obligation to formally report. Therefore, care is needed when discussing ways to elicit disease reports from farmers. If the farmers are not directly recruited to participate in a structured surveillance program, they are under no obligation to report non-notifiable diseases. However, farmers are encouraged to contact a veterinarian about all substantial cases of disease, especially those with unusual prevalence or clinical presentation through Australia's subsidised significant disease investigation (SDI) program (Animal Health Australia, 2017). Therefore, while improving passive surveillance may appear to require increased rates of 'farmer reporting', farmers are actually not obliged to report most of their observations. Improved passive surveillance therefore requires either new formal responsibilities for farmers to report, or increased veterinary contact more generally to increase the effectiveness of the traditional model of passive surveillance.

For traditional passive surveillance to support Australia's surveillance objectives, increased rates of veterinary contact for cases of disease on farm are needed, especially for unusual clinical presentations or prevalence. While Australian farmers reported confidence in their ability to identify emergency animal diseases in a study by Wright et al. (2016), this assumes that those diseases will present with

substantially different clinical signs or epidemiology to endemic disease. This may not be the case, especially in the early days of a disease being present on-farm. Cases of lameness or sudden death are unlikely to be reported despite the very small chance that they may be cases of notifiable disease (for example, foot-and-mouth disease or anthrax, respectively), particularly if the spatial and temporal patterns of cases match farmers' previous experiences of endemic disease (for example, foot abscess or clostridial diseases). Therefore, as farmers would not expect themselves to report cases of endemic disease, nor seek a veterinarian's input, these types of disease cases would not reach a passive surveillance system, unless the presentation of the disease within the flock changed from the pattern expected by the farmer. While this situation is problematic for effective surveillance and early detection, calling simply for increased 'farmer reporting' or investigating barriers to farmer reporting is unlikely to yield the information needed to actually improve case detection. Australian farmers perceive there "is no barrier" to disease reporting (Lanyon et al., 2015), but rather a question of when they do or don't see a need for veterinary advice. Nonetheless, disease reporting has been the focus of several studies which will be discussed in Section 2.5.2.3. This distinction between disease reporting and veterinary contact matters, especially when designing research to better understand farmer behaviour; the farmers' perspective of their actions must be taken into account.

As prefaced above, farmers in Australia have the option to engage private veterinary services to assist in management of animal health and disease problems. Farmers engage private veterinarians less frequently for sheep disease problems than in other industries such as dairy, pigs or poultry (Frawley, 2003). When farmers do contact a vet, they do so as part of good farm management, on the basis of the availability and accessibility of a suitably experienced vet, and expecting some economic or animal welfare benefit, rather than specifically for surveillance purposes. It then becomes the veterinarian's responsibility then to judge whether a case has surveillance value, and to subsequently communicate the information collected during consultation to a passive surveillance system. Ideally, this occurs with the permission and assistance of the farmer as appropriate. Australian farmers can also contact a government officer (veterinarian or animal health officer) directly, again doing so based on availability and accessibility, or seek government assistance via the emergency disease hotline. However, very few farmers would use the hotline in the first instance (Wright et al., 2016). Again, the farmer's primary motivation for reporting non-notifiable diseases

may be seeking diagnostic support or treatment advice, rather than to provide surveillance information. Little information is available to indicate what proportion of reports are received for surveillance purposes alone.

Traditional passive surveillance therefore depends on farmers' abilities to recognise signs of disease, and willingness to report unusual signs to private or government veterinarians. Disincentives or risks associated with reporting, such as perceived negative consequences by animal owners or veterinarians, can result in underreporting (Doherr and Audige, 2001). Government bodies lack confidence in both the on-farm detection and reporting of cases, two critical steps in the passive surveillance pathway. For example, Australia's estimated sensitivity to detect foot-and-mouth disease is most limited by the probability a farmer will recognise the disease as a problem worth reporting, and subsequently reporting it (Martin et al., 2015). Due to the overlap between the clinical signs of endemic disease and exotic disease, governments and veterinarians seem to expect farmers to consider contacting a veterinarian for any unusual disease case, especially if several animals are affected. However, farmers' expectations of what kinds of cases require veterinary assessment may not align with these government expectations. The kinds of cases that 'need reporting', as perceived by those responsible for a surveillance system, might be substantially different from those that a farmer judges as 'needing attention' from a veterinarian. It is therefore of interest to better understand the farmers' perspective of how diseases are managed, and the circumstances when veterinary involvement is, or is not, required.

An understanding of farmers' perspectives about livestock disease and their decision-making processes for responding to signs of disease is needed, to facilitate the design of system that can better capture farmers' valuable observations of signs of disease, and ultimately improve the effectiveness of passive surveillance. To improve our knowledge of farmer behaviour related to livestock health and disease, veterinary epidemiologists have adapted behavioural psychology methods to directly investigate issues such as disease reporting and biosecurity behaviours. In addition, valuable additional insights are available from the work of rural sociologists. The next section will critique the contributions these diverse scholars have made to our understanding of farmer behaviour, and their relevance to the effectiveness and representativeness of passive surveillance.

2.6.2 REASONS FOR LOW RATES OF VETERINARY CONTACT ON FARMS

It may seem intuitive to expect veterinarians to have substantial involvement with animal health on all types of farms, but this is not always the case. Veterinarians in the UK have expressed their perception of farmer decision-making as “something of a mystery” (Shortall et al., 2016) in some circumstances. In fact, it has been shown that farmers and veterinarians may have different objectives and perspectives when it comes to disease and disease management on-farm (Shortall et al., 2016; Duval et al., 2017). In Australia, only 20-30% of sheep and cattle farms engage a veterinarian at least annually (Frawley, 2003). This section will explore the evidence supporting proposed reasons why veterinary contact is so infrequent, focussing on three areas: what it means to be a farmer, farmer’s overall attitudes toward veterinarians, and known barriers to disease reporting.

2.6.2.1 THE FARMING CONTEXT AND FARMERS’ PERSPECTIVES

Farmers’ disease responses must be placed in the context of farming, farmer decision-making and problem-solving behaviour, before examining why veterinary contact is limited on sheep farms in Australia. This context includes how farmers manage the diverse problems that arise regularly on-farm, and the risks that must be tolerated when farming. Farmers’ coping strategies include aspiring to a personal concept of ‘good farm management’, which includes recognising that some problems cannot be eliminated and promotes self-sufficient problem solving. Alongside this, substantial diversity in attitudes and approaches amongst farmers means that there is no one simple explanation of how farmers behave, and no single solution to improving rates of veterinary contact.

Farming is a complex activity, requiring farmers to identify and respond to many problems that arise throughout the production cycle of the farm. Livestock disease is just one of many problems that can arise (Heffernan et al., 2008). By its very nature, farming involves managing risk and farmers must respond to situations that are out of their direct control. Most farmers seek a reasonable return for a reasonable amount of work, while tolerating reasonable risk (Vanclay, 2004), although what is considered reasonable varies between individual farmers. Contacting a veterinarian about a case of livestock disease reflects a risk assessment performed by the farmer (Duckett et al., 2015; Brennan et al., 2016), which is usually an unconscious process informed by the

beliefs, biases and risk perception of the farmer. In Europe and England, clear differences in risk perception when considering livestock diseases have been shown between farmers and veterinary services (both government and private), leading to low adoption of disease reporting and biosecurity activities by farmers (Bronner et al., 2014; Shortall et al., 2016). Similar differences in Australia are partly driven in uncertainty and lack of appreciation of the problem (Vanclay, 2004). The farmer's perception of the relative importance of disease on the farm, the perceived risk of disease occurring, and the farmer's assessment of any risks associated with contacting a veterinarian about the problem can all contribute to disease reporting being a lower priority than other activities on-farm.

When deciding how to respond to disease signs in their livestock, farmers must prioritise their time, energy and resources. Australian farmers typically are motivated to 'do the right thing' in managing their farms (Vanclay, 2004), particularly in view of being stewards of their land and animals (Krzywoszynska, 2015; Higgins et al., 2016). Similarly, British farmers perceive effective monitoring of their stock and vigilance about disease (Brennan et al., 2016), so that endemic disease problems are detected early and can be managed (Heffernan et al., 2008), as part of 'good farm management' (Vanclay, 2004). In an interview reported by Kaler and Green (2013), a sheep farmer in the UK suggested that "most farmers are pretty good with their stock", avoiding disease problems through good husbandry. Australian beef farmers similarly report that "good farmers should have little to worry about" (Higgins et al., 2016), with one farmer asserting, "if something were wrong I'd pick it up pretty quickly because I'm here managing it". Good farm management is perceived to be protective against problems arising from disease, and disease severe enough to cause problems on farm only occurs for 'bad' farmers (Heffernan et al., 2008).

Farmers are a heterogeneous population, and demographic variables tend to poorly circumscribe similar behaviours or attitudes to farming (Vanclay, 2004). Consequently, what good farm management actually looks like varies between farmers. Different farmers will tolerate different levels of risk, have different approaches to similar problems, and differ in their adoption of recommended best practices such as activities related to farm biosecurity (Shortall et al., 2016). O'Kane et al. (2016) have also shown that farmer personality and emotional response to disease in their livestock are associated with their response to disease problems. Thus, there

is a need to work with farmers' individual experiences, ideas and beliefs to drive behavioural change (Brennan et al., 2016; Frössling and Nöremark, 2016). As described by Kaler and Green (2013), "sheep farming is very complex and each farm is unique", meaning that while there may be common reasons why veterinarians have low levels of contact with these farms, there is unlikely to be a single way to increase veterinary attendance.

Furthermore, even if farmers consider 'good farm management' to include good animal health management, this does not always translate to early reporting and veterinary investigation of all disease problems. Some level of disease may be seen as a normal part of managing livestock. While many farmers pride themselves on "doing all they reasonably can to minimise disease risk" (Higgins et al., 2016), they also recognise that "disease cannot be avoided entirely" (Garforth et al., 2013). This suggests that rather than a fatalistic attitude, tolerance of some disease is simply a recognition of the realities of farming, especially where livestock numbers are in the hundreds or thousands. The consequence of this realist attitude to disease is that farmers may consider a given prevalence, incidence or severity of disease not to require action, including either direct action by the farmer or seeking external assistance including reporting the disease (Wright et al., 2016). Disease events which fall under these thresholds are very unlikely to be reported by farmers, even if the severity or scale of disease would be deemed concerning by a veterinarian (Shortall et al., 2016).

If good farm management includes the belief that veterinary attention is not required for all cases of disease, what alternate rational response do farmers have when faced with unwell animals? This response depends on the farmer's own expertise and intuition. Farmers' knowledge often comes from their experiences and experimentation on-farm (Vanclay, 2004), and their knowledge of diseases and disease management is no exception, described as having "learnt a bit over the years" by a farmer interviewed by Kaler and Green (2013). Like many farms in the UK (Kaler and Green, 2013), most sheep and beef cattle farms in southern Australia are multi-generational family businesses, with the next generation often growing up on-farm and apprenticed to farming from a young age. These farmers have locally-relevant expertise built up over years or decades of managing problems on their farm, based on experience, observation and experimenting to see what approaches work best

(Garforth et al., 2013; Krzywoszynska, 2015), making themselves the local expert on their farm and flock or herd (Kaler and Green, 2013). Of course, lacking a full scientific understanding of pathophysiology means sometimes false conclusions will be drawn, such as perceptions of poor vaccination efficacy in Britain as described by Richens et al. (2015). Nonetheless, experienced farmers report having the ability to analyse situations and determine the best action based on what normally works (Higgins et al., 2016). In this way, an experienced farmers' approach to disease bears some similarities to that of an experienced veterinarian's process of clinical judgement and pattern recognition. Alongside this experience is a level of intuition. This intuition is motivated by understanding that action must be taken to manage a problem on-farm, even if not all can be known about the problem itself (Krzywoszynska, 2015). Farmers report awareness of having responsibility for their own actions, and uphold this responsibility by making decisions based on their experience, even in the face of uncertainty. They do not seek to control their environment, but skilfully cope given the farm environment in which they make decisions.

Based on expertise and intuition, farmers report confidence in their ability to recognise when they require veterinary assistance in managing a problem. In a series of interviews with farmers in Western Australia, Palmer et al. (2009a) identified that they generally felt confident in diagnosing and treating sick livestock. Further, it was consistently felt that it was unnecessary to contact a veterinarian or animal health officer for a single sick or dead animal (Palmer et al., 2009a). In a related study, 80% of WA farmers surveyed reported having sufficient experience to know when to call a veterinarian (Palmer et al., 2009b), implying their experience was also sufficient to know when a veterinarian was not required. Farmers' confidence in their own ability to manage disease was reported as one reason for not contacting veterinarians or government (Palmer et al., 2009a). It is therefore useful to explore the kinds of situations where farmers do feel veterinary advice could be beneficial.

2.6.2.2 FARMERS' ATTITUDES TO GETTING ADVICE

While farmers consider themselves the local expert on their farm (Kaler and Green, 2013), they recognise this local knowledge can be complemented by broader scientific advice to assist in managing new problems (Vanclay, 2004). Farmers report benefitting from external advice when facing unusual disease situations, particularly those which fall outside the farmers' prior experience (Higgins et al., 2016), although

farmers' and veterinarians' perspectives of what is 'unusual' may not align. Veterinarians are repeatedly nominated by farmers as a trusted source of animal health information, even by farmers who infrequently actually contact them (Heffernan et al., 2008; Garforth et al., 2013; Toma et al., 2013; Hernández-Jover et al., 2016). Veterinary advice for disease management on-farm is particularly useful when veterinarians are able to adapt general recommendations appropriately for individual farms (Shortall et al., 2016). In addition, the broader 'disease intelligence' offered by veterinarians is valued, as they are often aware of the disease status of a local region, rather than just the individual farm as per the farmer's perspective (Richens et al., 2015).

However, the perceived role for veterinarians in many cases of disease is limited, because farmers report having confidence in their own ability to manage most routine disease problems independently. On Australian sheep farms, opportunities for incidental contact with veterinarians, such as dispensing of scheduled drugs or flock health accreditation (such as testing for *Brucella ovis*), are limited and may not provide sufficient opportunity for the detection of unusual disease problems. In France and England, dairy farmers expect their veterinarians to primarily focus on reactive 'fire engine' treatment rather than preventive medicine (Shortall et al., 2016; Duval et al., 2017), and sheep farmers likely see veterinarians in a similar way. If veterinary visits are viewed as reactive and expected to focus only on diagnosis and immediate treatment, then it is unsurprising to find little role for veterinarians to play when the farmer faces a disease problem that they are confident to diagnose and treat themselves. The approach reported by an Australian beef farmer interviewed by Higgins et al. (2016) is illustrative of this attitude: "Ok does it fall within the range of what we've seen before? If it does, we would probably just generally treat it. If it doesn't, we would probably ring the local vet and discuss". Farmers may also fail to appreciate the hidden costs of inaction, sub-clinical problems or outdated treatments with sub-optimal efficacy (Kaler and Green, 2013; Richens et al., 2016; Shortall et al., 2016), meaning that substantial economic losses can occur without triggering the farmer to contact a vet. Given farmers' confidence in their own knowledge and diagnostic skills, if they struggle to perceive the full cost of disease on their farm beyond obvious losses, persistently low rates of veterinary contact are unsurprising.

In livestock industries where veterinary visits to farms are uncommon, farmers may act as information sources to influence one another's disease response behaviour. However, Garforth's (2013) interviews with sheep and pig farmers in England identified that a farmer's own experience and judgement of sensible actions held far greater influence over their behaviour than other farmers' behaviours or opinions. This does not mean that farmers cannot be influenced or will not seek advice, but that they will temper the opinions of others by comparison with their own ideas. Nettle's (2017) investigation of farmer attitudes to farm advisors highlighted that Australian farmers preferred to source information from field days and workshops, as well as by talking to other farmers and searching on the internet. The uptake of any advice is tempered by the independence and trustworthiness of the information source (Nettle, 2017). Information is then filtered by the farmer for relevance and practicality to their own farm before it is implemented (Brennan et al., 2016; Shortall et al., 2016; Wiethoelter et al., 2017).

Another influence on the provision of veterinary advice is the behaviour of veterinarians themselves, in response to farmers' attitudes about disease management. Shortall (2016) reported that when veterinarians' biosecurity recommendations are frequently ignored or not implemented by farmers, the veterinarians become disheartened and subsequently reduce the strength and frequency of those recommendations. This is likely to also be true for veterinarians who attempt to provide veterinary services for livestock farmers. If veterinarians repeatedly experience farmers who are disinclined to seek veterinary advice for animal health problems, this may affect the kinds of advice given by veterinarians when they are contacted by farmers for assistance. For example, rather than strongly advocating for a farm visit and seeking opportunities to provide preventive health advice and further assistance to the farmer, they may be conditioned to expect these recommendations to be rejected and therefore soften their advice to incorporate the provision of free advice via phone. If a change in relationship between veterinarians and farmers is to occur, veterinarians must feel supported to advocate for their best service provision, even if they anticipate the farmer may be reluctant at first.

Thus, the ultimate effect of farmers' attitudes to managing and reporting disease is that, while they acknowledge and desire veterinary involvement in their management of animal health problems on-farm, the perceived role for veterinarians is limited

because farmers rely on themselves and on other trusted information sources when deciding how 'good farm management' is implemented. It is generally only for very unusual disease problems that a veterinarian's advice becomes relevant. Even after considering both the context of farming and farmers' general attitudes to seeking advice, disincentives and barriers to contacting a veterinarian still remain important. While simply removing these barriers is not sufficient to substantially increase rates of veterinary contact, they may still deter farmers from choosing to seek veterinary advice. The substantial information available about these disincentives and barriers, particularly for the purpose of disease reporting, will now be discussed.

2.6.2.3 DISINCENTIVES & BARRIERS TO SEEKING VETERINARY ADVICE

Veterinary epidemiological research into the disease reporting and biosecurity adoption behaviour of farmers has often focussed narrowly on specific barriers that could be overcome, with little consideration to the context of farming and why these barriers occur (Barnes et al., 2015; Shortall et al., 2016). In light of the wider context of 'good farm management' and the role of veterinarians on-farm as discussed above, this section explores factors that are hypothesised to contribute to low rates of veterinary contact. Primary research studies in this area are summarised in Table 2-2, with the barriers reported synthesised into 5 broad conceptual categories: cost, social or emotional factors, issues of trust, practical considerations, and farmers' attitudes to disease management.

The cost of veterinary services is an obvious potential barrier to farmers contacting veterinarians. However, absolute cost has rarely been reported by farmers as a prohibitive barrier for disease reporting. In some circumstances, cash-flow or profitability of a farm may affect an individual farmers' intention to contact a veterinarian (Frawley, 2003). However, in most cases, the decision to call a veterinarian arises from a cost-benefit judgement, weighing the cost of a veterinary investigation against the severity, productivity and profitability effects of the problem (Palmer et al., 2009a; Bronner et al., 2014; Wright et al., 2016). A problem affecting just one animal is rarely seen to warrant veterinary attention, because of the low perceived benefit rather than absolute cost (Frawley, 2003). The validity of this assessment depends on the farmer's ability to recognise all of the effects of disease including sub-clinical and production losses. However, even if the farmer were aware of all costs of disease and were able to make an accurate cost-benefit assessment, this

may not be enough to motivate them to report disease. Simply telling farmers that the cost of disease outweighs the cost of veterinary attendance does not overcome the contextual reasons why farmers don't see the need to contact a veterinarian, and alone is unlikely to motivate them to change their behaviour (Vanclay, 2004; Shortall et al., 2016). There are other historical issues that contribute to the economic barrier to effective on-farm disease investigation. For example, having experienced historical subsidisation of disease investigation by government and seen the value of investigation data to industry, some farmers believe that they should not bear any costs investigating health problems on their farms. They are reluctant to pay for investigations now, despite the lack of alternatives after changes to surveillance programs and funding (Frawley, 2003; Garforth et al., 2013; Kaler and Green, 2013). However, this attitude does not appear widespread; for example, many English farmers consider it appropriate that they are responsible for the cost of managing endemic diseases (Garforth et al., 2013).

Social and emotional factors are often suggested as barriers to disease reporting. Farmers may avoid reporting disease to avoid the perceived negative consequences of reporting, including the social stigma of being the first case in an outbreak, having neighbours know their farm is under quarantine or seeing government veterinarians visiting the farm, and fears of quarantine or movement restrictions without adequate compensation. Investigations of compulsory reporting of abortion in European cattle found that underreporting was common (Bronner et al., 2015; Poskin et al., 2016), with speculation that farmers attempted to avoid the social consequences of an unnecessary investigation when they felt the cause was unlikely to be an emergency or notifiable disease (Poskin et al., 2016). However, a similar study of underreporting in France identified several alternative factors that were the major drivers, especially practical issues including catching the cattle for testing and being able to locate aborted placental material (Bronner et al., 2014). In Australia, a recent study by Wright et al. (2016) including focus group discussions and a phone survey of farmers has revisited the barriers for farmers to report emergency diseases. In that study, the farmers actively refuted the effect of stigma and social consequences of disease reporting. This may reflect Australian farmer's attitudes that their own opinion and judgement more strongly influence their own behaviour, compared to the opinions of other farmers. It seems that stigma may have been overemphasised as a barrier to veterinary attendance to investigate cases of disease.

Another aspect of the effect of farmers' emotions on disease reporting is fear of control measures, when they are not accompanied by sufficient compensation. Farm quarantine and movement restrictions feature strongly when fear is discussed as a barrier to reporting disease (Frawley, 2003; Lanyon et al., 2015; Poskin et al., 2016). These fears stem in part from past experiences, such as the attempted control of ovine Johne's disease in Australia, which triggered some farmers to leave sheep industries altogether (Lade, 2002). However, in the studies listed above, fear is either given as a suggested response on a questionnaire, or is mentioned by study participants as a potential barrier for 'other farmers' in interviews, rather than being reported by the respondent themselves. The role of fear may therefore be overstated due to the preconceptions of researchers, rather than because it is truly a strong factor for farmers themselves. Further carefully designed investigation is required to differentiate the expectations of researchers from the opinions of farmers themselves, before firm conclusions are drawn about how strongly fear affects farmers' intentions to contact a veterinarian about disease problems.

Of all hypothesised barriers to disease reporting, trust in government is the most commonly discussed in Australia (Palmer et al., 2009a; Palmer et al., 2009b; Martin et al., 2015; East et al., 2016). This includes trust in the government's ability to respond appropriately to individual cases of unusual disease events, as well as the government's ability to control an emergency disease outbreak at an industry level. These attitudes primarily arise from past experiences, either personally or collectively within an industry. In the Netherlands, poor communication between government staff and farmers during past disease responses was a strong contributor to negative perceptions of government (Elbers et al., 2010a). In Australia, changes to government veterinary laboratories and the loss of government agricultural extension (as discussed in Section 2.4.3) have been a driver of loss of trust in government (Palmer et al., 2009a).

However, low levels of trust in government are not universal. A study of cattle farmers in England and Wales showed that only 20% of farmers held negative attitudes toward government veterinarians (Gilbert et al., 2014). Meanwhile in Australia, in a telephone survey reported by Wright et al. (2016), respondents had average to above-average attitudes toward the Australian Government Department of Agriculture and Water Resources, the national government department responsible for animal health.

Wright's study also demonstrated that farmers who trusted government agriculture services were more likely to report suspicious clinical signs of disease. This suggests that since Palmer's work (2009a; 2009b), the prevailing attitudes of Australian farmers toward government agencies may have shifted. Furthermore, Wright found that attitudes to government explained only 23% of the variance in farmers' intentions to report unusual signs of disease. It is therefore inappropriate to simplify disease reporting rates as primarily an issue of trust, because other factors also have substantial impact.

Practical and logistic factors, such as the distance of a farm from veterinary services, do influence disease reporting behaviour. Palmer et al. (2009b) showed that sheep and beef farmers in WA who live further from a veterinarian were less likely to have engaged a veterinarian about recent health events or deaths; farmers who lived less than 50 km from their nearest veterinarian had 3.1 (95% CI 1.4 to 6.8) times the odds of reporting deaths than those 101-150 km from their nearest vet, and 3.8 (95% CI 1.6 to 8.8) times the odds of reporting deaths compared to farmers living 201-250km away. Distance from a veterinarian was also a significant predictor of intentions to report unusual disease events in Wright's more recent study (Wright et al., 2016). In that study, the mean distance from surveyed farms to the farmers' preferred veterinarian was 70km, with the furthest veterinarian 600km from the farm. Australia's vast size is one of the challenges to effective passive surveillance and provision of veterinary services.

Farmers' attitudes to disease, while rational in the context of their farm operation, can act as a barrier to disease reporting when risks are not adequately understood or recognised. Farmers' risk perceptions may cause them to underestimate their susceptibility to new or unfamiliar diseases. This leads to inaction, such as in the limited uptake of biosecurity recommendations (for example, as reported by Nöremark et al., 2010, and more recently Brennan et al., 2016) or for zoonotic disease risk management on-farm (Mahon et al., 2017). Inaction arising from low perceived disease risk has also been documented in investigations of livestock disease reporting (such as Elbers et al., 2010a and Bronner et al., 2014).

The low perceived risk of unusual or important disease, when combined with farmers' confidence in their own abilities to manage endemic diseases, leaves little role for veterinarians to play in the routine management of disease on-farm. To remedy this,

attempts to alter farmers' risk perceptions have included the passive supply of information through communication campaigns, such as providing fact sheets and websites documenting the probability and consequences of disease incursions. However, these campaigns often generate little measurable change in behaviour, in part because low risk perception is only one piece of the puzzle and doesn't address the underlying complexity of what it is to be a farmer. Furthermore, in response to past communication campaigns, Australian farmers express frustration that they have very little time to spend absorbing and using information that is passively supplied to them (Wright et al., 2016). Farmers' perceptions of the low risk of important diseases, at the individual farm level, remains a challenging barrier to overcome. Promoting the value of veterinary services for the management and prevention of endemic disease, rather than trying to influence emergency disease risk perceptions, may offer an alternative approach to increasing contact between farmers and veterinary services.

Clearly, the reasons for low rates of veterinary contact on Australian farms are complex. Farmers aspire to good farm management and to respond effectively to disease situations, but are accustomed to being self-sufficient and seek advice only when a problem is outside their range of experience. Veterinarians are seen as useful sources of information regarding animal health, but have a very limited role to play for most disease cases on-farm. Barriers to veterinary contact and disease reporting do influence farmers' decisions to seek advice when dealing with disease. These barriers include the cost of veterinary services, concerns about the consequences of disease reporting, trust in government to conduct effective disease control activities, how readily accessible appropriately experienced veterinarians are, and farmers' perceptions of risk and of their own ability to manage disease effectively. However, it is rare that a single one of these barriers would be sufficient to deter a farmer from contacting a vet; rather, the sum of all these considerations that seems to be driving farmers' behaviour. Accordingly, it would be unlikely that removing any single barrier would substantially change the rate of veterinary contact or disease reporting on Australian sheep farms. Instead, a more nuanced approach to behaviour change is needed. This should be based on a better understanding of the specific drivers of Australian sheep farmers' disease response behaviour.

TABLE 2-2. PRIMARY RESEARCH STUDIES IDENTIFYING BARRIERS TO FARMERS REPORTING DISEASE EVENTS. DARK SHADING AND BOLD FONT INDICATE STUDIES OF AUSTRALIAN FARMERS.

<i>Cost</i>			<i>Social or emotional</i>		<i>Trust</i>			<i>Practicality</i>			<i>Disease management attitude</i>		<i>Reference</i>
Cost of veterinarian outweighs benefit	Cannot afford vet	Expects veterinary services should be free	Perceived risk to reputation	Fear of quarantine or inadequate compensation	Government services unreliable or untrustworthy	Don't know who to contact	Veterinarians perceived to lack relevant expertise	Delayed laboratory submission or results	Farmer too busy	Veterinarians too far away	Confidence in own ability to manage disease	Perceived risk of 'significant' disease low	
x	x	x		x			x	x			x		Frawley, 2003
					x						x	x	Palmer et al., 2009a
					x		x			x	x	x	Palmer et al., 2009b
			x		x							x	Elbers et al., 2010a
			x		x		x					x	Elbers et al., 2010b
			x	x	x	x	x					x	Delgado et al., 2012
		x									x		Garforth et al., 2013
x							x		x			x	Bronner et al., 2014
x				x		x			x		x	x	Lanyon et al., 2015
x					x		x			x	x	x	Wright et al., 2016
				x									Poskin et al., 2016

2.6.3 LIMITATIONS OF PREVIOUS WORK

While there is substantial literature about farmer behaviour as outlined above, much of this literature addresses what farmers do (or do not do), rather than the underlying motivations and influences driving why they behave that way. The challenge faced when attempting to understand farmer behaviour is that the research method and framing of results may not address the core drivers of the behaviour under investigation. For example, discussing barriers to disease reporting without recognising the influence of the farming context on farmer's attitudes and decision-making processes can lead to important problems being oversimplified. Recommendations for behaviour change based on oversimplification of complex farming systems are unlikely to succeed. Further studies that provide detailed description of the underlying attitudes and beliefs of farmers are needed, to allow the design and delivery of more nuanced, effective means of behaviour change to increase veterinary contact with farms. This is just one of the reasons why qualitative methods have a valuable place in veterinary epidemiology and public health research.

Previous investigations of the attitudes of Australian farmers towards contacting veterinarians and disease response behaviour have been limited by their scope, which has tended to focus on biosecurity implementation or emergency disease reporting behaviours. This is understandable, as biosecurity and emergency disease reporting are national priorities for animal health. However, these may not be the highest priority of individual farmers. Research taking a broader view is likely to provide a better understanding of the role of the veterinarian, or farmers' responses to disease in terms of whole farm management and not just emergency disease reporting. If the aim is for increased detection of disease events, focussing first on the diseases that farmers are seeing can give greater understanding of disease response behaviour and its underlying drivers, which can then inform surveillance design.

A further limitation of previous work specific to emergency disease reporting behaviour is the hypothetical nature of emergency disease reporting scenarios presented to farmers. Farmers' low perceptions of disease risk make it difficult to investigate their potential behaviour in the face of a very improbable outbreak. In countries with recent history of emergency diseases (such as highly pathogenic avian influenza or important swine diseases such as classical swine fever or foot-and-mouth

disease), farmers can comment directly on their own disease reporting behaviour, and the barriers to reporting (Delabouglise et al., 2016; Pham et al., 2017). By contrast, in Australia, no major emergency disease outbreaks in sheep or beef industries have occurred in recent decades, so emergency disease reporting has become an abstract concept to many farmers. For example, Australian beef farmers report seeing little relevance of foot-and-mouth disease prevention or detection in their day-to-day farming activities (Higgins et al., 2016). While farmers recognise that an exotic disease outbreak would have severe economic consequences, the likelihood of an outbreak happening either in Australia or specifically in an individual farmer's livestock is—in both perception and reality—very low (Palmer et al., 2009b). Researching emergency disease reporting therefore risks identifying only what farmers think they might or ought to do (intentions), rather than how they will actually respond (behaviours). The conclusions of such research may not reflect what farmers would do when truly faced with an outbreak situation. An alternative methodological approach would be to focus on farmers' recent experiences, such as endemic disease response behaviour, which will offer a more accurate description of decision-making and barriers to action.

Studies have also tended to view farmer behaviour related to disease reporting, as well as implementation of biosecurity recommendations, as a binary comparison of compliance or non-compliance. When approached in this way, current farm practices are seen as a barrier to compliance, rather than simply being the context in which behaviours are occurring (Higgins et al., 2016). Seeing current behaviour as a barrier leaves little room for collaborative behaviour change to take place. When studies focus solely on compliance as an individual responsibility, their view of farmers' behaviour can become narrow, with limited consideration of farm management and whole-farm decision-making. Shortall et al. (2016) suggest reframing 'compliance' issues to recognise the influence of factors outside the farmers' control, such as commodity prices or industry regulations. A broader qualitative perspective is useful when investigating the factors influencing disease response behaviour, rather than a reductionist quantitative approach. Studies using qualitative approaches can demonstrate how disease response decisions fit into farmers' broader farm management strategies. Insights generated in this way will reflect the complexity of decision-making in farming, potentially identifying new approaches to improve disease reporting that are compatible with farmers' existing priorities and approaches.

Effective passive surveillance relies on collaboration between the farmers and veterinarians who directly observe animal health, and the industry, government and policymakers at higher levels making use of aggregated surveillance data. Any misunderstanding between these groups will be detrimental to the surveillance process. In previous Australian studies describing farmer disease reporting, there is strong focus on the consequences of reporting as a major driver of farmers' disinclination to report disease to government surveillance systems (Frawley, 2003; Palmer et al., 2009a; Palmer et al., 2009b). The key outputs of these limited studies, focussing on a lack of trust and fear of the consequences of disease control, have been repeated with little additional research (Martin et al., 2015; East et al., 2016; Poskin et al., 2016). Consequently, a gap in understanding appears to have emerged between government policymakers and farmers around the motivators for disease reporting. Wright et al.'s (2016) more recent work has revisited some of this rhetoric, finding that previously held beliefs of government about these strongest barriers to disease reporting were not echoed by the farmers. This highlights the importance of ongoing research, to validate the relative importance of the most influential drivers of disease reporting and strengthen the overall understanding of farmer behaviour. If passive surveillance systems are to be improved, with better acceptability and participation rates, first we need further research to properly identify and describe the present state of disease reporting, in the context of extensively managed Australian farming systems. Making changes to reporting requirements or strategies without good evidence runs the risk of portraying a 'government knows best' attitude to farmers or directing resources into areas unlikely to bring significant or sustained changes to surveillance effectiveness.

The interpretation of findings of previous studies of farmers' disease reporting behaviour is also contentious. A consistent factor arising either explicitly or implicitly in many of the studies listed in Table 2-2 (including all of the primary research studies with Australian farmers) was farmers' confidence in their own abilities to manage most cases of disease. For example, Palmer et al. (2009a) described most farmers feeling confident to diagnose and treat sick livestock independently of external advice. Similarly, Wright et al. (2016) found that sheep farmers believed it was appropriate to manage small (non-exotic) disease outbreaks on-farm themselves. Frawley (2003) even goes as far as labelling this 'do it yourself' attitude as a 'long-standing ethic' of Australian farmers. These studies reported farmers' beliefs that they had the skills

needed to diagnose and manage disease, and to recognise when they did or did not require veterinary assistance, meaning contacting a veterinarian for most disease cases was irrelevant. Despite the prevalence of these beliefs in their results, few studies clearly identify its presence or discuss its relevance. The frequency of farmers' self-confidence as an element of farmer behaviour is more obvious when these previous studies are synthesised and examined retrospectively. The effect of farmer confidence therefore needs further investigation, to better understand how it influences farmers' overall response to disease situations in their livestock.

Finally, consideration should be given to the generalisability of studies of farmer behaviour between countries and between different types of farms (species kept, scale of production, etc.). Farmers' attitudes may vary substantially between populations, and behaviour is often a response to local context and historical influences. There is great value in validating findings in other populations, to understand how similar, or how different, the attitudes and behaviours of farmers might be. Further investigation of farmers' attitudes and behaviour in different contexts will improve understanding and generalisability of the underlying issues.

Based on the limitations described above, further investigation of the disease response behaviour of Australian sheep farmers is needed. The role of veterinarians on these extensively managed livestock farms appears limited, but the reasons why are only partly understood. Interestingly, in a survey conducted by Lanyon et al. (2015) in South Australia, nearly a quarter of beef farmers reported no substantial barrier to contacting a veterinarian, yet veterinary contact is infrequent on these types of farms. This may also be true for sheep farmers. If the farmers are not perceiving a 'barrier' to contacting veterinarians, then research approaches need to go deeper to understand what is motivating farmers to manage disease as they currently do. Based on the literature reviewed in this section, farmers' confidence in managing disease themselves is likely to be influencing their disease response decisions. In light of the broader objective of improving passive surveillance in the Australian sheep industry, a better understanding of the actions and underlying attitudes and motivations of sheep farmers when facing disease problems is needed. To achieve deep understanding of the farmers' behaviour, qualitative research methods are a clear choice. The next section will briefly discuss the validity of qualitative approaches for the investigation of farmer behaviour.

2.6.4 METHODS TO INVESTIGATE FARMER BEHAVIOUR

There are a relatively large number of studies of farmer behaviour in the veterinary epidemiology literature. Quantitative methods, long been a hallmark of veterinary epidemiology, have been used previously to investigate farmer behaviour. Such studies aim to gather information from a population subset, to allow inference about an issue, disease or risk to a broader population. For example, Lanyon et al. (2015) took a quantitative approach using a postal survey to investigate South Australian beef farmers' knowledge and attitudes to endemic disease management. While quantitative studies are entirely appropriate for inference, they are at risk of bias because closed or directed questions are needed to generate the required data. If the researcher has a firm idea of what they expect to find, the way questions are worded can be biased (whether intentionally or unintentionally) to confirm those expectations, and complex or nuanced issues are easily overlooked (Brinkmann and Kvale, 2015).

By contrast, qualitative methods seek to gain insight rather than to achieve inference. Qualitative studies provide more space for research participants' voices to be heard, and allow for unexpected issues to be raised and investigated. The exploratory mindset adopted by the qualitative researcher enables a more thorough understanding of participants' perspectives to be gained, rather than simplifying a problem prematurely. Because of the depth of insight desired, it is common for qualitative studies to have fewer participants, with prioritisation of information-rich participants rather than a representative sample of the broader population. These kinds of qualitative studies can result in novel findings, identifying factors that may have been previously unidentified or overlooked during quantitative investigation of complex issues such as farmer disease reporting (Denzin and Lincoln, 2011). Qualitative findings can subsequently be used to devise thoughtful quantitative work, to determine whether the conclusions of the initial qualitative work can be generalised to a broader population. Qualitative research is becoming well-established in veterinary epidemiology as a means to investigate farmer behaviour, although researchers are still grappling with the appropriateness of the specific methods and how to interpret their results. While specific qualitative methods are not presented in detail here, a brief review of relevant qualitative methods and comments

on their origin and application to veterinary epidemiological research are presented in Chapter 5.

2.6.5 BENEFITS OF IMPROVED UNDERSTANDING OF FARMER BEHAVIOUR

To improve the detection of unusual disease events on Australian sheep farms by passive surveillance, it could be argued that an increase in the general recording of disease occurrence by surveillance systems must occur first. Broadly, this could be achieved by increasing the exposure of veterinarians to disease events, or by creating an alternate pathway for farmers to report their observations of clinical syndromes directly to a passive surveillance system without requiring a veterinarian. To determine whether the former approach is feasible, we must first understand the present role of veterinarians on Australian sheep farms, and how the farmers manage disease cases with or without veterinary input. Although we know much about potential barriers to veterinary contact or disease reporting for sheep farmers, the disease response process itself on Australian sheep farms—which conceptually precedes any potential barriers to reporting—has not previously been well described. Therefore, an investigation of the disease response behaviour of sheep farmers in Victoria, Australia, is presented in Chapter 5 of this thesis.

A deeper understanding of how Australian sheep farmers manage disease in their livestock offers two potential benefits for passive surveillance. The first is identifying ways to increase veterinary presence on sheep farms, not just by removing barriers but by understanding how veterinarians may support farmers' requirements for disease management. This could improve the effectiveness of surveillance, as well as increasing the provision of veterinary advice for the management of Australian livestock, benefitting both animal welfare and farm productivity. The second is more indirect: understanding how farmers respond to disease also provides insight into how an enhanced passive surveillance program (where veterinarians are valuable but not necessary for surveillance) might fit into farm management, and how it could be designed to be useful and acceptable for farmers, industry and government. No surveillance system is perfect, but a better understanding of farmer behaviour will likely help improve the quality and sensitivity of passive surveillance designed for the complex, real world in which it must operate.

This second benefit—understanding farmers better to inform the design of a useful, acceptable and practical system to capture more information about the occurrence of signs of disease on sheep farms—assumes that an enhanced passive surveillance program can be used to collect farmers’ observations of disease in the absence of a veterinary diagnosis. The potential design of such a system will be explored in the next section, reviewing novel approaches to surveillance data collection that may help overcome the challenge of minimal veterinary contact. In particular, examples of syndromic surveillance and participatory surveillance systems in Australia and internationally will be examined, as background for the design of a new system for the Australian sheep industry.

2.7 SYNDROMIC AND PARTICIPATORY SURVEILLANCE DESIGN

2.7.1 THE NEED FOR A NEW METHOD OF DATA COLLECTION

As discussed previously, disease case information presently flows from Australian sheep farms to passive surveillance systems by two main paths: farmers reporting suspect emergency diseases to the emergency disease hotline (‘disease reporting’), or farmers seeking assistance from private or government veterinarians, or government animal health workers (broadly defined as ‘veterinary contact’). The volume of data currently collected by these two paths is only a small fraction of the total number of disease events occurring on sheep farms. For example, of 64 clinical syndrome cases recorded on 4 sheep farms in Western Australia, only one would have been detected by current passive surveillance activities (Butler and Loth, 2017). This volume of data may be insufficient for early detection of emerging diseases or to fully understand the prevalence of existing endemic diseases, and may also result in delayed detection of exotic disease incursions (Martin et al., 2015; Garner et al., 2016). A passive surveillance system that captures a greater proportion of all disease events could allow more effective monitoring of the sheep population for unusual disease trends that require investigation, and sheep farmers are an important potential data source. Thus the question arises: can the observations of farmers be collected in a way that creates useful surveillance data? Syndromic and participatory surveillance are both commonly used in human health and are emerging in animal health syndromic systems. They offer many of the characteristics needed for farmer observational surveillance. For example, these systems can use data generated prior to a diagnosis

being made, and can be designed to be acceptable and appropriate for farmers to use regularly. The advantages and weaknesses of these methods, and how they could be used in novel enhanced passive surveillance activities for the Australian sheep industry, will now be discussed.

2.7.2 SYNDROMIC SURVEILLANCE

Syndromic surveillance uses clinical signs grouped into syndrome categories, rather than specific diagnoses, to monitor disease trends (Vourc'h et al., 2006). It is an emerging and highly useful approach to surveillance, that complements traditional surveillance activities. Using syndrome reporting means that an exact diagnosis is not prerequisite for the case data to be useful to the surveillance system—this is an essential feature of syndromic surveillance. Initially, the objectives of syndromic surveillance tended to focus on early detection of outbreaks. Over time, its utility for other varied objectives has been shown, as reviewed by Vial and Berezowski (2015), including:

- Describing, detecting and facilitating responses to changes in endemic disease prevalence or distribution.
- Early detection and response to transboundary or emerging diseases.
- Detecting changes in the quality of health data.
- Situational awareness of changes in risk factors, including for disease and antimicrobial resistance.
- Detecting movement of disease to new areas during an outbreak.
- Confirming absence of disease in the face of natural disaster.
- Detecting non-specific changes in disease burden in populations.

In many developed countries, syndromic surveillance for human public health is well-established. It has been in use for human health in Australia for some time, with the Australian Sentinel Practice Research Network (ASPREN) collecting human health data using syndromic methods since 1991 (Fielding et al., 2005). Buehler et al. (2008) reported that 72% of the USA's population was covered by some form of syndromic surveillance from health departments. Despite common use, the ideal analytical methods for syndromic surveillance are still developing (Spreco et al., 2017). Syndromic surveillance of animal populations is less well established, although increasing numbers of pilot and fully operational systems are being reported (Dórea

and Vial, 2016), such as those listed in Table 2-3 and Table 2-4. Developments in technical and analytical approaches, as well as the growing body of evidence from operational syndromic systems, are providing additional support for its broader uptake for animal health surveillance (Ziemann et al., 2015).

There is some variation in how syndromic surveillance has been implemented, and so before discussing examples, it is worth reflecting on what makes a surveillance system 'syndromic'. Two distinct types of syndromic surveillance were categorised by Katz et al. (2011): syndrome-based surveillance and syndrome-non-specific surveillance, and this distinction is a useful basis to approach syndromic surveillance design. Systems for syndrome-based surveillance are hazard-specific, and are designed to detect and monitor one or more specific diseases determined before the system is active, such as signs of influenza-like illness or haemorrhagic diarrhoea in human health surveillance (World Health Organization, 2001). Despite a narrow scope, these systems use a broad case definition to increase the sensitivity of case detection. Examples of animal health syndrome-based surveillance include monitoring community member observations of three specific syndromes (abortion, nervous signs and red urine) as proxies for several important diseases in cattle in Kenya (Walker et al., 2011), and a system being developed in France using the frequency of nervous signs occurring in horses for early detection of West Nile virus (Faverjon et al., 2016; Faverjon et al., 2017). By contrast, a syndrome-non-specific surveillance system seeks to detect any unusual disease signs that suggest an outbreak is occurring, without focussing on specific risk events or particular diseases—this is an example of general surveillance. Syndrome-non-specific systems may use a number of syndrome categories, without prospectively identifying the particular hazards each syndrome is designed to detect. These systems take advantage of non-traditional data sources to conduct surveillance for many hazards, including emerging diseases where the typical clinical presentation is not yet known. Syndrome-non-specific surveillance activities in animal health include a program collecting data from pig veterinarians to monitor swine disease in Canada (Amezcuca et al., 2013) and a UK program monitoring the frequency of inconclusive laboratory investigations for sheep and cattle (Kosmider et al., 2011).

Although the above terminology proposed by Katz et al. has not been widely adopted, it is a useful starting point to consider how syndromic surveillance might be useful for the Australian sheep industry. A syndrome-based approach would be appropriate if

the system were being designed to detect specific exotic diseases such as foot-and-mouth disease, where increases in rates of lameness, decreased milk production and increased hypersalivation could provide early detection of an outbreak. This was the rationale behind the 'BOSSS' system design piloted in the northern Australian cattle industry by Shephard (2006). By contrast, syndromic-non-specific surveillance is more suited to the detection of emerging diseases and endemic disease outbreaks, with a broad scope of diseases which might be detected by the system. This kind of syndromic surveillance has great potential value for the Australian sheep industry to more accurately describe the current prevalence of endemic diseases, as has been called for in industry-commissioned reports (Lane et al., 2015). However, before it can be implemented, the design considerations, advantages and potential limitations associated with syndromic surveillance must be considered.

2.7.3 THE USE OF SYNDROMIC SURVEILLANCE IN ANIMAL HEALTH

While all syndromic surveillance systems are united by the use of syndromes as proxy measures for diseases in the population under surveillance, there are several distinct ways this can be implemented. These can be specifically considered under the broad concept of the surveillance process, as described previously in Section 2.3.2. Here the processes used in existing syndromic surveillance systems will be explored, highlighting the diversity of syndromic approaches and important design considerations for new systems. This diversity is illustrated in Table 2-3 and Table 2-4, which gives an overview of several animal health syndromic surveillance systems reported in the literature. These examples will be used to demonstrate the validity of the multiple possible approaches to syndromic surveillance.

Several key aspects of successful syndromic surveillance systems should be considered, including the type of data collected, the participation of those partnering to provide data, conditions that will improve willingness to participate, the practicalities of data collection, and the appropriate analysis of data, including both simple description as well as complex temporal approaches. By considering the successes of existing syndromic systems and learning from their challenges, new systems can be designed using an evidence-based approach to maximise the likelihood of successful and useful operation.

TABLE 2-3. EXAMPLES OF ANIMAL HEALTH SYNDROMIC SURVEILLANCE SYSTEMS: OBJECTIVES, LOCATION AND TYPE OF SYNDROMIC SURVEILLANCE. (FURTHER DETAIL OF DATA COLLECTION, ANALYSIS, REPORTING AND INCENTIVES FOR THESE SYSTEMS IS GIVEN IN TABLE 2-4.)

System ID	Species	System focus	Objective	Location	System status ^a	Type of SyS ^b	Reference
A	Cattle	Diseases of cattle	Determine feasibility	Northern Australia	Pilot	SNS	Shephard, 2006
B	Pigs	Swine health & disease	Determine feasibility	Ontario, Canada	Pilot	SNS	Amezcuca et al., 2010
C	Cattle, sheep & goats	Bluetongue virus	Determine feasibility	Belgium	Retrospective analytical study	SBS	Mintiens et al., 2011
D	Dogs & cats	Endemic diseases of dogs and cats	Early detection of outbreaks	Australia	Active	SBS	Ward and Kelman, 2012
E	Dogs	Labrador health	Identify environmental and genetic risk factors	United Kingdom	Active	SNS	Clements et al., 2013
F	Cattle	Clinical syndromes in cattle	Early detection of outbreaks	Ontario, Canada	Retrospective analytical study	SNS	Dórea et al., 2013
G	Cattle, horses, sheep, goats & pigs	Diseases of livestock	Early detection of outbreaks	Ontario, Canada	Terminated after active function	SNS	Zurbrigg and Van den Borre, 2013
H	Various	Signs of disease in domestic & wild animals	Early detection of exotic diseases	Northern Australia	Active	SBS	Cookson, 2014
I	Cattle	Mastitis in dairy cattle	Detect clinical cases	Belgium	Retrospective analytical study	SBS	Huybrechts et al., 2014

System ID	Species	System focus	Objective	Location	System status ^a	Type of SyS ^b	Reference
J	Horses	Companion animal and equine health	Estimate baseline prevalence	New Zealand	Pilot	SNS	Muellner et al., 2016
K	Cattle	Milk production and udder health in dairy cattle	Increase communication among veterinarians	Southern Belgium	Active	SNS	Poskin et al., 2016
L	Horses		Early detection of outbreaks	Switzerland	Active	SBS	Struchen et al., 2016
M	Cattle	Bluetongue and Schmallenberg viruses	Early detection of outbreaks	Netherlands & Belgium	Retrospective analytical study	SBS	Veldhuis et al., 2016
N	Sheep	Diseases of sheep	Estimate baseline prevalence	Western Australia	Pilot	SNS	Butler and Loth, 2017
O	Pigs	PRRS virus ^c	Early detection of outbreaks	Minnesota, USA	Retrospective analytical study	SBS	Silva et al., 2017

^a System status at time of publication; ^b SyS = syndromic surveillance, either SBS = syndrome-based surveillance and SNS = syndrome non-specific surveillance;

^c Porcine reproductive and respiratory syndrome virus.

TABLE 2-4. EXAMPLES OF ANIMAL HEALTH SYNDROMIC SURVEILLANCE SYSTEMS: DATA COLLECTION, ANALYSIS, REPORTING AND INCENTIVES.

(FURTHER DETAIL OF OBJECTIVES, LOCATION AND TYPE OF SYNDROMIC SURVEILLANCE FOR THESE SYSTEMS ARE GIVEN IN TABLE 2-3.)

System ID	Data source	Data type	Method of data provision ^e	Data capture	Frequency of data provision	Method of analysis	Method of results communication	Incentive to participate
A	Animal owners or managers	Field observations of disease signs	Paper or email	Prospective [#]	At least monthly, option for real-time	Descriptive	Not described	Not described
B	Veterinarians	Clinical records or observations ^d	Paper or digital	Prospective [#]	Weekly	Automated descriptive analysis and cluster detection	Newsletter	Information, financial (subsidy)
C	Rendering plant	Rendering plant records	n/a	Existing records	n/a	Comparison of automated aberration detection algorithms	n/a	n/a
D	Veterinarians	Clinical records or observations	Digital	Prospective [#]	Not reported	Descriptive and spatial	Website access to anonymised data & maps of case distribution	Information
E	Animal owners	Field observations of disease signs	Digital	Prospective	Monthly for first 12 months, then 3 monthly	Descriptive	Newsletter	Material (prize draw), social
F	Diagnostic laboratory	Laboratory submission requests	n/a	Existing records	n/a	Comparison of automated aberration detection algorithms	n/a	n/a
G	Veterinarians	Clinical records or observations	Paper or digital	Prospective [#]	At least monthly, option for real-time	Not reported	Not described	Financial (subsidy), financial (payment)

System ID	Data source	Data type	Method of data provision^e	Data capture	Frequency of data provision	Method of analysis	Method of results communication	Incentive to participate
H	Local rangers	Field observations of disease signs	Not described	Prospective	Quarterly	Descriptive	Not described	Not described
I	Animal owners or managers	Farm records	n/a	Existing records	n/a	Automated aberration detection algorithm	n/a	n/a
J	Veterinarians	Clinical records or observations	Built into existing software	Existing records	Daily (automated)	Not reported	Not described	Not described
K	Veterinarians	Field observations of disease signs	Email list	Prospective	Ad hoc	Not reported	Social media presence, two annual forums	Information, professional development
L	Veterinarians	Clinical records or observations	Digital	Prospective [#]	At least monthly, option for real-time	Not reported	Website access to aggregated data, monthly newsletter	Information, professional development
M	Third-party industry company	Farm records	n/a	Existing records	n/a	Automated aberration detection algorithm	n/a	n/a
N	Animal owners or managers	Field observations of disease signs	In-person visit by veterinarian	Prospective	Monthly	Descriptive	Not described	Not described
O	Animal owners or managers	Farm records	n/a	Existing records	n/a	Automated aberration detection algorithm	n/a	n/a

^dThis system also recorded a minimum data set for all non-cases seen by veterinarians. ^e'Digital' can encompass either or both of hand-held devices (personal digital assistant, tablet or mobile) or desktop/laptop accessible systems providing for online data entry and submission.

[#] system required data to be double-entered (into prospective surveillance system separately from normal record-keeping). Rows with some n/a values were retrospective analytical studies that did not report the delivery of a fully operational surveillance system, and for which these columns were deemed not relevant.

The ability to generate useful information from a variety of types of data is an attractive feature of syndromic surveillance. In their review, Abat et al. (2016) identify many potentially relevant data types, including environmental data such as weather records and water quality, as well as animal and human health data such as telephone hotline records, pharmaceutical sales, medical records and laboratory request forms. Useful data that can be for animal health syndromic surveillance can include:

- observations of animal owners (Clements et al., 2013; Butler and Loth, 2017) and veterinarians (Amezcuca et al., 2010; Zurbrigg and Van den Borre, 2013; Muellner et al., 2016; Struchen et al., 2016);
- data generated during the diagnostic process, such as laboratory submission paperwork (O'Sullivan et al., 2012; Dórea et al., 2014) and records of inconclusive investigations (Hyder et al., 2011; Kosmider et al., 2011);
- routine data generated by livestock industries, such as animal production records including dairy cattle milk production or reproductive records (Huybrechts et al., 2014; Veldhuis et al., 2016), and measurements taken at slaughter by abattoirs (Dupuy et al., 2013; Vial and Reist, 2014; Alton et al., 2015) or carcass disposal facilities (Mintiens et al., 2011).

In some cases, these data may be held by a third-party, allowing access to aggregated datasets (such as a government organisation or private company, such as the cattle improvement company in Belgium reported as a data source by Veldhuis et al., 2016). However, in many cases (including all but one of the examples illustrated in Table 2-3 and Table 2-4), relevant data are held only by the individual people who generate them, requiring the surveillance system to identify and recruit those individuals to contribute data for the surveillance system. When considering recruiting individuals to collaborate in data provision for a syndromic surveillance system, a related surveillance approach becomes relevant: participatory surveillance.

Participatory surveillance was defined in the context of animal health by Mariner et al. (2011) to describe the use of techniques from participatory rural appraisal and participatory epidemiology to achieve surveillance objectives (Catley et al., 2012). The term 'participatory' refers to the active role that stakeholders like livestock owners play in these surveillance systems, sharing in control and ownership of the system in a 'bottom-up' approach. One benefit of the active inclusion of stakeholders in these systems is to help align system outputs with the needs of those directly in contact with

the animals of interest. Participatory surveillance recognises these valuable local technical knowledge of stakeholders, and has the potential to incorporate the social context of diseases. While most examples of participatory epidemiology and participatory surveillance in animal health have arisen from developing countries (as described by Catley et al., 2012 and Mariner et al., 2011), the challenges of doing surveillance 'in the real world' are not restricted to these countries. The philosophy of participation is also relevant to developed countries, to improve the quality of information that can be generated by surveillance as well as the engagement of those at the 'coal-face' of animal health. For specific examples of sophisticated participatory surveillance systems in developed countries, it is worth diverting briefly to systems reported for human health surveillance.

In human health surveillance, the term 'participatory' is used more generally, to describe surveillance activities that engage the general population (or a subset of it) in recording and reporting health data. This broader definition is the intended meaning of the term when references to participatory surveillance occur throughout the rest of this thesis. For example, in the USA, 'Flu Near You' (Chunara et al., 2013) uses a weekly email to solicit symptom self-reporting on a website from participants sourced from the general population, for ten symptoms indicative of influenza-like illness. A similar system in Europe, 'Influenzanet' (Paolotti et al., 2014), also uses anonymised data entered voluntarily into a website by people living in the ten participating countries for syndrome-based surveillance of influenza-like illness. Participatory surveillance has also been used for early detection of public health threats at mass gatherings including the FIFA World Cup (the 'Healthy Cup' mobile app, 2014) and Olympic Games (the 'Guardians of Health' app, 2016) in Brazil (Leal-Neto et al., 2016; Leal Neto et al., 2017). This kind of surveillance can be considered as 'crowdsourcing' surveillance data (Leal-Neto et al., 2016). Although well established in human health surveillance, crowdsourcing appears to be minimally utilised in animal health, apart from wildlife health monitoring through voluntary reporting (deemed 'citizen science' by Lawson et al., 2015 and Dissanayake et al., 2017). One particularly relevant benefit of the participatory approach applied in human health, as reviewed by Smolinski et al. (2017), is the ability to overcome surveillance system dependence on individuals who seek health care when they have symptoms of illness. Clearly, these methods are also relevant for animal health surveillance in certain livestock industries where few disease cases are brought to the attention of a veterinarian.

The willingness of individuals to contribute data is crucial for both human and animal health definitions of participatory surveillance. Alongside this, it is important to understand how data recording and submission activities can occur alongside their regular duties or lifestyle. In some cases, the data of interest is already being captured in a format that is appropriate for integration into a surveillance system, and simply needs to be regularly updated to the surveillance database for analysis. This is the case for most examples of human health syndromic surveillance systems (Paterson and Durrheim, 2013). However, many animal health syndromic surveillance systems require prospective data entry, including most of the examples listed in Table 2-3 and Table 2-4. This is either because no formal record of the data of interest is being kept, or because the format of the data that is recorded is unsuitable for the surveillance system. Aligning data recording between user needs and system requirements is a major challenge for syndromic surveillance, as the need to double-enter data can reduce acceptability. It would be ideal for record format to meet the needs of both data providers and the system itself, for example using a software patch to classify and extract data from veterinary clinical records as has been demonstrated in the UK (O'Neill et al., 2013) and New Zealand (Muellner et al., 2016). However, this approach is only feasible if a small number of software programs are being widely used to manage broadly appropriate data; there are situations where many different software programs are used, records are kept without software, or written records are not kept at all. Therefore, prospective data collection may still be required.

Where data must be prospectively sourced for syndromic surveillance, data collection can include both paper and digital forms. Ease-of-use is critical, for example avoiding extended free-text fields when collecting data on mobile devices (Amezcuca et al., 2010). Based on their experience collaborating with livestock veterinarians in Canada, Zurbrigg et al. (2013) found improved acceptability if data collection could be aligned with the kind of record keeping participants were used to – in their case, a paper-based system. In that system, automated processes were used to convert paper records to digital data to make the process more efficient. However, as the uptake of mobile devices increases, solely digital approaches are more feasible through websites or mobile 'apps' for data entry, especially if data can be recorded without an internet connection and later uploaded (Higgins et al., 2015). Moving toward digital data collection, it would be ideal for case data to be recorded at the time it is generated, for example during the veterinarian's consultation. But despite the

aspirations of those who design surveillance, it is not always practical for surveillance records to be generated in real-time, as farmers, veterinarians and other types of participants may have competing priorities when observations of specific diseases or clinical syndromes are made. Even without real-time reporting, data can still be received by the system in a timely manner, with the overall timeliness of the system determined by both data acquisition and analysis.

As in every aspect of surveillance design, the analytical approach should reflect the surveillance system's objectives, which may in turn be influenced by the expertise and technical infrastructure available for the system. Syndromic surveillance systems for early detection of outbreaks are increasingly using automated 'aberration detection' algorithms for analysis of syndromic data (Dórea et al., 2014; Gates et al., 2015). In these analyses, historical data are used to generate expected 'baselines' for syndromic measures, and then alert signals are generated when new incoming data exceed the expected baseline (Dórea et al., 2015). These automated analyses can minimise the time elapsed between data becoming available to the system and information being generated, making them ideal for early-warning surveillance. For example, a system for detection of West Nile Virus in France (Faverjon et al., 2016) found that the virus was best detected by looking for simultaneous increases in nervous signs in horses (reported by sentinel veterinarians) alongside increased mortality in wild birds (reported by people employed or engaged in hunting). Syndromic surveillance can offer a sophisticated approach to detecting animal health problems when multiple types of data can be collected and analysed simultaneously, although ongoing research is needed to identify and refine the algorithms suitable for animal health surveillance data (Vial et al., 2016).

However, because of variation in surveillance objectives and practical constraints, it is not always desirable or feasible to analyse syndromic data using complex algorithms. Simpler approaches including descriptive analysis or manual review of data can also be valid ways to turn syndromic surveillance data into information that drives action. Consider, for example, the emergence of Schmallenberg virus in Europe. Poskin et al. (2016) report that the earliest indicators of Schmallenberg virus occurring in Belgium were discussions between dairy cattle veterinarians on an email list. Simply monitoring the content of these observational reports would have produced useful information in the early stages of emergence. In some cases, this kind of content

analysis may be most effectively delivered by a suitable expert person, rather than an automated computer program. Additionally, if the system's objective is to determine baseline disease occurrence or detect changes in endemic disease prevalence, descriptive analyses may provide sufficient information without substantial investment in complex algorithm generation and validation, for example as has been shown in Myanmar (Hanks et al., 2017).

In summary, when designing a syndromic surveillance system, there is no single 'most' valid approach. Rather, syndromic surveillance encompasses a constellation of methods, centred on the idea of detecting syndrome changes rather than specific diagnoses. This diversity makes conversations about syndromic surveillance challenging, even amongst surveillance experts, as the experiences of each individual drive their understanding of what syndromic surveillance 'ought' to look like. In fact, there are multiple valid ways to implement syndromic surveillance. The objectives of the surveillance system, and therefore what attributes should be prioritised, will determine whether syndromic surveillance is an appropriate choice in the first place, and will also inform the process by which the system operates. To design the process for a syndromic surveillance system, it is worth considering what sort of data would be valuable, who holds or can generate that data, how it can be captured in a format suitable for surveillance, and how it could be analysed to best meet the system's objectives. The advantages and limitations of syndromic surveillance will now be discussed, to frame how a syndromic surveillance system might contribute to overcoming challenges to effective disease surveillance, such as those faced by the Australian sheep industry.

2.7.4 ADVANTAGES OF SYNDROMIC SURVEILLANCE

There are several advantages of syndromic surveillance, that stem either directly or indirectly from the potential to capture pre-diagnostic data for surveillance. These include improved timeliness and sensitivity for case detection, the ability to detect emerging disease issues, the potential to capture both case and non-case data, cost-effectiveness, flexibility, and engagement of wider stakeholders in the surveillance process. Each of these advantages will now be briefly explored.

Timeliness is one of the clearest advantages of syndromic surveillance. Because the system requires only a syndrome for case detection, rather than a laboratory

diagnosis, cases can enter the system without being delayed by the full process of clinical investigation and diagnosis. Using data generated before a diagnosis is reached removes the laboratory turn-around time from the surveillance process, in some cases hastening detection of cases by several days. Using syndromes to capture observations on-farm would also mean that any delay between the farmer first detecting signs of disease, and the disease being investigated to achieve a diagnosis, no longer influences the timeliness of surveillance. For emergency diseases, improved timeliness is crucial, because the number of days to detection is correlated with the size and therefore cost of control for disease (McLaws and Ribble; East et al., 2016). Amezcua et al. (2010) identified that the time delay between disease occurrence in the field and the availability of case data for analysis by the system, is commonly the limiting factor for establishing real-time surveillance. Of course, real-time surveillance is not always the objective of syndromic surveillance, and the importance of timeliness should be tempered by the objectives of the surveillance system. Nonetheless, the potential improvement in timeliness offered by a syndromic approach is a substantial benefit.

Another substantial advantage of syndromic surveillance is its sensitivity. Because the case definition used for syndromic surveillance is, by definition, a broad one, the likelihood that syndrome cases in the population under surveillance will be misclassified is low (low false-negative rate). Of course, observation of syndromes does not perfectly correlate with particular diseases: for example, not all feedlot cattle with bovine respiratory disease will show detectable clinical signs (White and Renter, 2009; Timsit et al., 2016). However, almost all feedlot cattle in the population under surveillance that do show signs of clinical disease will be detected. Syndromic surveillance is sensitive to detect changes in the prevalence of clinical signs, which may represent cases of interest for particular hazards. Increased case numbers can then trigger follow-up investigation or verification against other surveillance data sources, to determine the underlying cause and whether it is truly a hazard of interest for the surveillance system's objectives.

The sensitivity of syndromic surveillance is particularly useful when paired with the approach's flexibility. Because these systems are structured around syndromes rather than specific diagnoses, they can be adapted to include new suitable syndromes to detect and monitor new or re-emerging hazards by adding new syndromes or data

types. Furthermore, in the face of an emerging disease with similar syndromic presentation to endemic diseases, an operational syndromic surveillance system may already have captured relevant data that can be re-analysed to rapidly generate useful information. Consider bovine theileriosis, which was not previously recognised in Victoria, Australia, and emerged in cattle in that region in the early 2010s (Islam et al., 2011; Perera et al., 2013), or Schmallenberg virus which emerged in Europe in 2011 (Poskin et al., 2016). In each case, if affected farms had been participating in syndromic reporting of observed signs of disease (i.e. increases in anaemia and recumbency, and abortions and neonatal malformations, respectively) these disease emergencies may have been detected sooner. The benefits of high sensitivity and flexibility for disease detection are one of the substantial benefits of syndromic surveillance, compared to more traditional surveillance approaches.

Syndromic surveillance also has the ability to generate data describing both case occurrence and case absence. In many other types of surveillance, the absence of disease in the population is inferred by the absence of cases reported to the system. However, in syndromic surveillance, it is possible for true absences to be captured by the system. For example, a system which detects abnormal trends in routinely collected farm production records can also show that production records appear follow normally expected values. Alternatively, by asking farmers or veterinarians to report syndromes as either present or absent, a system collecting observations can also generate evidence of absence, at least in the population under surveillance. One example is a system that collected clinical data from swine veterinarians in Canada, with the data describing both disease cases and routine non-disease visits (Amezcuca et al., 2010). Collecting this 'negative' data means the total number of events under surveillance can be enumerated, allowing syndrome frequency to be expressed as prevalence rather than as case counts. Furthermore, it gives direct evidence that syndrome cases are not present in the population, rather than using the lack of positive cases absence to imply absence.

The cost-effectiveness of syndromic surveillance is another advantage of this approach, for two reasons. Firstly, it may leverage existing data that is collected for other purposes, providing additional useful information without requiring additional resources. In addition, because observations can be collected without needing laboratory confirmation in every case, the number of cases that can be feasibly

submitted to the system can be substantially greater than an active surveillance approach that requires more costly laboratory diagnosis. While syndromic surveillance systems still require resources to acquire, aggregate, and analyse data, and communicate the information that is generated, the cost of data collection can be substantially reduced compared to other surveillance approaches that could achieve similar objectives.

The final major advantage of syndromic surveillance is the potential to directly involve stakeholder groups in the surveillance process, rather than viewing stakeholders as only beneficiaries of the information that is generated. Syndromic surveillance offers the opportunity to create new collaborations between government, industry, and the individuals on the ground directly caring for the animals. This allows each stakeholder group to have greater ownership and responsibility for surveillance. For example, farmers have become involved through collaborative use of their routine farm production data including dairy records in Belgium (Huybrechts et al., 2014) and pig records in the USA (Silva et al., 2017), or alternatively through their observations of signs of disease in ruminants in Kenya (Walker et al., 2011), Chad (Jean-Richard et al., 2014) and Australia (Butler and Loth, 2017). Similarly, veterinary observations and clinical records have been used in equine (Struchen et al., 2016), companion animal (Anholt et al., 2014; Hennenfent et al., 2017) and livestock (Van Metre et al., 2009; Sundufu et al., 2015) settings. However, for the relationships built through participation in syndromic surveillance to become meaningful, communication of the relevant information generated from their data must flow back to these stakeholder groups. The aim should be for partnership in the surveillance process, to create sustainable and mutually beneficial relationships. This is a great opportunity available when establishing a new syndromic surveillance system: surveillance activities can help build collaborative relationships that are also beneficial for animal health more broadly.

Syndromic surveillance is a promising emerging approach to animal health surveillance, with several distinct advantages over alternative approaches. Common surveillance objectives such as the rapid, detection of cases including emerging diseases with high sensitivity can be achieved by a well-designed syndromic system. The addition of providing non-case data as evidence of the absence of disease, as well as advantages in cost-effectiveness, flexibility, and stakeholder engagement, mean that

it has become an attractive type of surveillance. However, it has taken some time for syndromic surveillance systems to become established in animal health (Dórea et al., 2011; Dórea and Vial, 2016), because of the limitations and challenges faced in implementing syndromic approaches.

2.7.5 LIMITATIONS OF SYNDROMIC SURVEILLANCE

Despite the advantages outlined above, the limitations of syndromic surveillance must be carefully considered. These include how to appropriately interpret and analyse non-diagnostic data, the limitations in specificity that come with syndromic case definitions, challenges with sustainability, acceptability and biases including representativeness. This section will outline the causes and implications of each potential drawback, including discussion of how the surveillance system can be designed to work around them.

The use of non-diagnostic data for surveillance is a great advantage of syndromic surveillance, but requires new approaches to the interpretation and analysis of that data. Information where cases are not confirmed, termed ‘pre-diagnostic data’, can have poor specificity, and this must be accounted for in system design (Dórea et al., 2011). It is therefore necessary to follow up detected cases or outbreaks, to confirm that they are relevant to the system’s objectives. This need for follow up investigation in response to a surveillance signal is not unique to syndromic surveillance, as the usefulness of any surveillance system is defined by the action that occurs in response to information generated by the system (see Section 2.3.3). Confirmatory activities are particularly important for syndromic systems, to identify the underlying cause of an increase in syndrome cases. This will help avoid expending unnecessary resources initiating disease response activities for false-positive outbreaks. In the first instance, follow-up may simply mean making contact with those observing the syndrome, to gather more data about the case and determine whether a field visit for further investigation (and/or diagnostic testing) is required. This helps ensure that as many cases in the system receive appropriate attention as is feasible, but that large and resource-intensive disease responses are reserved for the cases where they are most needed. Syndromic surveillance allows disease investigation efforts to be directed to highly suspect cases. Furthermore, if potential case numbers exceed the capacity of investigators, syndromic data can also allow active prioritisation of response efforts.

The high probability of false-positives could potentially be overcome through appropriate procedures for case confirmation, that are appropriately funded and built into the system from the beginning.

In addition to field investigation of cases, confirmatory activities can also include comparison with other temporally relevant data. For example, in an early-warning system monitoring sheep mortality in Scotland which detected increases in deaths, the signals generated by the syndromic surveillance system were validated by comparison with contemporaneous weather data and laboratory diagnoses (Tongue et al., 2017). These comparisons showed that the deaths were associated with adverse weather events and endemic liver fluke, meaning that a further disease response was not required. The integration of multiple signals to detect and confirm disease events, such as combining syndromic surveillance alongside other surveillance activities to help increase the system's specificity, is a promising new direction for surveillance.

Sustainability is another common surveillance challenge relevant to syndromic systems (Dórea and Vial, 2016). For prospective data collection, participants must be retained over time to maintain the flow of data into the system. This usually means some incentive is required for their ongoing contributions. The intrinsic desire to contribute to surveillance has been reported as a strong motivator for providing data to participatory human health systems (Smolinski et al., 2017), but alone may not be sufficient incentive to for animal health syndromic surveillance. Suitable alternative incentives may include financial benefit. For example, subsidised diagnostic testing was a successful motivator for veterinary practitioner reporting in Canada over a three-year period (Zurbrigg and Van den Borre, 2013). However, financial benefits depend on the long-term availability of suitable funding, and the associated cost may limit the feasibility of scaling-up a system to increase coverage.

Intangible incentives can also be powerful motivators for ongoing participation, such as access to information generated by the surveillance system. Providing relevant information in exchange for farmer participation was used in the early 2000s for a sentinel farm surveillance project in New Zealand (Black and Vujcich, 2002), although its effectiveness was not reported. Surveillance information has been successfully demonstrated as an incentive in France for equine disease reporting by veterinary practitioners (Struchen et al., 2016). It has also been piloted in a system built to capture data from veterinary clinical record software in New Zealand (Muellner et al.,

2016), using the system's data to compare individual veterinarians' case frequencies to regional averages. The same concept of local and regional 'benchmarking' of disease occurrence data could also be useful for farmers. Given surveillance systems are already creating information from data, that information can be a valuable incentive to participate if it can be summarised to highlight interesting findings that are relevant to participants, and then effectively communicated. This does not mean simply providing general reports designed for other stakeholders to participants, however; it means taking the time to make sure participants receive useful information that is directly relevant and applicable to their own interests. Therefore, despite a lower cost than financial incentives, resources are still needed to effectively deliver information back to participants.

The incentives used, whether financial, intangible or a combination, should be tailored to the sub-population of potential participants who are actually willing to partner with syndromic surveillance systems to provide data. For example, a farmer reporting system should have incentives that appeal to the types of farmers who are willing to participate. To achieve this, the behaviour and interests of willing participants need to be investigated and understood early in the system's operation. Consider also that the long-term incentives required for a sustainable system may differ from those initially used for recruitment, and that incentives that are effective in for one population may not be generalisable to others (Barnes et al., 2015). Despite the many options and considerations for incentivising system participation, however, even a system with very appropriate incentives will still experience some participant drop-out. Therefore, ongoing recruitment is usually necessary for sustainable long-term operation.

Acceptability can also be an obstacle for syndromic surveillance, especially if prospective data collection is required. The way data are collected must be appropriate and practically feasible for those providing data. For example, Black and Vujcich's (2002) sentinel farm project in New Zealand found that farmers lacked time to enter every individual clinical syndrome they observed into the system. Similarly, when reviewing Amezcua et al.'s (2010) practitioner reporting system, participating veterinarians recommended that syndromic recording be aligned with their own medical records and billing system, to avoid the need for double-entering data. Acceptability can be improved by careful consultation during the design phase with the people who will provide data. This should encompass preliminary investigation of

what volume of data and methods of data entry will be feasible or tolerable as part of their daily workload, and then ongoing follow-up to review how satisfied users are with the practicalities of the system. Furthermore, the system collect only the data that is needed, only as often as it is needed (i.e. be as simple as possible), so that time is only invested in providing data of value for the system's objectives. Examples of veterinary practitioner reporting are useful to illustrate this. A system for surveillance of equine diseases in Switzerland evaluated by Struchen et al. (2016) collected specific symptoms and cases of specific diseases from sentinel practitioners. By contrast, a Canadian system evaluated by Zurbrigg et al. (2013) collected data for all investigations of disease issues in cattle, horses, small ruminants and pigs by participating veterinary practitioners. Even more broadly, the pilot surveillance study in the Canadian pig industry evaluated by Amezcua et al. (2010) collected data for both disease and routine veterinary visits and phone calls for participating practitioners. For some systems, it may be necessary for a greater volume of data to be collected from each participant, but the value of collecting more data must be considered against any losses in acceptability. While these studies reported their systems to be acceptable to participants, acceptability was not measured quantitatively and the potential for further improvement was not explored. Seeking feedback from current participants to improve the user experience for those providing data can help drive improved acceptability, which will also flow on to support the sustainability of the system.

Even systems using existing data sources can have issues related to acceptability, arising from the ownership and security of data. Concerns about privacy and data security are beginning to emerge as a barrier to the development of syndromic surveillance systems (Hennenfent et al., 2017). In all syndromic surveillance systems, the privacy implications of data sharing must be considered, documented and effectively communicated. Again, this problem can be reduced by keeping the system simple, avoiding collecting data that has no value for analysis and reporting (Vial and Berezowski, 2015). If confidential or identifying data are not specifically required by the system to achieve its objectives, they need not be collected. Where individual records are not essential for the useful operation of the system, collecting only aggregated data can reduce concerns around privacy, supporting acceptability.

A further limitation of syndromic surveillance is representativeness, especially if observational reporting is required to generate data for syndromic surveillance. The number of participants who can feasibly contribute syndromic surveillance data to the system (i.e. the coverage of the system) depends on the type of data collected, whether additional activities are required to generate or record the data outside those individuals' normal work, and the cost of any incentives provided to data partners. Generally speaking, larger numbers of participants (increased coverage) will improve the usefulness of syndromic surveillance. However, representativeness is also affected by selection bias. Only those individuals who are willing to participate will be able to be recruited to provide data to the system. These individuals may be systematically different, and have systematically different access to cases of disease, than those who are unwilling to provide data (Smolinski et al., 2017). In this way, the population under surveillance may not reflect the true population of interest – an issue no increase in coverage will solve. This can affect both the volume and types of cases that are reported. For example, the types of human health clinicians who participate as sentinel practitioners in syndromic surveillance programs may be systematically different from non-participant clinicians (Fielding et al., 2005; Brottet et al., 2015), and this may influence the volume and variety of cases they see and report to the system. Some studies have selected combinations of sentinel sites, such as abattoirs (Alton et al., 2015) to be broadly representative of the wider population, although this may not be practical for other types of sentinels such as farms or clinicians. Where bias may be an issue, syndromic surveillance data can be verified by comparison with other surveillance results to avoid false-positive disease responses.

Other types of bias may also affect syndromic data, including recall and detection bias. Because it may not be feasible to have all disease events recorded in real-time, substantial delay between event occurrence and reporting to the system may affect the accuracy of how events are reported. Similarly, the magnitude or severity of disease events can bias which cases are reported to the system, with minor or infrequent problems not be deemed sufficiently important to report, or forgotten when retrospective reports are completed. Detection bias can occur if veterinary case records or farmer notes about disease is incomplete, which is a common occurrence. For example, only 64% of problems discussed and 58% of actions taken were recorded in the patient record in a small study of 36 veterinary consultations (Jones-Diette et al., 2017). These biases may be reduced by careful training and

communication to clarify exactly what kinds of cases should be reported. While it is difficult to entirely avoid bias in syndromic surveillance, identifying potential sources of bias up-front means they can be considered in the design of the system, and accounted for in during the analysis and interpretation of the surveillance information generated.

Syndromic surveillance systems also require careful presentation and communication of the information they generate. Due to high sensitivity and low specificity, the actual case numbers reported to a syndromic surveillance system may not reflect case numbers of specific diagnoses in the population. Therefore, syndromic data are most appropriately analysed as a time-series, interpreting changes over time rather than the magnitude of static snapshot values. This means it is useful to aggregate data to produce summary measures for temporal analysis. However, syndromic data can also have substantial depth, with different sub-populations represented and potentially complementary information (e.g. free-text comments) provided along with numeric data. It is advantageous to collect this complementary information if it aligns with system objectives, as it can bring clarity and meaning to small changes or trends seen in the aggregated data. It is also useful to analyse multiple different aggregations of data for temporal patterns, to ensure that changes in sub-populations are more likely to be detected.

Finally, it is crucial to communicate the results from syndromic surveillance carefully, especially to those who make decisions based on surveillance data. Syndromic results must be presented in an appropriate form for the target audience to maximise the information's value and avoid misinterpretation. This is most important where international trade is involved. If syndrome prevalence is consistent over time, this is suggestive of the absence of substantial disease outbreaks, but must be presented alongside other complementary surveillance data to make a compelling argument for disease freedom.

The major challenges of the syndromic surveillance approach as outlined here include how to effectively analyse and communicate non-diagnostic case data, how to interpret information of low specificity, and how to design a system that is sustainable and acceptable, all while minimising or accounting for biases in the data. Of course, many of these challenges are not unique to syndromic surveillance. Despite these limitations, a syndromic approach is often the only way to effectively collect and

utilise non-traditional data from novel sources. It can generate new insights, with the advantages of increases in timeliness, sensitivity, flexibility and stakeholder engagement.

2.7.6 POSITIONING SYNDROMIC SURVEILLANCE WITHIN A BROADER SURVEILLANCE STRATEGY

The limitations of syndromic surveillance mean that the information generated can rarely be interpreted in isolation. Rather, syndromic surveillance should be seen as part of an overarching surveillance strategy. Incorporating the new information that can be generated by syndromic surveillance alongside data generated by more traditional surveillance methods can result in a highly effective, multi-system integrated surveillance strategy. For example, Welby et al. (2017) demonstrate through scenario tree modelling that a combination of passive surveillance together with syndromic surveillance of reproductive production data is the most cost-effective, high-sensitivity approach for detection of new outbreaks of bluetongue serotype 8 in cattle in Belgium, France and the Netherlands, with active cross-sectional surveys reserved for substantiating proof of freedom after detection and eradication of new outbreaks. This suggests that the future of surveillance lies in multiple, complementary surveillance activities occurring simultaneously. Each activity will have its own strengths and weaknesses in terms of surveillance attributes, but together can produce a useful surveillance system that achieves its objectives within the resource constraints of the real world.

Surveillance in the Australian sheep industry is a useful example to demonstrate the benefit of integrating syndromic surveillance alongside existing surveillance activities. By capturing broad data on a wider range of the disease events occurring on-farm, a system could have greater sensitivity to detect unusual or increased disease occurrence. Thus, a farmer-reporting syndromic surveillance system is useful when it operates alongside complementary systems that can verify underlying causes and prioritise cases. This combination of systems should be able to detect potential problems that threaten the industry and initiate appropriate responses, in a cost-effective manner. The potential value of such a system is clear for emergency diseases, but is also relevant for detecting emerging diseases and surveillance of significant endemic diseases. Syndromic surveillance could be used to help better describe

‘baseline’ disease occurrence in Australia’s sheep population, to provide a point of reference to detect changes in disease frequency or the presence of new diseases—this is the basis for the surveillance system described in Chapter 3 and Chapter 4 of this thesis. In addition, involving farmers directly in the surveillance process has the potential to build collaborations between government and high-level industry bodies, and those at the coalface of disease problems. Increasing the cohesion between these different stakeholders in surveillance will lead to future benefits including more effective surveillance.

2.8 TARGETING SURVEILLANCE BASED ON LIVESTOCK MOVEMENT INFORMATION

The preceding section has described the potentially important role of syndromic surveillance in a broader surveillance strategy. These systems could be made more efficient by deliberately recruiting participants who are more likely to experience the diseases of interest. One way to target surveillance to farms with increased risk of disease is to understand the livestock movement behaviours of different farms, as purchasing and selling livestock is a major potential route of disease transmission. The final part of this review will focus on the use of livestock movement records to understand trading behaviour in livestock industries, to direct the recruitment of farms as participants for targeted surveillance activities such as on-farm syndromic surveillance.

2.8.1 THE VALUE OF LIVESTOCK MOVEMENT INFORMATION FOR TARGETED SURVEILLANCE

Targeting surveillance data collection to individuals or farms with increased risk of disease, or occupying critical niches in a livestock industry, can make surveillance systems more efficient in the face of limited resources. This targeted approach is useful for both endemic and exotic disease surveillance, as targeting farms at greatest risk of an exotic disease incursion increases the probability of early detection, and the likelihood of an effective response. For endemic diseases present at low frequency in the wider population, surveillance on farms with greatest disease risk can identify circulating diseases with increased sensitivity compared to random sampling. If the disease risk of individual farms is stable over time, changes in disease frequency

within targeted high-risk farms can also reflect the pattern of disease in the wider population, allowing important changes in prevalence to be efficiently detected. Targeted approaches can therefore be an effective part of objective-driven surveillance design.

One way to target farms at increased risk of disease is through analysing the patterns of livestock movement between farms, particularly if infectious diseases are of interest. Although infection can be transmitted between farms in several ways, livestock movement is associated with the risk of a farm acquiring or dispersing many diseases. High-risk farms can be identified by analysing the network created by movement of animals, using the established methods of social network analysis (Martínez-López et al., 2009). In general terms, network data occurs when information is available about both individual units of interest as well as the relationships between them. Analysis of network data is well established in many disciplines, including computer science, sociology and infectious disease research. The term 'social network analysis' is derived from its origins in social and behavioural science, as well as reflecting the relational nature of the data, describing not just individuals but the connections between them (Wasserman and Faust, 1994). However, it is increasingly common to refer to the collection of methods simply as network analysis, and this term will be used throughout this thesis.

Network analysis is increasingly used in veterinary epidemiology to understand the implications of livestock movement for disease spread, surveillance and disease control. Network analysis has been used to understand contact and potential disease spread patterns in livestock industries including cattle (Brennan et al., 2008; Pinior et al., 2012; Mweu et al., 2013), pig (Rautureau et al., 2012; Thakur et al., 2014), poultry (Van Kerkhove et al., 2009; Lockhart et al., 2010) and sheep (Webb, 2005; Webb, 2006), and also applied to horses (Firestone et al., 2011; Spence et al., 2017) and wildlife (Corner et al., 2003; Drewe, 2010). While several types of contact between individual animals, or between farms, can be considered as connections in a network, this review will focus on analyses of the network created by the movement of animals between farms.

A livestock movement network is defined by the geographic area of interest (a province, state, country, etc.), the time period that is explored (ranging from weeks to multiple years), and the unit of concern (what epidemiological unit will form the

individuals in the network e.g. individual animal, farm, village, or other geographic aggregation) (Dubé et al., 2011b). There are several potential objectives of network analysis of livestock movements. The patterns of livestock movement in the network can be described, including how the trading behaviour of farms and others in the network drive those patterns (for example, Dutta et al., 2014). The effect of the network on disease spread can also be estimated, compared to random spread ignoring the pattern of connections between farms. Network analyses can contribute to 'peacetime' development of disease response strategies and policy by understanding how to reduce the connectedness of the network (Rautureau et al., 2011). They can also be used to estimate the potential maximum size of future epidemics, to inform resource planning (Dubé et al., 2008). Assessing the network during an outbreak can help retrospectively identify improved disease response strategies (Shirley and Rushton, 2005; Ortiz-Pelaez et al., 2006; Firestone et al., 2011), and comparison of the network before and after changes in policy can reveal whether the desired effect has been achieved (Robinson and Christley, 2007; Hidano et al., 2016). Network analysis can also be used to generate inputs for disease modelling that more accurately reflect the real world than random spread models (Dubé et al., 2009). Although many of these objectives focus on the overall structure of the network, the position and connectedness of individual nodes (e.g. farms) in the network can also provide useful information for targeted surveillance.

Targeting surveillance based on network analysis parameters was first proposed by Christley et al. (2005b). The relationship between a farm's connectedness in the livestock movement network and disease prevalence has since been demonstrated. Martin et al. (2011) showed an association between the poultry movement network in China and the presence of H5N1 influenza. Similarly, Frössling et al. (2012) found that, for two endemic viral diseases of cattle detected from serological samples in Sweden, more positive cases were found using risk-based sampling based on cattle movement patterns, compared to random sampling of farms. There are several relevant measures that can be used to identify high-risk farms to target, as discussed by Nöremark et al. (2011). These measures will be defined in the next section, but first the principles of increased connectivity and their relevance to surveillance in the Australian sheep industry will be discussed.

The spread of infectious disease through a population can be described by the basic reproductive number, R_0 , of the disease. R_0 is the number of infections in a naïve population that are caused by a single infectious individual, assuming homogeneous contact between all individuals. Considering individual farms as the epidemiological unit, this assumes that the probability of any farm contacting another is equal, which is rarely the case. Rather, each farm contributes its own contact pattern to the potential value of R_0 . Due to their animal movement patterns, approximately 20% of the most highly connected livestock properties usually contribute 80% of the value of R_0 (Woolhouse et al., 2005). This means that, if these highly connected farms can be identified and control measures targeted accordingly, the potential of an infectious disease to move between farms can be substantially reduced. By the same logic, highly connected farms are likely the farms of interest for surveillance purposes. The proportion of nodes that form this key contribution to R_0 is not necessarily fixed at 20%, but is determined by the contact patterns of the population (May et al., 2001), which may vary cyclically or change over time. For example, Gates and Woolhouse (2015) examined a model cattle movement network based on British data, finding that targeted removal of movements between farms with high connectivity (top 10% of betweenness, described below) reduced disease prevalence by over 80%. This illustrates the power of targeting surveillance using network analysis of livestock movement data.

In Australia, the important effect of inter-farm connections on disease spread is reflected in the requirement to maintain traceability of food-producing animals for international trade assurance (Britt et al., 2013). Livestock movement data has been used to describe broad patterns of cattle movement (Iglesias and East, 2015), but sheep movement patterns in Australia have only been investigated in a single published study (East and Foreman, 2011), which preceded the introduction of the National Livestock Identification Scheme (NLIS) for sheep in 2009. Analyses of data from the NLIS database have broad potential to better understand the epidemiological consequences of sheep movement in Australia, including how to select target farms for on-farm disease surveillance. Such a study is also of interest because few sheep movement networks have been fully described. While network analysis of cattle movement has been demonstrated worldwide, including England (Brennan et al., 2008), Denmark (Mweu et al., 2013), the USA (Nelson et al., 2014), New Zealand (Hidano et al., 2016), Uruguay (VanderWaal et al., 2016) and East Africa (Sintayehu et

al., 2017), there are far fewer studies investigating the movement of sheep. Despite the substantial role of sheep in the widespread dissemination of FMD in the UK (Gibbens et al., 2001), comprehensive databases recording sheep movements are less common than the corresponding systems for cattle. Some studies have been reported including sheep-only (Webb, 2005; Kiss et al., 2006; Webb, 2006; Volkova et al., 2010) and multiple livestock species including sheep (Tildesley et al., 2011; Waret-Szkuta et al., 2011; Marquetoux et al., 2016b), however the characteristics of these networks may not be directly generalisable to other countries.

2.8.2 THE SPATIAL AND TEMPORAL NATURE OF LIVESTOCK MOVEMENT NETWORKS

The network measures discussed to this point have been largely borrowed from other disciplines and adapted to describe livestock movement networks. Early studies (including Webb, 2005, Woolhouse et al., 2005 and Kiss et al., 2006) relied on established methods and network measures, which were suitable for initial descriptive work. However, there are several features of livestock movement networks that are not always accounted for by the measures used by other disciplines. These features include the fixed geographic location of nodes (i.e. farms), and edges being directed as previously discussed. Furthermore, livestock movement network edges are usually temporally dynamic rather than permanent, because each livestock movement occurs on a given day. Multiple temporally distinct links (edges) between the same pair of nodes can occur in a defined time window, with each representing the movement of one or multiple individual animals, up to hundreds or thousands of animals at a time. These characteristics have prompted the development of additional measures and techniques specifically relevant to livestock movement networks.

Techniques for the analysis of spatial and temporal networks have only recently emerged in veterinary epidemiology. Other fields of study have investigated these types of networks further, developing relevant analyses and measures. Because some of these measures were developed simultaneously across multiple disciplines, terminology is used inconsistently (Holme and Saramäki, 2012), making it challenging to simply translate those measures to be applied in veterinary epidemiology. Furthermore, interpretation of the relevance of specific spatial and temporal network measures to livestock movement networks has been limited. Some proposed concepts

are presented below, along with a discussion of potential further directions for development.

Because a livestock movement network is not static in time, it is useful to understand the temporal variation in the network over various timescales. Results of analyses performed in other countries have identified temporal variation, such as seasonality in sheep trading patterns in Great Britain with increased connectedness in the network (increased GSCC size) between late spring and early autumn (Kiss et al., 2006). Identifying these seasonal changes can inform policy to underpin surveillance for early detection or a disease response required during periods of increased connectivity, where potential outbreak size is substantially increased. It has further been shown that, in the Scottish sheep population, the specific properties that are at highest risk of disease and therefore targets for surveillance may change from year to year, as animal movement patterns change over time (Volkova et al., 2010).

One approach to account for the temporality of livestock movements is to divide the data into temporal subsets (for example, into weeks (Kiss et al., 2006; Robinson and Christley, 2007; Rautureau et al., 2012), months (Rautureau et al., 2012), seasons (VanderWaal et al., 2016) or years (Robinson and Christley, 2007; Schulz et al., 2017)), and then to compare these networks to detect changes over time. Ideally, where infectious disease spread is the focus of analysis, the time period over which the network is constructed should reflect the epidemiology of the disease of interest (Schulz et al., 2017). Observed network topology can also vary depending on the timescale involved (Thakur et al., 2014). For example, Bajardi et al. (2011) demonstrate that despite consistency of the distributions of degree values in the network over aggregation time scales of 1, 7, 28 and 365 days, the individual farms that had highest degree values in one 7- or 28-day aggregation were not always the highest degree nodes in other 7- or 28-day aggregations. The same authors also found the sub-network of 'backbone' edges connecting the network in one month do not persist through successive months. This complicates the identification of high degree nodes for targeted surveillance, as those identified in one month may no longer be the relevant nodes the following month. The time frame for these kinds of analyses may be based on practicalities such as data availability or managing large data files, rather than *a priori* knowledge of the ideal time period that should be included to detect consistently highly influential nodes in the network. Retrospective studies to identify

highly connected nodes, or highly connected sub-networks, should therefore be approached with caution, particularly as the time gap between the data investigated and the future time period of interest widens.

The temporal aggregation required to convert livestock movement data to a static network removes the temporal order of edges, and therefore obscures the ‘causality’ of connections in the network. For example, in the German pig trade network (Lentz et al., 2016), 26% of potential infectious paths in the static network aggregated over 4 years are actually not linked once the temporal order of edges is taken into account. The temporality of livestock movement networks can be incorporated into network analysis by considering time-respecting paths in the network. That is, a path can only potentially carry an infectious disease from farm A to farm D on a path via farms B and C if the edges occur in the appropriate temporal order (edge ‘A to B’ precedes edge ‘B to C’, both of which precede edge ‘C to D’). Several measures that estimate the time-respecting connectedness of nodes in a network have been developed. These include the ingoing infection chain (equivalent to time-respecting ingoing reach, (Nöremark et al., 2011)) and outgoing infection chain (equivalent to time-respecting outgoing reach, (Dubé et al., 2008, 2011a)). It is perhaps more appropriate to refer to the first two measures as the ingoing and outgoing contact chain respectively as per Nöremark et al. (2014), as they represent contact between farms that has the potential to transmit an infectious disease, rather than confirmed spread. The ingoing contact chain has been extended by Frössling et al. (2014) to the probability of disease ratio (PDR), weighting the ingoing contact chain for the number of animals moved to each edge, and adding the ability to specify farm-level disease prevalence for each node. The ingoing and outgoing contact chains can be calculated using Nöremark and Widgren’s *EpiContactTrace* (2014) package in R (R Core Team, 2017), increasing the accessibility of these measures for future network investigations.

Studies treating livestock movement networks as truly temporal networks (also known as dynamic networks or time-varying networks), rather than just comparing between aggregation time scales or by incorporating time-respecting paths, are emerging. For example, Lentz et al. (2016) compared the analysis of the pig trade network in Germany as a temporal network to the results from aggregated static networks. This study highlighted that although examining network data as a time series with various temporal aggregations is useful for understanding the frequency

of connections in the network (and therefore, for example, the resource requirements for a contact-tracing effort), it fails to capture the sequential nature of movements potentially significant for infectious disease spread. Therefore, treating the network as a temporal network is a more meaningful approach that can capture this additional information. For example, Lentz et al. demonstrated that the small-world property of the network (with an average path length of 5.5 steps) was overshadowed by the temporality of movements. Taking into account the temporal order of edges, on average it took 120 days for those 5.5 movements to occur, a phenomenon termed a slow-world network property (Karsai et al., 2011). This suggests that the small-world characteristic found in so many previous analyses may have a modest or even negligible effect when it comes to the spread of diseases with short incubation periods. However, the small-world property of a network may still render the network at risk for diseases with prolonged incubation, such as bovine tuberculosis or bovine spongiform encephalopathy. New insights like this suggest it is worthwhile to pursue the temporal network analysis of livestock movement data.

The applicability of static network measures to temporal networks must be carefully considered. In cases where the static measure does not account for time-respecting paths in the network, alternative measures should be sought. For example, the shortest path between two nodes (geodesic) from a static network is replaced in a temporal network by three possible concepts (Casteigts et al., 2012): the topological shortest path (the time-respecting path with the fewest ‘steps’ between two nodes, i.e. from node i to node j), and two temporal shortest paths, namely the foremost path (the time-respecting path from node i to node j , that can occur in the shortest time period, preferring the path of least temporal duration over a topologically shorter one or an earlier arrival. This is also termed latency, as per Holme and Saramäki (2012)) and the fastest path (the first time-respecting path leaving node i after a specific timepoint which results in the earliest arrival at node j , despite being topologically ‘further’ or temporally ‘longer’ than alternative later paths). These may be summarised as the paths with fewest steps, shortest duration and earliest arrival, in a given time window (Casteigts et al., 2015). Similarly, there are topological and temporal versions of other measures such as diameter (Casteigts et al., 2012). However, not every measure need be altered to provide information about a temporal network. Interestingly, Lentz et al. (2016) demonstrated that for node-level centrality measures, the results given by a static network aggregated over a year or more

remain meaningful to detect highly connected nodes. This suggests we need not throw out all of the static network measures, but consider more carefully their assumptions and the correlations between easily calculated static measures and computationally expensive temporal measures.

Several other static network concepts can be extended to temporal network analysis. For example, the concept of neighbourhoods can be applied to temporal networks once the time-relevance of movements is incorporated (Holme, 2015). However, such approaches can be computationally expensive when the network is on the scale typical of livestock movement networks (~10,000 nodes). Holme (2015) also discusses alternative temporal centrality measures from other fields, however their relevance specific to livestock movement networks needs to be established. These measures have the potential to incorporate weighting of the amount of time a path takes to traverse or how recently the path existed to summarise the connectedness of nodes in the network, as well as incorporating the spatial nature of livestock movement data. It would be useful for these measures to be explored through application to a livestock movement network dataset, including appropriate visualisation and interpretation of the meaning of specific temporal measures, although this is beyond the scope of this thesis.

In contrast to the substantial work on the temporality of livestock movement networks, spatial analyses are often restricted to investigating the spatial distribution of nodes in the network, and distances over which movements occurred (for example, as demonstrated by Fiebig et al., 2009 and VanderWaal et al., 2016). VanderWaal et al. (2016) also reported assessing the correlation between geographic distance and the shortest path length (geodesic distance) between individual node pairs, finding poor correlation overall and no correlation for nodes with shortest path length >3. Spatio-temporal cluster detection has also been occasionally demonstrated in animal movement network analyses, for example combining contact tracing data with spatial information to better understand the spread of an outbreak of equine influenza in Australia (Firestone et al., 2011). In network studies of human disease transmission, the strength of network association with infectious disease spread has also been measured while accounting for spatial association, for example as shown by Emch et al. (2012). This allows the effects of the spatial distribution of nodes to be differentiated from the effects of their network connectivity. Integrated spatial and

temporally dynamic network analyses have also been reported in other disciplines, for example Fowler and Christakis' study of happiness and wellbeing (2008). Preliminary investigations of centrality and other measures in temporo-spatial network have also been reported, based on urban transport networks (George and Kim, 2013; Williams and Musolesi, 2016). However, despite calls for further development of these more sophisticated approaches to be applied in infectious disease studies (Giebultowicz et al., 2011), they are yet to be applied to veterinary epidemiological datasets such as livestock movement data.

2.8.3 FUTURE DIRECTIONS FOR LIVESTOCK MOVEMENT NETWORK ANALYSIS IN THE FACE OF SURVEILLANCE CHALLENGES

There is great scope for further development of network analysis approaches for livestock movement data, including more explicitly incorporating the spatial and temporal information associated with these data. As the availability of relevant data continues to increase, we have an increasing need for meaningful and computationally feasible network measures that give relevant epidemiological information. Despite differences in context, collaboration with other disciplines analysing network data with similar approaches can help advance network analysis more efficiently and minimise duplicated effort. Achieving consistent terminology between disciplines will be an important part of this work. Network analyses are useful in veterinary epidemiology to support policy development, inform disease modelling efforts, and develop targeted surveillance. Policymakers, government and industry can all benefit from the information generated by network analyses, if it is effectively communicated in context to demonstrate the effects of network size and connectedness for animal health.

The benefits of livestock movement network analysis are clear, especially to help direct the scarce resources available for surveillance to where they are needed most. To maximise the benefit and impact of these resources, analyses must be meaningful and accurate. The accuracy of network analysis is influenced by the completeness of the data available. As with many sources of data, livestock movement records may be incomplete, so a greater understanding of the effect of missing data on the results of network analysis is needed. The challenge of incomplete livestock movement network data is reviewed and explored in Chapter 6 of this thesis. However, even incomplete

data can provide useful insights into the epidemiological effects of animal movements on disease risk, including for targeted surveillance.

Livestock movement networks between countries share some common structural features, including topology and typical values for common network measures. Knowledge of these common features may be sufficient to model networks for disease spread without having current specific movement data for a specific geographic area. However, because of potential seasonal patterns, and the varying influences of saleyard or abattoir trading behaviours on movements in the network, there is still value in describing additional livestock movement networks, such as the Victorian sheep movement network. Based on the present availability of appropriate data and the absence of prior published analysis, Chapter 7 of this thesis will endeavour to describe the sheep movement network in Victoria, Australia, and to demonstrate different ways that the results of analysis can support the selection of farms for on-farm surveillance efforts targeted to high-risk farms.

2.9 CONCLUSION

This review has highlighted the complexities of designing and delivering effective animal health surveillance that meets its objectives. Because it is not possible to create the perfect surveillance system, the attributes of surveillance must be prioritised and select appropriate surveillance methods selected to achieve the system's objectives. With careful surveillance design, including integrating data from multiple complementary surveillance activities, realistic surveillance objectives can be achieved despite the challenges of the real world. Common challenges illustrated using the example of the Australian sheep industry include conducting effective surveillance on large numbers of farms over a huge geographic area; farms with large numbers of animals where there are practical limitations to how frequently and closely animals can be observed for subtle signs of disease; and farmers who are not accustomed to frequent veterinary oversight of their farms.

While there is no perfect surveillance system, there are several opportunities to improve animal health surveillance in the Australian sheep industry. Because veterinary involvement in sheep health problems is unlikely to substantially increase in the short term, syndromic surveillance is a possible method to increase the disease information captured from sheep farms. However, it is unclear whether farmers are

willing and able to report observations of signs of disease to a syndromic surveillance system reliably, and this will be the focus of Chapter 3. Chapter 4 will then investigate whether the information that can be collected has surveillance value. Even if syndromic surveillance can be used to collect farmers' observations, it would be beneficial to better understand of how Australian sheep farmers manage animal health problems, especially given low rates of veterinary contact might adversely affect animal welfare and productivity. An investigation of sheep farmers' disease response behaviour using qualitative methods is therefore presented in Chapter 5. If syndromic surveillance of farmers' observations proves useful, farms at increased disease risk could be preferentially recruited to the system, for example by targeting high-risk farms identified through network analysis. Network analysis of Australia's National Livestock Identification System (NLIS) sheep movement data has not been previously reported, in part because the NLIS records a targeted subset of sheep movement in Australia. Therefore, it is also worth considering the effect that incompleteness may have on the network features identified, as reported in Chapter 6. The potential of NLIS sheep movement data to support targeted surveillance will then be presented in Chapter 7. While these investigations cannot solve the many surveillance challenges faced by the Australian sheep industry, they offer new information to help fill current gaps in knowledge, to empower policymakers and sheep industries to design more effective surveillance strategies.

Chapter 3.

SYNDROMIC SURVEILLANCE SYSTEM DESIGN AND FARMER PARTICIPATION

PREFACE TO CHAPTER 3

Given the challenges of effective surveillance in the real world, there is a need to develop approaches to collect new types of data from new sources. This chapter describes a syndromic surveillance system implemented in Victoria, Australia, designed to collect observations of clinical syndromes in livestock by sheep and beef cattle farmers. An analysis of the participation of the 39 farmers enrolled in the system is presented, to understand farm and farmer characteristics associated with desirable response behaviour. A modified version of this chapter has been submitted for peer-review to Preventive Veterinary Medicine under the title, "Using farmers' observations for animal health syndromic surveillance: Identification and importance of timely and reliable respondents."

3.1 ABSTRACT

Farmers who observe their animals regularly are a rich potential source of surveillance information. However, to utilise that information, it must be captured reliably in a format that can be used by a surveillance system. Syndromic surveillance of farmers' observations is a suitable approach to improve animal health data capture from extensive livestock farming systems. However, because it is rarely feasible to recruit a random sample of farmers to provide observational reports, a purposive sample of farmers aligned with surveillance objectives provide a reasonable and practical alternative. Farmers who will report reliably are desirable participants; to target these farmers, one of the objectives of the first stage of a program should be to identify characteristics associated with reporting behaviour. Better knowledge of the demographic and managerial characteristics of good reporters, can inform efforts to recruit additional farms into the system. This chapter describes the operation of a farmer syndromic surveillance system in Victoria, Australia, over its first two years from 2014 to 2016. Survival analysis and classification and regression tree analysis were used to identify farm level factors associated with reliable participation. Response rate and timeliness were not associated with whether farmers had observed 'disease events' to report, or with different months of the year. Farmers keeping only sheep were the most reliable and timely respondents. Farmers aged under 43 years had lower response rates than older farmers. Farmers with veterinary qualifications and those working full-time on farm provided less timely reports than other educational backgrounds and farmers who worked part-time on farm. This chapter demonstrates the feasibility of using syndromes to record farmers' observations of clinical syndromes, and provides a starting point to guide recruitment of participants to such a system. Once farm characteristics associated with reliable participation are known, they can be incorporated into surveillance system design in accordance with the objectives of the system.

3.2 INTRODUCTION

Animal health surveillance is important to detect the presence or demonstrate the absence of exotic or emerging diseases, and is also valuable for monitoring endemic disease trends to inform disease control efforts (OIE, 2013a). Effective surveillance of livestock health requires reliable disease information to be collected frequently, particularly when changes in disease patterns need to be detected. In Australia, stakeholders in livestock disease surveillance include national and state governments, trading partners and the OIE, and livestock industries as a whole, as well as individual farmers managing the day-to-day productivity, health and welfare of their livestock. Because veterinarians are infrequently called to sheep and beef farms in Australia (Frawley, 2003), farmers are often the people most aware of disease problems in their livestock, especially for endemic diseases. Farmers' observations can provide valuable data about cases of clinical syndromes that would otherwise be undetected by traditional surveillance approaches. The challenge is to collect these observations in an accurate and consistent way that is useful as surveillance data (Gates et al., 2015).

Historically, farmers' observations have primarily been collected sporadically as a way to detect notifiable diseases, rather than collect information about endemic disease. However, the probability a farmer will report a possible notifiable disease depends on their disease awareness and decision-making (Doherr and Audige, 2001). Passive surveillance is useful for detecting outbreaks of exotic diseases (Hadorn et al., 2008) but rarely reveals the true incidence or distribution of disease. Active surveillance, by contrast, can provide improved estimates of disease frequency, for example as shown by Bertolini (2011) in scrapie surveillance in Italy. However, active surveillance can be resource-intensive and is often only suited to high priority diseases (Reist et al., 2012). Therefore, 'enhanced passive' surveillance approaches are emerging (Hoinville et al., 2013), as a way to collect farmers' observations more comprehensively to give more accurate insights into livestock health.

Syndromic surveillance methods continue to develop in animal health (Dórea et al., 2011; Dórea and Vial, 2016), offering a structured way collect of farmers' observations as surveillance data. The suitability of syndromic surveillance to collect Australian farmers' observations of signs of disease has been investigated previously (Shephard et al., 2006; Butler and Loth, 2017), but a fully-functioning Australian syndromic surveillance system for livestock health has not previously been reported.

Such a system could help fill crucial information gaps, including providing much needed improved estimates of endemic disease patterns occurring in sheep and beef cattle industries (Lane et al., 2015). Furthermore, the disease occurrence information generated from farmers' observations can complement the outputs of other, more traditional surveillance activities. Farmers cannot be expected to make a full aetiological diagnosis of every case they observe, but they can classify diseases into syndromic categories based on the presence of clinical signs (Shephard et al., 2006).

There are growing, but currently few, descriptions of syndromic surveillance to collect farmers' observations (Black et al., 2001; Walker et al., 2011; Monkemeyer and Schmidt, 2014). Evaluation of fully operational programs has not been previously reported. Evaluation of surveillance may include assessment of many different criteria (Drewe et al., 2012). Surveillance system attributes that are valuable indicators of overall usefulness include the timeliness of reporting and response rate as a crude measure of system acceptability. Not all farmers behave similarly, and their response rate and timeliness of reporting are likely to vary. For syndromic surveillance of farmer's observations, online reporting is a practical way to collect data frequently and minimise recall bias, but reports must be provided consistently over time. When recruiting for farmer reporting, if farm or farmer characteristics associated with timely and reliable response behaviour could be identified, these individuals could be preferentially recruited. This could improve overall surveillance system performance, as long as potential biases are considered—that is, if we can be reasonably sure that the prevalence of clinical syndromes reported are a true reflection of the disease state of the animals under surveillance. Alternatively, if particular types of farmers or farms were identified as high priority for surveillance for other reasons, understanding the association of these characteristics with response behaviour could help predict the likely performance of the surveillance system and inform efforts to improve system efficiency. In either case, having prior knowledge of the effect of farm characteristics on response behaviour could increase the likelihood that a farmer reporting system can form a sustainable part of surveillance strategy. An example of such an investigation, using survival analysis to understand medical practitioner factors associated with timely participation in human health surveillance reporting has been reported by Chauvin et al. (1997). However, no similar examples have been reported for animal health surveillance.

This chapter describes the design and evaluation of a syndromic surveillance system that was implemented in Victoria, Australia, from 2014 to 2016, that collected farmers' observations of clinical syndromes in their sheep and/or beef cattle. Given this is the largest farmer-based syndromic surveillance system reported in Australia to-date, this chapter will focus on the successes and challenges faced during its operation, and present an evaluation of the timeliness and response rates of participating farmers. The objectives of this study were to demonstrate the feasibility of collecting surveillance data based on farmers' observations, and to understand whether farm or farmer factors might be used to predict participation behaviour. These investigations aimed to inform future purposive recruitment of participants for similar systems.

3.3 METHODS

3.3.1 SYNDROMIC SURVEILLANCE SYSTEM DESIGN

3.3.1.1 SURVEILLANCE SYSTEM OBJECTIVES

A syndromic surveillance system, the Local Area Network for Disease Information surveillance system (LANDI surveillance system or 'LANDI'), was developed to collect farmers' observations of signs of disease and to facilitate disease investigations on sheep and beef farms in Victoria, Australia. The system operated August 2014 to November 2016. Each month, participating farmers' observations of disease signs in their livestock were recorded in an online report, summarised into syndromic categories (or simply 'syndromes'). The main objective of the LANDI surveillance system was to collect information about endemic diseases in sheep and beef cattle on farms in Victoria, Australia, to better describe the prevalence of common disease presentations and inform disease control strategies. To achieve this, the monthly reports recorded both the presence of disease (events) and absence of disease (non-events) longitudinally from participating farms. The monthly reports were screened for signs of disease that warranted veterinary investigation, complementary to the established Significant Disease Investigation scheme already operated by Agriculture Victoria.

Secondary objectives of the system included confirming the absence of emergency and emerging livestock diseases on participating farms and increasing farmer engagement

with disease surveillance activities. Although early detection and proof of freedom were not primary objectives of the system, the data generated by the system was expected to support other surveillance activities designed for these purposes.

3.3.1.2 CLINICAL SYNDROMES

All signs of disease observed on each participating farm each month were summarised in a single report, using 10 syndromes (Table 3-1). These syndromes were adapted from a system previously used successfully with beef farmers in a pilot syndromic surveillance system in Northern Australia (Shephard, 2006).

TABLE 3-1. SYNDROMES USED IN LANDI SYNDROMIC SURVEILLANCE SYSTEM, A PILOT INVESTIGATION COLLECTING FARMER OBSERVATIONS OF SIGNS OF DISEASE IN BEEF CATTLE AND SHEEP.

Clinical syndrome	Example observation
Deaths	Deaths in lambing ewes
Reduced production or ill-thrift	Weaner sheep “ill-thrift”
Gut or mouth signs	Diarrhoea
Lameness or limb signs	Foot abscess
Reproductive failure	Abortion
Nervous system signs	Opisthotonos (star-gazing posture)
Respiratory signs	Coughing
Skin or eye signs	Conjunctivitis
Urinary tract signs	Red urine
Other	Any other signs

3.3.1.3 STUDY SAMPLE AND RECRUITMENT OF FARMS

Farms participating in LANDI were recruited from clients of the Mackinnon Project, a livestock farm advisory and veterinary service operated by the University of Melbourne. Eligible farms were pasture-based farms grazing sheep and/or beef cattle in Victoria, Australia. Farms had to intend to continue production for the duration for the study (until at least December 2016) and the manager or owner had to be willing to provide monthly summary reports of their observations using an online interface.

Between May and August 2014, presentations made at two farmer meetings to publicise the project and identify potential participants. In addition, suitable farmers

in the Mackinnon network were approached individually. In total, seventy-nine farmers were invited to participate. Background and demographic data about the farmers who agreed to participate, and their farms, were collected at enrolment into the study and verified at the conclusion of data collection (December 2016).

3.3.1.4 ELICITATION OF REPORTS

Invitations to provide reports sent to participants via email with an embedded web link each month. Where a report was not provided in response to the initial invitation, up to four reminder emails were sent at approximately 10 day intervals.

3.3.1.5 MONTHLY REPORT FORMAT

The surveillance system aimed to collect information about both the occurrence of clinical syndromes, as well as the absence of those syndromes, each month. Each report used the ten syndromes to summarise this information for the month preceding the report, allowing the farmer to report each syndrome for 7 classes (age-sex groups) of both sheep and cattle.

The monthly report had two structures, the initial structure (used during 'period A', from August 2014 to November 2015) and an amended structure (used during 'period B', December 2015 to November 2016). Amendments were made for two reasons: to reduce the need for data cleaning prior to analysis, and to address an additional research questions arising during the study. The system infrastructure was sufficiently flexible to implement the amended structure without otherwise affecting the user experience.

The system was designed with online report submission using RedCAP software (Harris et al., 2009), hosted at the University of Melbourne. Online reporting was used to minimise manual data entry by the researchers, and to test the farmers' acceptance and ability to use an online syndromic reporting system. RedCAP is designed for electronic capture and management of research data including survey data, and is freely available to universities worldwide. The software's built-in system for longitudinal survey data management, including scheduling and managing email communication to participants, proved extremely valuable for the management of LANDI. At the time of the study, the RedCAP interface was not optimised for mobile devices, so a desktop or laptop computer was required for farmers to enter data into the system.

In the system, data were collected about 'disease events'. A 'disease event' was defined as the observation of one or more syndromes with a single (known or unknown) cause, reported in one or more stock classes in a given month. When a disease event was reported to the system, data were collected in a branching structure, as shown in the schematic (Table 3-2). For example, the farmer was asked about a syndrome, and if that syndrome were present, to specify the species affected, the class of stock affected, and then to provide details of the event itself, specifically the number affected, number at risk and any free-text comments the farmer wished to provide. Multiple species and classes could be selected at the branching points, if relevant. This avoided the need for cumbersome 'event by event' reporting if there were multiple species or classes of stock affected by similar syndromes. The structure was identical for reporting of all syndromes except reproductive failure, where events could only be reported in reproductively active classes of stock (adult cows and bulls, and hogget ewes, adult ewes and rams). Branched survey logic was used to control the fields visible to the user, so that only relevant fields were presented for data entry. This reduced the effective number of items on the report from the total 581 possible fields to a minimum of twelve fields. Each disease event reported added an average of six fields to the report as visible to the user. An example report provided in period A is given in Appendix A.

In period B, minor amendments were made to this structure. No cases of 'urinary tract signs' were reported in period A, so this syndrome was removed. Urinary signs could still be reported in the 'other' syndrome. For the remaining nine syndromes, checkboxes to indicate 'sub-syndromes' and suspected causes of disease were (summarised in Appendix B). These observations were previously recorded in the free text comments in period A, but had been reported inconsistently and required processing of free-text for analysis. The sub-syndromes and suspected causes included all causes reported in the free-text comments during period A, as well as other common causes identified from veterinary literature. For all sub-syndromes, the farmer could also indicate when they were 'unsure' of the cause of signs. This allowed non-response to be differentiated from the farmer being truly unsure, which was ambiguous in the period A data.

For each disease event recorded in period B, additional data were collected: which group of animals was affected within each class (a single paddock, multiple paddocks,

or all animals in that class on-farm); the farmer's certainty about the reported cause; and the level of veterinary contact that had occurred. The farmer's certainty was classified by the type of diagnostic investigation that had occurred (laboratory confirmation, veterinary diagnosis, or response to treatment), or in the absence of those investigation types, by self-reporting their level of confidence in the suspected diagnosis (strong suspicion, moderately certain, somewhat uncertain, very uncertain). Veterinary contact was categorised as either a visit to the property, contact by phone only, 'other' contact (with clarification of what that meant for each case in a free-text comment), or no contact. Farmers could also use a free-text comment field for each syndrome/class combination to make any further comments about each disease event.

In both periods, stock count data were also collected in two ways. Every monthly report had an additional question, asking farmers to report any routine stock counts occurring on-farm, for example during a management event such as shearing or lamb marking. If stock had been counted, farmers were asked to enter the reason for the count, the species and breed counted, and the number of stock in each class that had been counted. Farmers could also provide free-text comments about the counted stock. However, because these counts may not represent a full muster of all animals of a given class on the farm, estimated full stock counts were requested periodically (at study enrolment, January 2015 and June 2015 for period A, and in January, April, July, September and December 2016 in period B). These full stock counts required an estimate of all stock numbers on-farm at the time of report completion, reported by species and class. In addition in period B, each monthly report asked for details of any animals purchased or sold in the preceding month, including the first five digits of the property identification code (PIC) of the source or destination of those animals. The abbreviated PIC could be decoded to give spatial information about the source/destination property while maintaining confidentiality of the actual farm identity. For each purchase or sale event, the number of animals in each stock class were reported, along with the type of source/destination (saleyard, 'AuctionsPlus' online sales, direct to/from farm, direct to abattoir, or other).

3.3.1.6 DATA ANALYSIS

The system was not designed for real-time analysis of data or aberration detection. Reports received were visually inspected by the author at least once weekly, to detect any unusual disease events where veterinary investigation was warranted. Where an unusual event was detected, the farmer was contacted directly by phone for further details of the case. All data collected were stored on a University of Melbourne server and accessed via the RedCAP interface. They were subsequently downloaded manually in batches and analysed using R statistical software and Microsoft Excel. This analysis is further described and reported in Chapter 4.

3.3.1.7 DISEASE INVESTIGATIONS

The main incentive for farmers to participate in the LANDI surveillance system was access to fully subsidised disease investigations. When appropriate, Mackinnon Project veterinary consultants conducted investigations either on-farm or in a pathology facility, including necropsy and appropriate diagnostic testing to achieve a diagnosis and provide management and preventive advice back to the farmer. These investigations either arose from disease events reported through the syndromic system, or more commonly by pro-active contact from the participating farmer at the first sign of an unusual or unexpected clinical syndrome. The case investigations were reported to the Agriculture Victoria's existing surveillance database for incorporation into existing surveillance reporting and response channels.

3.3.1.8 RESEARCH ETHICS

The University of Melbourne Human Research Ethics Committee approved the collection, management and use of all data collected from the 39 farms participating in the LANDI surveillance system (ethics ID 1442478). As the disease investigations were conducted as part of the Mackinnon Project's routine veterinary service provision, no animal ethics approval was deemed necessary.

TABLE 3-2. SCHEMATIC OF LANDI MONTHLY REPORT FORMAT DURING PERIOD A, FROM AUGUST 2014 TO NOVEMBER 2015. EACH MONTHLY REPORT CONTAINED TEN SYNDROMES AS DESCRIBED IN TABLE 3-1. ELLIPSES INDICATE REPEATED QUESTIONS AS IN TOP CELLS OF SCHEMATIC.

Have you observed this syndrome in the past month?	Yes	→ Relevant fields appear	Species affected				Number affected	
							Number at risk	
							Free-text comments	
				Cattle	Breed(s) affected	Class(es) affected	Weanlings (weaning to 1 year old)	...
							Heifers (1-2 years old)	...
							Yearling steers (1-2 years old)	...
							Adult cows (2 years and older)	...
							Adult steers (2 years and older)	...
							Bulls (1 year and older)	...
				Sheep	Breed(s) affected	Class(es) affected	Sucking lambs (unweaned)	...
Weaners (weaning to 1 year old)	...							
Hogget ewes (1-2 years old)	...							
Hogget wethers (1-2 years old)	...							
Adult ewes (2 years and older)	...							
Adult wethers (2 years and older)	...							
			Rams (1 year and older)	...				
No	→ Proceed to next syndrome							

3.3.2 METHODS FOR ASSESSING COMPLIANCE

To investigate the response behaviour of the participating farmers, reports received during the first two years of system operation from August 2014 to July 2016 were analysed. The objective of this analysis was to determine what farm characteristics were associated with either time to response, or overall response rate. Data for each report included the date of each email request, the total number of email requests sent per report, whether a report was received, and whether any disease events were reported. Farm data described the species kept, number of sheep and number of cattle present at enrolment into the system, total farm grazing area, long-term average annual rainfall, winter stocking rate (dry sheep equivalents per hectare, DSE/ha), winter stocking rate per 100mm annual rainfall, and labour availability (full-time employees per 10,000DSE). Farmer characteristics included the number of people completing the reports (one or two), and for the primary person completing reports, their age, gender, role on farm (owner or manager), number of years' experience in farming, highest education level, whether they worked full- or part-time on the farm, and whether they had other off-farm employment.

The association between farm and farmer characteristics with non-response was investigated, using response or non-response as the outcome of interest for all farm-months where a report was requested. A univariable generalised linear model with a logit link function was constructed for each farm or farmer variable as well as for month of reporting. Confidence intervals for the resulting response odds ratios were calculated using cluster-robust standard errors to account for repeated measures on each farm.

Timeliness of reporting was investigated by assessing only farm-months where a report was received, to separate the farm or farmer characteristics association with timeliness from their association with non-response. Therefore, the population of interest for timeliness was those farm-months where a surveillance report was received. The outcome of interest was the number of days taken to submit a surveillance report. Survival analysis was used to quantify the timeliness of responses, using time from email invitation to report completion as time-to-event data and response as the 'failure' outcome (Hosmer et al., 2008). The hazard throughout the observation period was plotted as a kernel-smoothed estimate of the hazard

contributions from each farm-month (Klein and Moeschberger, 2003). Univariable Kaplan-Meier survival curves were estimated for each farm or farmer characteristic variable and used to calculate median response times. Difference between survival curves was tested using both the log-rank and Peto-Peto modification of the Gehan-Wilcoxon tests, with the greater of the two p-values from these tests reported in the text. Univariable analysis of timeliness for continuous explanatory variables was implemented using categorical indicator variables. Each continuous variable was split into two, three and four categories (by quantile), with the split demonstrating greatest difference in timeliness between groups reported in this paper.

A multivariable Cox proportional hazards model was then constructed using a manual backwards stepwise approach. True random effects could not be included due to the modest sample size. As an alternative approach to account for repeated measures, participant identifier was included as a cluster term using a generalised estimating equation (GEE) approach to account for repeated outcomes over time and derive robust sandwich variance estimators (Kalbfleisch and Prentice, 2002). Winter stocking rate was non-linear in its log hazard and was reclassified as dichotomous variables based on quartiles for the multivariable model. Because the species kept on each farm was related to the number of sheep or cattle kept, these three variables (sheep and cattle, and herd/flock size) were combined into a single categorical 'farm type' variable with eight groups, describing the species kept and whether the number of sheep and/or cattle were greater or less than the median for all participating farms. These groups were then collapsed where there was no statistically significant difference between groups in the model for timeliness of response, with four final farm-type categories resulting: farms with sheep only, farms with cattle only, multi-species farms with both sheep and cattle numbers below median (small sheep & cattle), and large multi-species farms with either or both sheep and cattle numbers above median (large sheep & cattle). Biologically plausible interaction terms were introduced to the model but were not statistically significant and offered no improvement to model fit, so were excluded from the final model. The proportional hazards assumption was tested by plotting the variability bands of the scaled Schoenfeld residuals and visually inspecting whether these were linear. Deviance plots were evaluated visually for influential outliers in each variable, and Martingale residual plots inspected for linearity of log-hazards for variables in the final model.

To investigate major farm or farmer characteristics associated with non-response, a classification and regression tree (CART) model was fitted. In a CART model, data are split one predictor variable at a time using recursive partitioning, and prediction models are fitted and compared for each partition to determine the optimal split (Loh, 2011). Several algorithms are available for this process. In this study, RPART which is implemented based on the CART algorithm (Breiman et al., 1984) was used to determine the variable and values at which each split occurs, so that the two resulting groups have the greatest similarity within groups and greatest difference between groups with regards to the outcome of interest. This process of splitting data by individual variables is repeated within each branch of the developing tree, until a single optimal tree is produced. The CART approach is useful when the data may contain complex non-linear interaction terms. It is more flexible than conventional regression techniques, and is easy to interpret and communicate by visualising the final tree.

The variables available to the CART model included all farm and farmer characteristics as described above. In contrast to the Cox regression model, separate variables for species and the number of sheep and cattle on each farm were maintained because the tree structure of the model could account for the relationship between these variables. Farmer age was initially included as a continuous variable in a univariable CART model to determine what cut-points provided the greatest difference between groups, then included in the final model as a categorical with two groups (≤ 43 and ≥ 44 years) to simplify interpretation. To understand the influence of repeated measures on the model, the same parameters were fitted to a RE-EM tree, which uses the expected-maximisation (EM) algorithm to add random effects to the tree (Sela and Simonoff, 2012). RE-EM trees were fitted using both maximum-likelihood and restricted maximum likelihood approaches. The resulting models (not shown) gave the same hierarchy of parameters as the CART model, indicating that the structure of the CART model was not altered by the presence of repeated measures. Because each farmer contributed approximately 3% of all observations and all predictor variables were associated with the farm/farmer rather than individual reports, splits that partitioned the data into groups comprising less than 4% were excluded from the final CART model.

All analyses were performed with R statistical software v3.4.1 (R Core Team, 2017) using the *survival* (Therneau, 2015), *rpart* (Therneau et al., 2017) and *REEMtree* (Sela and Simonoff, 2011) packages. Visualisations of the survival analysis and CART model were produced using the *survminer* (Kassambara and Kosinski, 2017) and *rattle* (Williams, 2011) packages.

3.4 RESULTS

3.4.1 PARTICIPATING FARMS

Victorian sheep and/or beef cattle farmers willing to provide observations to the system were recruited between May and August 2014. Of the 79 farmers approached to participate, 54 (68%) agreed to provide monthly reports. However, of these, 19 (35%) failed to provide farm background data in the required 8-week time period and were subsequently excluded from surveillance reporting. Four additional farms were recruited into the study after data collection commenced in September 2014 (two in January 2015 and two in April 2015), giving a total of 39 participating farms. The farms were geographically dispersed throughout the state as shown in Figure 3-1.

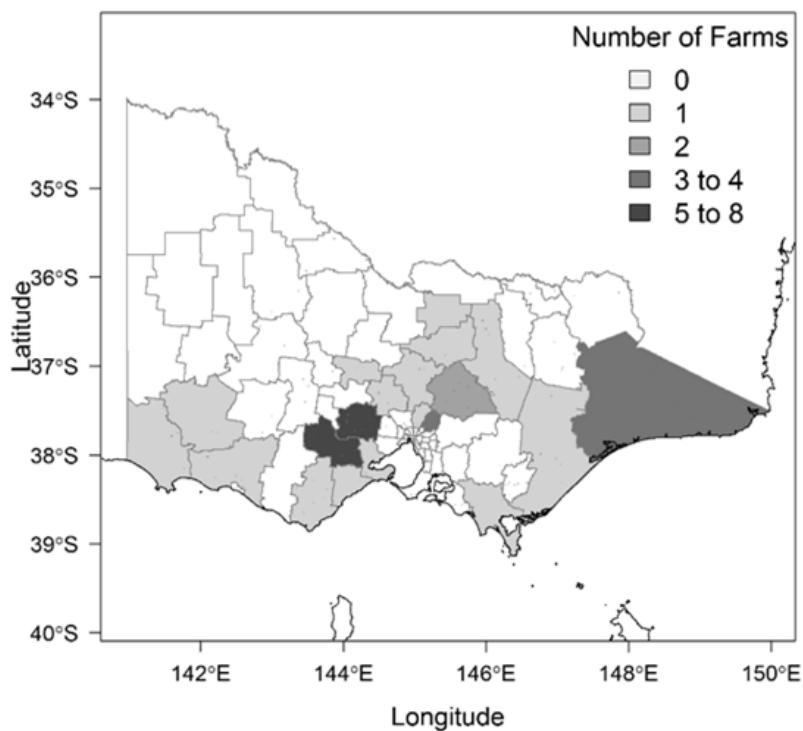


FIGURE 3-1. GEOGRAPHIC LOCATION OF FARMS PARTICIPATING IN LANDI SURVEILLANCE SYSTEM, AGGREGATED BY SHIRE.

The demographics of the participating farms and farmers are summarised in Table 3-3. Some demographic data were unavailable for one farm because the farmer was lost to follow-up, including data about both the farmer (age, education status, years of farming experience, off-farm work) and farm (annual rainfall and winter stocking rate).

The reports were completed online by a single farm owner-operator for 28/39 farms. The remaining farms' reports were completed online by two owner-operators (4/39 farms), the manager (3/39 farms), and or the son of the main farm operator (3/39 farms), all of whom had substantial responsibility on-farm. The remaining farmer, a sole owner-operator, declined to complete online reports and instead gave their report by telephone each month. Where two people completed the reports together, in all cases this included one male and one female (3 sets of spouses and 1 father/daughter). For the remaining 35 farms, there were six farms where the reporting farmer was female and 29 with a male reporting farmer. In total, 43 farmers individuals in completing reports for the 39 farms.

These farmers represented various educational and working backgrounds. Fourteen had some level of secondary education only (years completed were not distinguished), while the remaining 28 had tertiary (university or TAFE) qualifications. This included 12 with agricultural qualifications, seven with veterinary degrees, and nine with tertiary qualifications in other areas of study. Education details were unavailable for one farmer. Aside from two farmers for whom relevant data were unavailable, the farmers had been employed in agriculture for a mean 33 years (range 7 to 57 years), with the number of years employed associated with age as would be expected. Assuming employment begins at around 16 years of age, 72% of the farmers had spent over 50% of their working life in agriculture, and 49% over 80% of their working life.

TABLE 3-3. DEMOGRAPHICS OF FARMERS AND THEIR FARMS, RECRUITED TO PROVIDE DISEASE SURVEILLANCE REPORTS TO THE LANDI SURVEILLANCE SYSTEM IN VICTORIA, AUSTRALIA.

		Number of farms	Percentage of farms	Median	Min	Max
FARM CHARACTERISTICS		(N = 39)				
Species kept	Sheep only	16	41%			
	Cattle only	7	18%			
	Both sheep & cattle	16	41%			
Number of sheep (on farms with sheep)		32	82%	2908	22	17,490
Sheep production type	Wool	21	66% ^a			
	Prime Lamb	15	47% ^a			
	Stud sheep	2	6% ^a			
	Wool & Lamb	6	15% ^a			
Number of farms breeding lambs		31	79%			
Time of lambing (farms breeding lambs)	'Spring'-lambing (June to November)	28	90% ^b			
	'Autumn'-lambing (April)	1	3% ^b			
	Year-round or split (autumn and spring)	2	6% ^b			
Number of cattle (on farms with cattle)		23	59%	141	30	890
Number of farms breeding calves		21	54%			
Time of calving (farms breeding calves)	Spring-calving (July to September)	11	52% ^c			
	Autumn-calving (January to April)	8	38% ^c			
	Split (autumn and spring)	2	10% ^c			
Farm size (grazing area, ha)		39		360	32	2900
Winter stocking rate (DSE/ha)		39		13	4	24
Long-term average rainfall (mm)		39		643	450	950
Rainfall-adjusted winter stocking rate (DSE/ha/100 mm)		39		2	0.9	3.3
Labour availability (full-time employee equivalents)		39		1	0.1	4

		Number of farms	Percentage of farms	Median	Min	Max
Labour availability – scaled (full-time equivalent per 10,000 DSE)		39		2.3	0.4	17.9
FARMER CHARACTERISTICS		(N = 39)				
Number of people completing monthly report	One	35	90%			
	Two (one male, one female)	4	10%			
Age ^d		39		59	27	92
Years of farming experience ^d		38		34.5	4	54
Gender ^d	Male	33	85%			
	Female	6	15%			
Highest level of education ^d	Secondary	13	33%			
	Tertiary (Agriculture)	11	28%			
	Tertiary (Veterinary)	6	15%			
	Tertiary (Other)	8	21%			
	Unknown	1	3%			
Alternative employment ^d	Employed on-farm only	21	54%			
	Also employed off-farm	17	44%			
	Unknown	1	3%			
Days per week spent working on-farm ^d	Full-time (>4 days/week)	23	59%			
	Part-time (≤4 days/week)	16	38%			

^a Percentage of farms with producing lambs, N = 31; ^b Percentage of farms producing calves, N = 21; ^c Where two people completed reports, these values are reported for the person with greater responsibility for farm management; ^d Years of farming experience, highest level of education and alternative employment status were unavailable for one farmer.

3.4.2 SUMMARY OF CLINICAL SYNDROME REPORTS

3.4.2.1 MONTHLY SYNDROMIC REPORTS

Over the full 28 months of surveillance operation (August 2014 to November 2016), 802 reports were received out of 1027 farm-month reports requested, an overall response rate of 78% (Figure 3-2). The response rate showed slow decline over the duration of operation, largely due to nine farmers who were intermittent then consistent non-responders (submitting <60% of all reports requested overall).

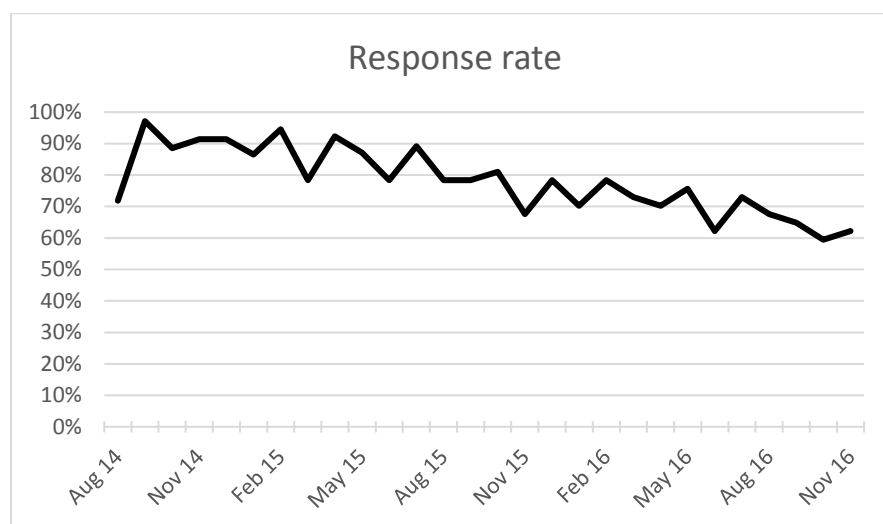


FIGURE 3-2. RESPONSE RATE FOR MONTHLY FARMER REPORTING OF CLINICAL SYNDROMES TO THE LANDI SURVEILLANCE SYSTEM IN VICTORIA, AUSTRALIA.

Of the 802 reports received, 558 (70%) reported at least one disease event. Disease events were reported more commonly in sheep (71% positive reports) compared to cattle (31% positive reports). The most common syndrome reported was deaths, followed by lameness and skin and eye signs (Table 3-4). These were also the most common syndromes in both sheep and cattle when examined by species. Although mortality was reported year-round, some syndromes showed a seasonal pattern, as expected for common endemic diseases (Figure 3-3 and Figure 3-4).

The 'other' syndrome was used in 22 cases, 17 for signs of disease in sheep and 5 in cattle. The sheep cases included infectious arthritis, facial swelling, unexplained weight loss, lice, flystrike, anaemia, and vaginal prolapse. There were 5 farm-months where infectious balanoposthitis (pizzle rot) in wethers was reported, in the months after 'urinary tract signs' had been removed from the syndrome options. The cattle

cases included: unexplained weight loss in a heifer, mastitis, exercise intolerance and calving-associated disorders. The inclusion of the 'other' category allowed these cases to be detected and manually re-classified into the appropriate syndrome. The farmer using the other category could also be trained further in correct classification of syndromes, although the small number of cases in this system meant such corrective action was not undertaken during this study.

TABLE 3-4. SUMMARY OF SYNDROMES REPORTED IN MONTHLY SUMMARY REPORTS TO THE LANDI SURVEILLANCE SYSTEM IN VICTORIA, AUSTRALIA BETWEEN AUGUST 2014 AND NOVEMBER 2016.

Syndrome	Number (percentage) of reports with syndrome					
	Sheep & Cattle		Sheep only		Cattle only	
Reports received	802		641		452	
All syndromes	558	70%	457	71%	139	31%
Deaths	409	51%	376	59%	55	12%
Lameness or limb signs	201	25%	159	25%	49	11%
Skin or eye signs	95	12%	61	10%	34	8%
Reduced production or ill-thrift	69	9%	62	10%	8	2%
Reproductive failure	61	8%	44	7%	17	4%
Gut or mouth signs	53	7%	48	7%	5	1%
Nervous system signs	33	4%	29	5%	4	1%
Other	22	3%	17	3%	5	1%
Respiratory signs	18	2%	15	2%	3	1%
Urinary tract signs	6	1%	6	1%	0	0%
No syndromes observed	244	30%	184	29%	313	69%

Further analyses of the results related specifically to ewe mortality are reported in further detail in Chapter 4.

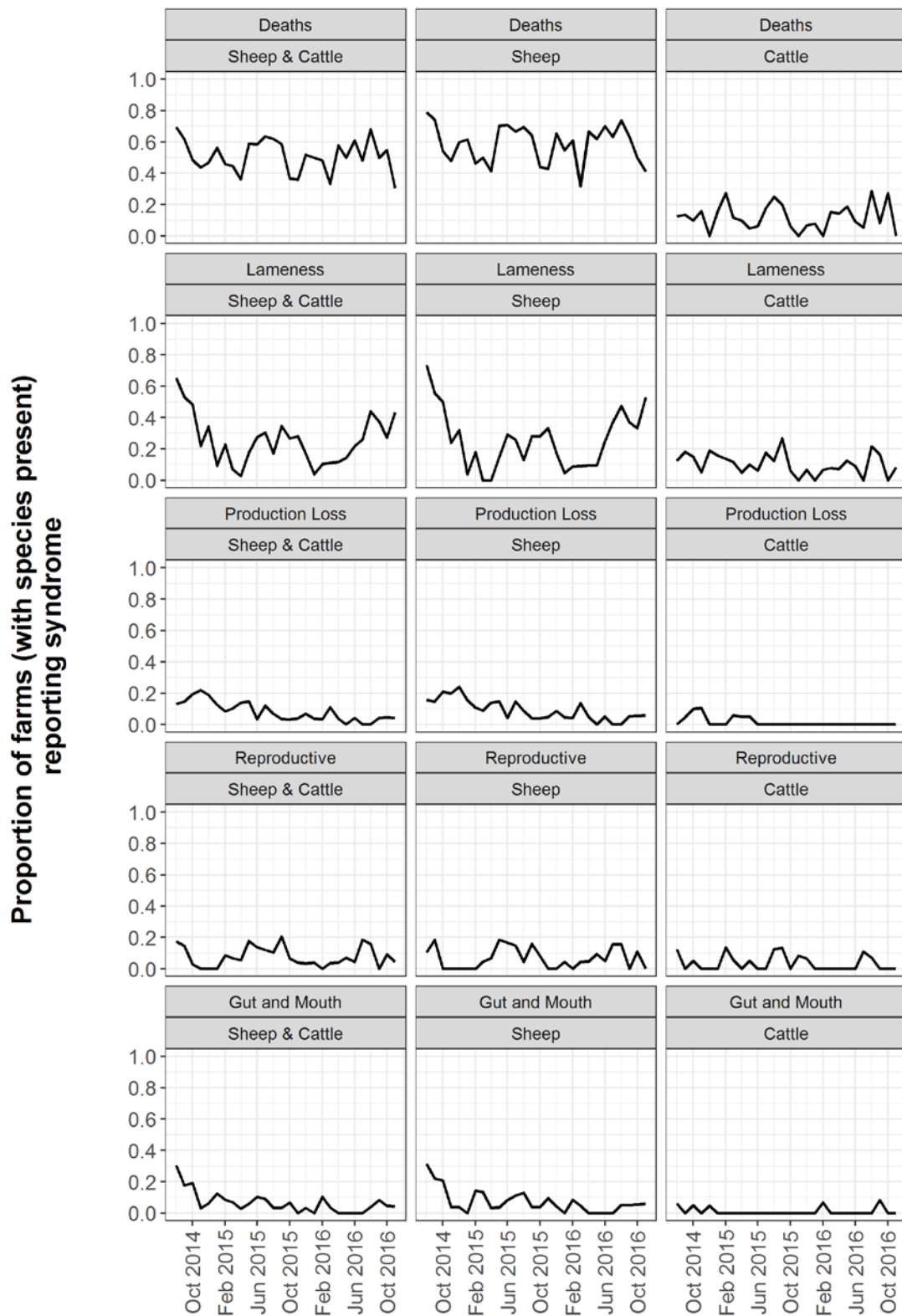


FIGURE 3-3. LINE PLOTS SHOWING THE PROPORTION OF RESPONDING FARMS EACH MONTH WHO REPORTED AT LEAST ONE ANIMAL AFFECTED BY A SYNDROME (DEATH, LAMENESS, PRODUCTION LOSS, REPRODUCTIVE FAILURE OR GUT AND MOUTH SIGNS), AS A FUNCTION OF CALENDAR MONTH BETWEEN AUGUST 2014 AND NOVEMBER 2016.

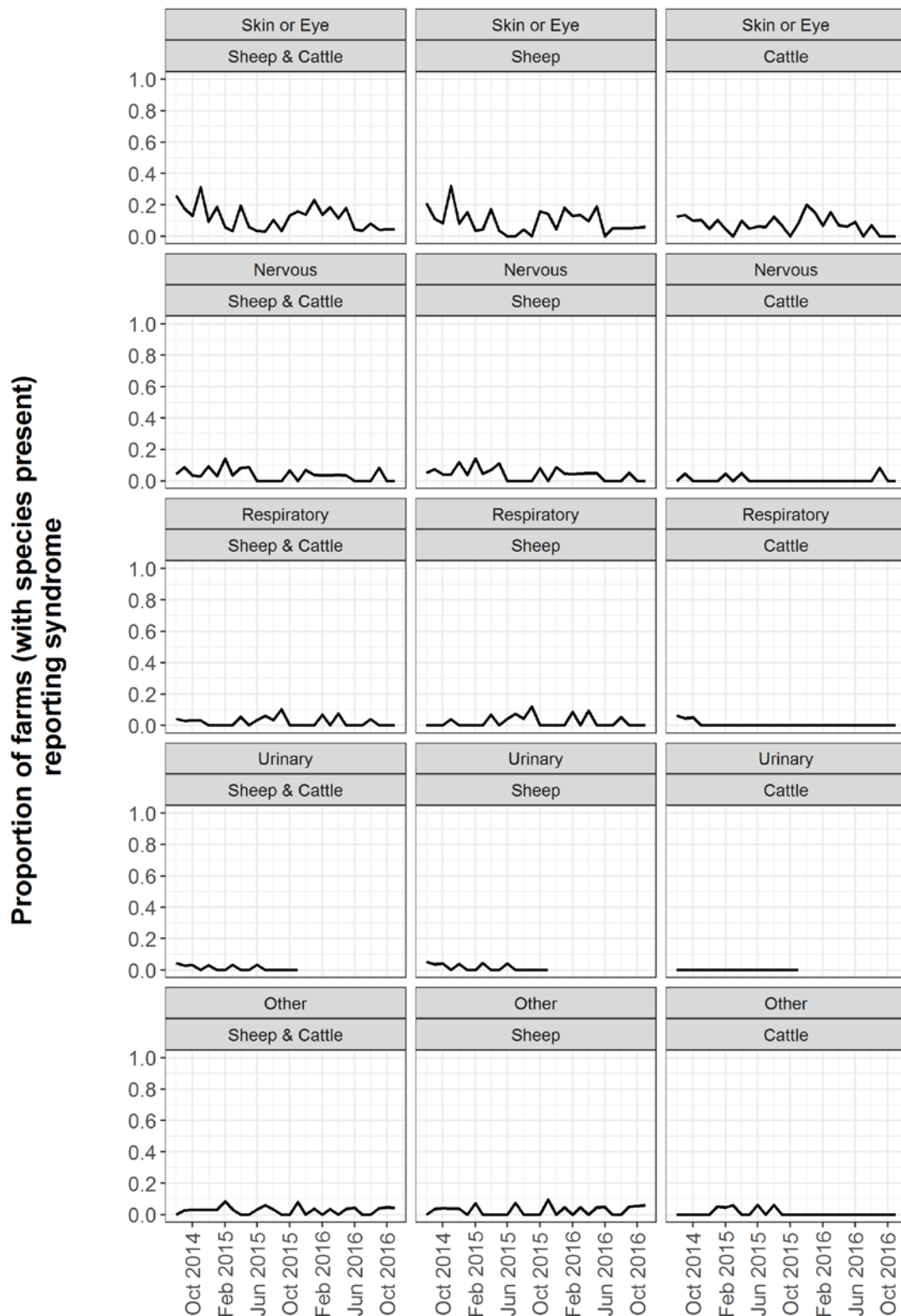


FIGURE 3-4. LINE PLOTS SHOWING THE PROPORTION OF RESPONDING FARMS EACH MONTH WHO REPORTED AT LEAST ONE ANIMAL AFFECTED BY A SYNDROME (SKIN OR EYE SIGNS, NERVOUS SIGNS, RESPIRATORY SIGNS, URINARY SIGNS OR OTHER), AS A FUNCTION OF CALENDAR MONTH BETWEEN AUGUST 2014 AND NOVEMBER 2016.

3.4.2.1 DISEASE INVESTIGATIONS

A total of 98 investigations were completed on 28 of the 39 participating farms. The remaining 13 farms did not report a disease event requiring investigation or were unable to facilitate investigation of any eligible disease events occurring during the investigation period (January 2014 to December 2016). Additionally, 103 investigations were completed on 55 other farms during the investigation period. This was to increase the total number of events being submitted to the system, given that the number of events requiring investigation on the 39 participating farms did not exceed the maximum caseload manageable by the system. In all, over three years from 2014 to 2016 inclusive, 201 investigations were conducted. These additional events were considered contemporary to the disease events being reported into the syndromic surveillance system, being similar in timing and animal characteristics. A summary of the cases investigated in provided in Appendix C.

3.4.3 PARTICIPATION OF FARMERS

3.4.3.1 DESCRIPTIVE ANALYSIS OF RESPONSE RATE

Participation of farmers was investigated for the first two years' operation of the system (August 2014 to July 2016). Of 872 farm-month reports requested by the surveillance system, 703 responses were received, of which 488 (69%) reported at least one disease event. At the conclusion of the study period, the participating farmers estimated it took a median of 15 minutes to complete their report each month (range 5 minutes to 1 hour). This included months where clinical syndromes had been observed and denominator values (numbers of livestock at risk) in particular groups of sheep or cattle therefore had to be determined by the farmer, requiring extra time.

The overall response rate between August 2014 and July 2016 was 81%, with a mean monthly response rate of 81%. The response rate declined over the two years of the study, largely due to nine farmers who were intermittent then consistent non-responders (submitting < 60% of all reports requested over the 2 year period). Based on all farm-month reports requested, non-response was associated with farm size, farmer age and the number of people on the farm who completed the report (full results of univariable analysis of response given in Table 3-5). Every 100ha increase in farm size was associated with 0.95 (95% CI 0.90 to 0.99) times the odds of a response being provided. Farms where two people completed the report were

associated with 2.16 (95% CI 1.16 to 4.02) times the odds of a response, , while for 10 year increments in age of the farmer at the start of the study the odds of response increased by a factor of 1.69 (95% CI 1.06 to 2.70). No other variables were statistically significantly associated with increased responsiveness.

TABLE 3-5. UNIVARIABLE ASSOCIATIONS BETWEEN RESPONSE RATE AND FARM OR FARMER CHARACTERISTICS, FOR PARTICIPANTS IN THE LANDI SURVEILLANCE SYSTEM IN VICTORIA, AUSTRALIA.

		n	Within-group response rate	Response odds ratio	95% CI (robust SE) ^a
FARM CHARACTERISTICS					
Species kept	Sheep only	339	88.8%	Ref.	—
	Cattle only	154	90.9%	1.26	0.26 to 6.26
	Both sheep & cattle	379	69.1%	0.28	0.08 to 1.02
Number of sheep (on farms with sheep)	Per +1000 sheep greater than 0	718	78.4%	0.90	0.81 to 1.01
	< 2908	359	81.1%		
	≥ 2908	359	75.8%		
Number of cattle (on farms with cattle)	Per +100 cattle greater than 0	533	75.4%	1.01	0.78 to 1.31
	< 141	248	72.6%		
	≥ 141	285	77.9%		
Farm size (grazing area, ha)	Per +100ha centred at 360ha	872		0.95	0.90 to 0.99
	< 360	418	89.2%		
	≥ 360	454	72.7%		
Winter stocking rate (DSE/ha)	Per +1 DSE centred at 13 DSE/ha	872		0.93	0.79 to 1.11
	< 13	410	82.0%		
	≥ 13	462	79.4%		
Long-term average rainfall (mm)	Per +100 mm centred at 600 mm	872		0.82	0.48 to 1.41
	< 643	425	80.0%		
	≥ 643	447	81.2%		
Rainfall-adjusted winter stocking rate (DSE/ha/100mm)	Per +1 from 0	872		0.74	0.19 to 2.93
	< 2	401	83.5%		
	≥ 2	471	78.1%		

		n	Within-group response rate	Response odds ratio	95% CI (robust SE) ^a
Labour availability	Per +1 from 0	872		1.20	0.98 to 1.48
(full-time employees scaled per 10,000 DSE)	< 2.3	452	75.4%		
	≥ 2.3	420	86.2%		

FARMER CHARACTERISTICS

Number of people completing monthly report	One	796	79.8%	Ref.	—
	Two	76	89.5%	2.16	1.16 to 4.02
Gender (primary person completing report)	Female	136	92.7%	Ref.	—
	Male	736	78.4%	0.29	0.05 to 1.76
Age (primary person completing report)	Per +10 years centred at 60 years	872		1.69	1.06 to 2.70
	< 59	457	77.9%		
	≥ 59	415	83.6%		
Years of farming experience ^b (primary person completing report)	Per +10 years centred at 34 years	849	80.0%	1.18	0.72 to 1.94
	< 34.5	462	80.5%		
	≥ 34.5	387	79.6%		
Highest level of education ^b (primary person completing report)	Secondary	292	78.4%	Ref.	—
	Tertiary (Agriculture)	253	79.5%	1.06	0.26 to 4.33
	Tertiary (Veterinary)	141	82.3%	1.28	0.23 to 7.16
	Tertiary (Other)	163	82.2%	2.69	0.45 to 16.2
Alternative employment ^b (primary person completing report)	Employed on-farm only	454	72.7%	Ref.	—
	Also employed off- farm	395	88.6%	2.92	0.95 to 9.04
Days per week spent working on-farm (primary person completing report)	Full-time (> 4 days/week)	551	76.4%	Ref.	—
	Part-time (≤ 4 days/week)	321	87.9%	2.23	0.66 to 7.51

CI = confidence interval. ^a 95% confidence intervals calculated using cluster-robust standard errors to account for repeated measures; ^b These variables were unavailable for one farmer, records for that farmer were excluded from analysis of this variable.

3.4.3.2 DESCRIPTIVE ANALYSIS OF TIMELINESS

Analysis of time to reporting after the initial email request showed that reports were received steadily over the first 3 weeks following the first email, with a median of 8 days (95% CI 7 to 10 days) between initial email and report completion (Figure 3-5). When reports with no response were included in the data as right-censored observations, the median time to response was 13 days (95% CI 11 to 15). Few reports were received beyond 40 days after the initial email, reflecting the cessation of reminders after 30 days. The first email request for a report elicited a response in 57% (398/703) of all cases where a report was received. In the remaining cases, up to four reminder emails were sent before the report was received. Timeliness of responses did not vary markedly by month.

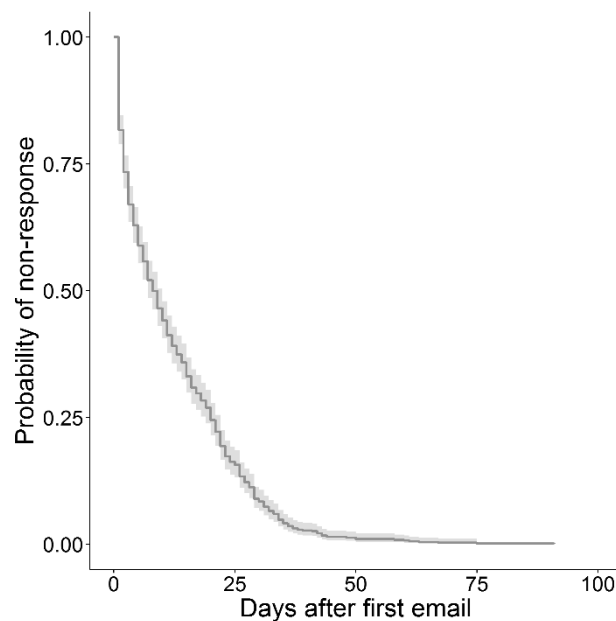


FIGURE 3-5. KAPLAN-MEIER SURVIVAL CURVE SHOWING THE CUMULATIVE PROPORTION OF FARMERS THAT HAD NOT YET SUBMITTED A SURVEILLANCE REPORT AS A FUNCTION OF THE NUMBER OF DAYS SINCE THE DATE ON WHICH THE FIRST EMAIL WAS SENT REQUESTING A REPORT. THE SHADED AREA INDICATES THE 95% CONFIDENCE INTERVAL.

The association between disease status (disease event either present or absent) and non-response could not be tested, as disease status was only known for farm-months where a response was recorded. Of 701 responses received, 69% (487/701) reported at least one disease event in the animals on-farm that month. There was no significant difference in Kaplan-Meier estimated survival curves for disease event positive and negative reports, meaning that the presence or absence of clinical syndromes was not

significantly associated with time-to-response. Reports with no disease event reported were received in median 7 days (95% CI 5 to 10 days), while reports with one or more disease events were received in median 9 days (95% CI 7 to 10 days).

3.4.3.3 UNIVARIABLE ANALYSIS OF TIMELINESS

Univariable associations between the timeliness of report submission and report, farm and farmer characteristics are presented in Table 3-6. The median number of days to response describes the number of days after the initial request for half of all reports to be received within that sub-group. When reports with no response were included in the data as right-censored observations, the rate of response was greatest immediately after the first email, with a second peak at around 22 days due to the second reminder email, which was sent approximately 20 days after the initial email (Figure 3-6).

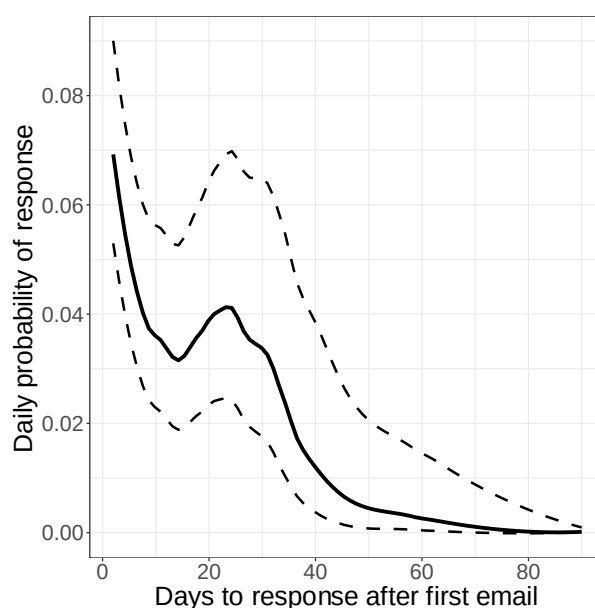


FIGURE 3-6. LINE PLOT SHOWING THE DAILY PROBABILITY OF REPORT SUBMISSION (AND ITS 95% CONFIDENCE INTERVAL) AS A FUNCTION OF THE NUMBER OF DAYS SINCE THE DATE ON WHICH THE FIRST EMAIL REQUESTING A REPORT WAS SENT. NON-RESPONSES WERE INCLUDED AS RIGHT-CENSORED OBSERVATIONS.

TABLE 3-6. UNIVARIABLE ASSOCIATIONS BETWEEN REPORT TIMELINESS AND REPORT, FARM AND FARMER CHARACTERISTICS, REPORTED AS MEDIAN DAYS TO RESPONSE FROM KAPLAN-MEIER ESTIMATED SURVIVAL CURVES, FOR PARTICIPANTS IN THE LANDI SURVEILLANCE SYSTEM IN VICTORIA, AUSTRALIA.

		Median days to response (95% CI)	Log-rank p-value ^a	Peto-Peto p-value ^b
FARM CHARACTERISTICS				
Species kept	Sheep only	8 (7 to 11)	0.724	0.861
	Cattle only	7 (5 to 11)		
	Both	9 (7 to 11)		
Grazing area	< 360 ha	5 (4 to 7)	< 0.001	< 0.001
	≥ 360 ha	12 (10 to 14)		
Sheep numbers (farms with sheep)	< 2908 sheep	6 (4 to 8)	< 0.001	< 0.001
	≥ 2908 sheep	11 (9 to 14)		
Cattle numbers (farms with cattle)	<141 cattle	10 (8 to 13)	0.412	0.175
	≥ 141 cattle	6.5 (5 to 9)		
Winter stocking rate (reported by farmer)	≤ 10 DSE/ha	6 (3 to 8)	0.046	0.043
	10 to 12.5 DSE/ha	10.5 (9 to 15)		
	13 to 14.5 DSE/ha	9 (7 to 11)		
	≥ 15 DSE/ha	7 (5 to 11)		
Average annual rainfall	< 550 mm	7 (5 to 9)	0.005	0.006
	550 to 650 mm	12 (9 to 15)		
	≥ 650 mm	8 (7 to 9)		
Rainfall-adjusted stocking rate	< 2.2 DSE/ha/100 mm	9 (7 to 10)	0.137	0.897
	≥ 2.2 DSE/ha/100 mm	9 (7 to 11)		
Labour availability	Low (< 2 full-time employees /10,000 DSE)	11 (9 to 13)*	< 0.001	< 0.001
	High (≥ 2 full-time employees /10,000 DSE)	7 (5 to 9)*		
FARMER CHARACTERISTICS				
Individual response rate	> 60%	8 (7 to 9)	0.002	< 0.001
	≤ 60%	16 (11 to 22)		
Age	< 59 years of age	9.5 (8 to 11)	0.449	0.043
	≥ 59 years of age	7 (5 to 9)		
Farm role	Manager	6 (3 to 10)	0.059	0.076
	Owner-operator	9 (7 to 10)		

		Median days to response (95% CI)	Log-rank p-value^a	Peto-Peto p-value^b
Number of people completing monthly report	One	7 (6 to 9)	< 0.001	< 0.001
	Two	19 (14 to 23)		
Gender ^c	Male	7 (6 to 9)	0.640	0.822
	Female	9 (5 to 12)		
Education level	Secondary	10 (7 to 13)	0.014	0.004
	Tertiary agriculture	6 (4 to 8)		
	Tertiary veterinary	11 (9 to 15)		
	Tertiary other	7 (5 to 12)		
Years of farming experience	< 34	8 (7 to 10)	0.683	0.867
	≥ 34	9 (7 to 11)		
Off-farm employment	Employed off-farm	7 (5 to 9)	0.129	0.007
	Employed on-farm only	10 (9 to 12)		
Time spent working on-farm	Full-time (> 4 days/week)	11 (10 to 13)	<0.001	<0.001
	Part-time (≤ 4 days/week)	4 (3 to 6)		

^a p-value from log-rank test; ^b p-value from Peto-Peto modification of Gehan-Wilcoxon test; ^c Univariable association calculated excluding farms where two people completed the monthly report.

Timeliness of reports was not associated with month (Log-rank $p = 0.41$ from estimated Kaplan-Meier curves, Table 3-7) nor the content of the report (disease event positive vs. negative, Log-rank $p = 0.68$, Figure 3-7a). The nine farms that became consistent non-responders (overall response rate < 60% of reports) were also slower to respond, having double the median response time of the more reliable farmers (Log-rank $p = 0.002$, Table 3-6).

Farms above population medians for grazing area (> 360 ha) and sheep numbers (≥ 2908 sheep) took longer to provide reports (Table 3-6). Reports were also received more slowly from farms with intermediate winter stocking rates (Figure 3-7b) and intermediate annual rainfall, compared to farms at the upper and lower extremes of each of these measures (Table 3-6). Farms with greater labour availability (> 2 full-time employees per 10,000 DSE stock) provided reports more quickly than those with less labour availability. The species kept on-farm was not associated with response timeliness in the univariable analysis.

The farmers' characteristics were also associated with timely reporting (Table 3-6). Farmers of above median age (≥ 59 years old) provided responses more quickly, with comparable reporting timeliness between genders. In cases where two people completed the reports together (which in all cases were a male-female pair), the reports were on average slower. Veterinarians were slower to provide reports than those with other tertiary education or secondary education only. Farmers who were employed off-farm or who worked only part-time on their farms (Figure 3-7c) provided their reports significantly faster.

TABLE 3-7. MEDIAN RESPONSE TIME FOR MONTH OF REPORTING FOR 703 MONTHLY ONLINE CLINICAL SYNDROME REPORTS PROVIDED BY FARMERS IN VICTORIA, AUSTRALIA.

Month	Number of reports	Median days to response	95% confidence interval
January	59	10	7 to 15
February	62	7	6 to 14
March	58	8	6 to 13
April	63	5	3 to 16
May	60	9	6 to 12
June	51	10	6 to 20
July	55	8	3 to 15
August	53	5	3 to 9
September	63	12	6 to 19
October	62	7	4 to 12
November	56	8	4 to 12
December	61	10	6 to 18

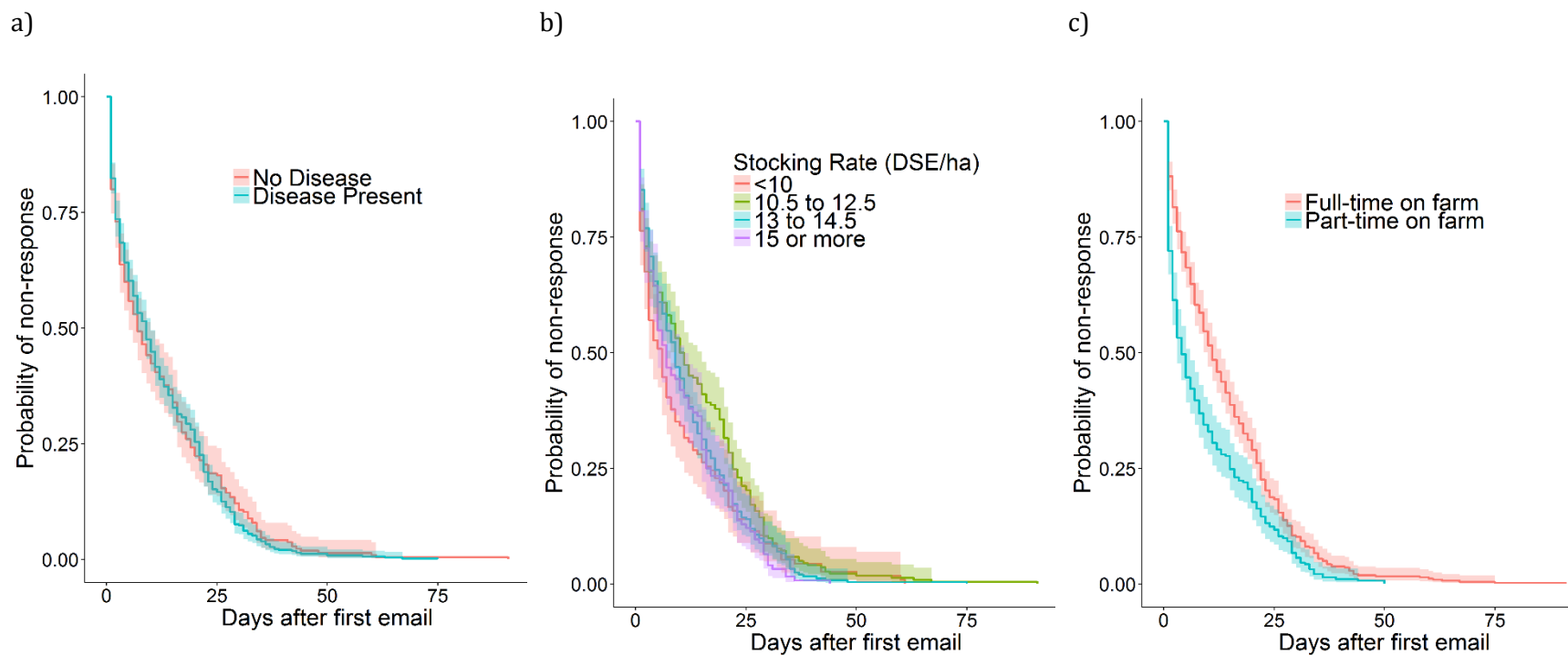


FIGURE 3-7. ASSOCIATION OF (A) REPORT DISEASE EVENT STATUS (POSITIVE/NEGATIVE), (B) WINTER STOCKING RATE, AND (C) FULL OR PART-TIME FARMER, WITH TIMELINESS OF REPORT SUBMISSION. CURVES SHOW DIFFERENT GROUPS WITH SHADED 95% CONFIDENCE INTERVALS.

3.4.3.4 MULTIVARIABLE ANALYSIS OF TIMELINESS

In the Cox proportional hazards model (Table 3-8), the hazard ratio represents the relative change in rate of reporting compared to the reference group (Hosmer et al., 2008). Here, a hazard ratio > 1 indicates that group was more timely than the reference group (i.e. provided reports at a faster rate than the comparison group), while a hazard ratio < 1 means that group was less timely, meaning slower to provide their reports than the comparison group. Visual assessment of plots of the variability bands of the scaled Schoenfeld residuals indicated that the proportional hazards assumption was upheld. Outliers were not detected from deviance plots and linearity of log-hazards was confirmed by inspection of Martingale residual plots. The overall predicted pattern of responses from the model agreed well with the pattern seen in the original data (Figure 3-8).

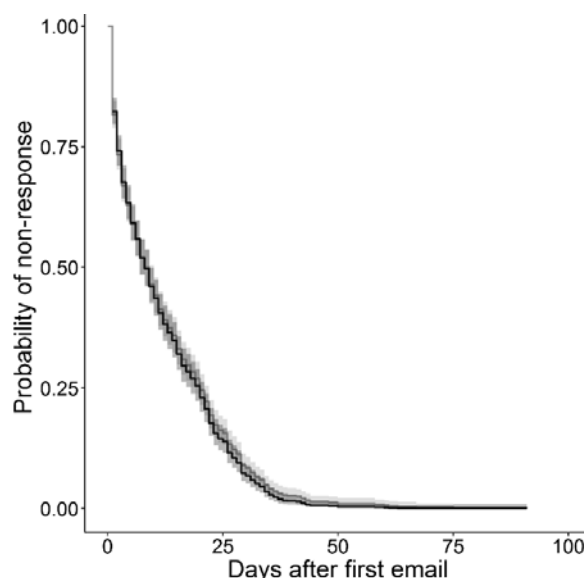


FIGURE 3-8. COMPARISON OF RAW DATA (GREY) AND FINAL COX MODEL (BLACK) ESTIMATES OF THE PROPORTION OF NON-RESPONSES OVER TIME FOR MONTHLY ONLINE CLINICAL SYNDROME REPORTS SUBMITTED BY SHEEP AND BEEF FARMERS IN VICTORIA, AUSTRALIA. THE SHADED AREA INDICATES THE 95% CONFIDENCE INTERVAL.

In the Cox model, part-time farmers' reports were more timely than full-time farmers (Figure 3-9a), while farmers with veterinary qualifications were less timely than farmers with other educational backgrounds (Figure 3-9b). Farm factors were also associated with timeliness, as farms with intermediate winter stocking rate (13 to 14.5 DSE/ha) were significantly faster to respond than those with low winter stocking rate (≤ 10 DSE/ha), although the same difference was not observed for farms with stocking rates in the remaining two categories (Figure 3-9c). Timeliness was also

associated with farm type (as defined in Section 2.2), where farmers from cattle-only and small sheep & cattle farms were less timely than sheep-only or large sheep & cattle farms (Figure 3-9d).

TABLE 3-8. MULTIVARIABLE COX PROPORTIONAL HAZARDS REGRESSION MODEL FOR TIMELINESS OF RESPONSES IN MONTHLY ONLINE CLINICAL SYNDROME REPORTING FOR PARTICIPANTS IN THE LANDI SURVEILLANCE SYSTEM IN VICTORIA, AUSTRALIA.

		n	Coeff.	Robust SE	p-value	Hazard Ratio^a	95% CI
Winter stocking rate	≤10 DSE/ha	153	Ref.	—	—	1.00	—
	10.5 to 12.5 DSE/ha	257	-0.122	0.155	0.432	0.89	0.65 to 1.2
	13 to 14.5 DSE/ha	295	0.615	0.252	0.015	1.85	1.13 to 3.03
	≥15 DSE/ha	167	0.207	0.212	0.328	1.23	0.81 to 1.86
Time spent working on-farm	Full Time	551	Ref.	—	—	1.00	—
	Part Time	321	0.946	0.151	< 0.001	2.58	1.92 to 3.47
Highest level of formal education	Secondary	292	Ref.	—	—	1.00	—
	Tertiary (agriculture)	253	-0.351	0.207	0.091	0.7	0.47 to 1.06
	Tertiary (veterinary)	141	-0.673	0.175	< 0.001	0.51	0.36 to 0.72
	Tertiary (other)	163	-0.273	0.196	0.163	0.76	0.52 to 1.12
	Unknown education	23	0.891	0.186	< 0.001	2.44	1.69 to 3.51
Farm type	Sheep only	339	Ref.	—	—	1.00	—
	Cattle only	154	-0.526	0.253	0.037	0.59	0.36 to 0.97
	Small sheep & cattle	95	-0.401	0.16	0.012	0.67	0.49 to 0.92
	Large sheep & cattle	284	-0.013	0.164	0.938	0.99	0.72 to 1.36

Number of observations = 703. Final model with 12 degrees of freedom, AIC = 7832.149, likelihood ratio test 79.82 ($p < 0.001$), robust logrank statistic 13.68 ($p = 0.251$), $R^2 = 0.107$.

n = number of observations (farm-month reports) per category; Coeff. = regression coefficient; Robust SE = robust standard errors of the regression coefficient, calculated from robust sandwich variance estimates with farm ID as a cluster term to account for repeated measurement; Ref. = reference category.

^aThe hazard ratio represents the relative probability that a report will be provided, with hazard ratio >1 meaning timely reporting is more likely.

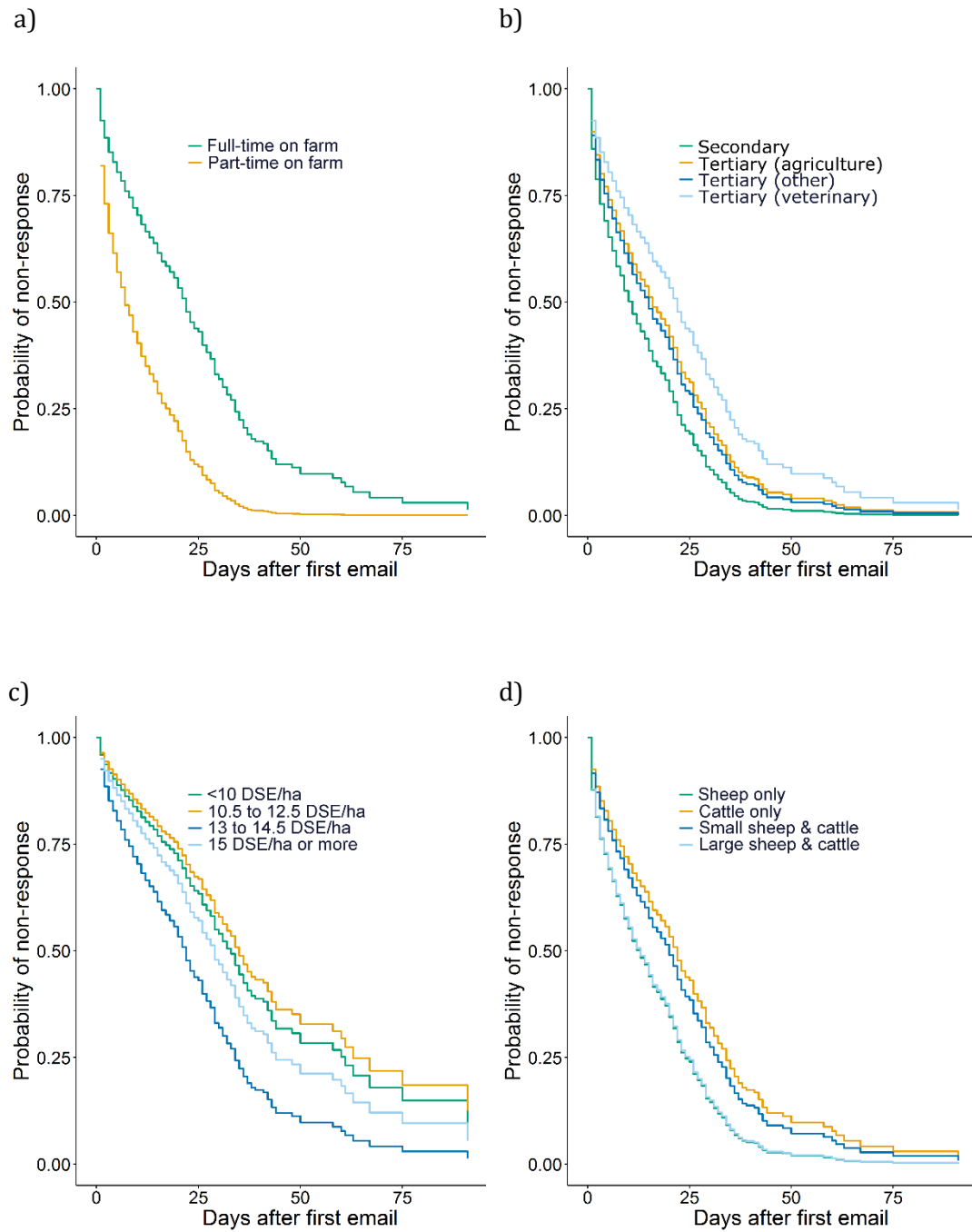


FIGURE 3-9. MARGINAL PREDICTED SURVIVAL CURVES FROM THE COX REGRESSION MODEL FOR INDIVIDUAL FARMS, BY: (A) TIME ON-FARM , (B) EDUCATION, (C) WINTER STOCKING RATE, AND (D) FARM TYPE. REFERENCE CATEGORIES: FARM TYPE CATTLE ONLY, FULL-TIME ON-FARM, VETERINARY EDUCATED, WINTER STOCKING RATE 13 TO 14.5 DSE/HA.

3.4.3.5 MULTIVARIABLE ANALYSIS OF NON-RESPONSE

Outputs of CART analysis of farm or farmer characteristics associated with response are presented in Figure 3-10. The strongest association with response was farmers greater than 43 years of age. Just 32% of requested reports were provided by farmers younger than 43, compared with a response rate of 86% from older farmers. Within reports from farmers 43 years or older, those with both sheep and cattle were less likely to respond (77% response rate) compared with those with just sheep or cattle alone (93% response rate, the largest and most reliable subset of farmers representing 54% of all reports requested). Farmers 43 years or older with both sheep and cattle were further split by stocking rate and labour availability, with response rate 97% from farms with stocking rate > 10 DSE/ha and > 2.06 labour units per 10,000 DSE, compared to 74% with stocking rate > 10 DSE/ha and < 2.06 labour units per 10,000 DSE. One farm with stocking rate < 10 DSE/ha was very unreliable, providing just 12% of requested reports.

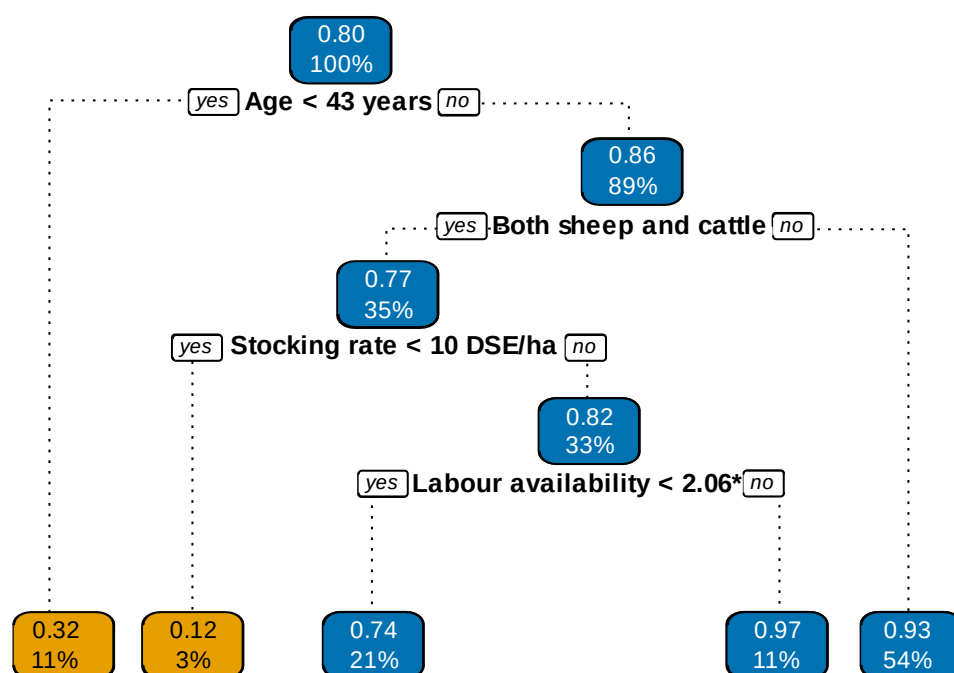


FIGURE 3-10. CLASSIFICATION TREE FOR FARMS PARTICIPATING IN MONTHLY ONLINE CLINICAL SYNDROME REPORTING¹.

¹ Each 'branch' of the tree splits the preceding node at a single variable giving maximal difference in response rate between split groups. In each node box, upper number is the proportion of responses in group, and lower number is percentage of all reports represented by that node. blue = majority of group responded; orange = majority did not respond. *Labour availability measured as full-time labour units per 10,000 DSE of livestock.

3.5 DISCUSSION

3.5.1 FEASIBILITY OF FARMER SYNDROMIC SURVEILLANCE

Overall, LANDI was able to effectively capture relevant data about the occurrence of clinical syndromes on the 39 participating farms. While the response rate declined over time, this was driven by the response behaviour of a small number of farmers, while the rest of the participating farmers provided their reports consistently over the 28 months of operation. Most of the syndromes used for data collection were reported in both sheep and cattle at some point during system operation. These reports captured a large number of disease events, with 558 reports positive for at least one syndrome, and a total of 1211 syndrome events reported. This gives a mean number of 2.2 syndromes per positive report, and 1.5 syndromes per report overall. This is similar to the findings of Butler and Loth (2017) on four Western Australian sheep farms, with 64 syndromes over 12 months and a mean 1.3 syndromes per farm per month.

Most of the events reported to LANDI were considered minor problems by the farmers and would not have been sufficient to initiate contact with private or government veterinarians. In most cases where disease events reported to the syndromic system had not received an investigation at the request of the farmer, it had been managed independently by the farmer and resolved by the time the monthly report was submitted. By capturing these events, temporal and spatial patterns of clinical syndrome occurrence can be investigated, allowing better understanding of the baseline disease prevalence in the population and facilitating early detection of increases in prevalence. Butler and Loth (2017) observed an association between syndrome and the likelihood an event would be reported to a veterinarian, with skin disease and lameness less likely to be reported than other syndromes such as mortality. Given that skin disease and lameness can be clinical signs of emergency diseases such as scrapie and foot-and-mouth disease, it is particularly relevant to understand the normal patterns of these syndromes occurring in sheep (and cattle) populations, such as by summary of syndromic report data.

All ten syndromes were reported during the system's operation, with deaths, lameness, and skin and eye signs the most commonly reported disease events. The seasonal patterns captured matched the expected seasonal occurrence of several

syndromes, including reproductive issues and lameness in the winter and spring months (May to November). This is both when most sheep farms were lambing, as well as when pastures tend to be long and wet, resulting in chronic wetting of the animals' feet. Skin or eye issues were more common in summer and autumn (November to May) when grass seeds and infectious conjunctivitis are more prevalent.

Despite recording 1211 disease events, as well as veterinary investigation of 201 cases of disease, no emergency or emerging diseases were detected by the system. Similarly, no such diseases were detected in this population by parallel surveillance activities by Agriculture Victoria over the same time period (Agriculture Victoria, pers. comm.). While detection of these types of diseases was not the main objective of LANDI, the system can give supportive evidence that these events are not occurring in the population under surveillance. The presence of the same, or similar, diagnostic indicators from multiple independent information sources provides a means for increasing the sensitivity of detection of unusual disease patterns (Stevenson et al., 2007). All disease investigations performed were also entered into Agriculture Victoria's animal health surveillance database, which has its own protocols for detecting unexpected clusters of disease and initiating appropriate further surveillance activities or field investigation. Therefore, a system like LANDI can be seen as complementary to other more traditional surveillance activities.

3.5.2 PURPOSEFUL RECRUITMENT OF FARMERS FOR SYNDROMIC SURVEILLANCE

The participation analysis reported in this chapter demonstrates that farm and farmer factors associated with response behaviour can be identified within an operational surveillance system. Overall, sheep farms provided the most consistent and timely responses. Farmers from farms grazing both sheep and cattle had a lower response rate than those from farms with a single species (sheep or cattle). Of all responses received, farmers from cattle farms and small farms with both sheep and cattle were less timely in providing reports than sheep farms or large farms with both species; the latter two farm categories were similar in report timeliness. While the existing use of a herd-flock information management system could have influenced reporting speed, only six farmers in this study used such software and consequently its effect was not assessed. It may be surprising that reports from large farms with both sheep and

cattle were similarly timely to sheep farms of all sizes, and more timely than small farms with both species. This suggests that *a priori* assumptions about how 'busy' farmers are based on their farm type may not accurately predict response behaviour. Analyses of operational systems, such as reported here, can therefore offer value to inform selective recruitment of farmers for surveillance reporting.

Younger farmers (< 43 years of age) had a poorer response rate than older farmers, although timeliness of responses was not associated with age. Contrary to the expectation that younger farmers may be more computer-literate and therefore able to participate in online reporting, our results suggest the majority of the population are likely to be suitable participants based on age. Given the average age of Australian farmers is 57 years (Australian Bureau of Statistics, 2017b), the majority of farmers that might be approached to participate surveillance reporting are likely to be of this age. All of the farmers under 43 years of age in this study had an overall response rate <60%, but the reasons for this association are unclear. If a similar pattern emerged in future data for a similar system, further investigation of the reasons for this would be beneficial.

Having two people complete the report each month resulted in higher response rates but poorer timeliness of reporting, compared to a single farmer completing in the univariable analyses. A spouse or parent-child team completing the report may have meant reports were less likely to be overlooked but more likely to be delayed until both people were available. However, as this system required completing farmers to have both sufficient knowledge of disease events in their animals and computer literacy to enter reports, in some cases these partnerships were necessary for participation.

Increased timeliness for providing reports was associated with part-time farmers, non-veterinarian participants, and moderate winter stocking rates, as well as farm type as discussed above. Although most part-time farmers had alternative off-farm employment, these jobs may involve sitting at a computer more often than a full-time farmer, providing greater chance of being able to respond when an email is received. The apparent effect of moderate winter stocking rates should be interpreted with care, as there is little biological explanation why particular stocking rates, rather than an ordinal trend, would be associated with reporting timeliness. This association instead suggests that, despite statistically correcting for the longitudinal design,

unmeasured confounders may remain. The types of farmers able to provide more timely reports cannot therefore be determined from this study alone. Along with prediction of response behaviour *a priori* based on farm characteristics, systems should also monitor participation in real-time to allow selective removal of farmers with unsatisfactory reporting behaviour despite favourable characteristics identified at recruitment. This reinforces the need for ongoing and repeated evaluation of the performance of surveillance systems (German et al., 2001).

There were six farms run by seven veterinarians in this study, including two farms where the veterinarians were full-time farmers with no off-farm employment. Although veterinarians were not significantly less likely to respond, their reports were received more slowly than from farmers with similar educational and professional backgrounds. Veterinarians' additional background knowledge and understanding of animal disease, while considered advantageous, was not required by the system design. Furthermore, the delay in their responses means they may be less desirable contributors. This suggests that, with an appropriately user-friendly system design, non-veterinarian farmers who are attuned to detecting clinical syndromes in their livestock should remain the target population for surveillance reporting.

In this system, 80% of requested reports were received over the two-year period, with a median response time of 8 days for all reports received and 13 days including non-responses. Surveillance timeliness does not have a defined ideal cut-off, but should be assessed relative to the objectives of the surveillance system. In this case, a median reporting time of 13 days for a retrospective report describing disease events in the preceding 31 days gives an overall median timeliness of up to 14 to 44 days, depending when the event occurred in the preceding month. This is adequate for a system designed to establish and monitor the prevalence of endemic disease, and minimises recall bias compared to approaches where only periodic (e.g. annual) farmer reports are requested. This timeframe is also appropriate for providing intermittent information to stakeholders in the surveillance system, including veterinary authorities, participating farmers and industry. For exotic disease detection, reports should ideally be received as soon as clinical disease is noted, although this rarely occurs. In outbreaks of foot-and-mouth disease (FMD) occurring between 1992 and 2003, the median delay between initial infection and disease detection by veterinary authorities was 15 days (first quartile 8 days; third quartile 22 days, McLaws and Ribble, 2007). In Victoria, the likely delay between infection and

detection of FMD on a single farm has been estimated at 21 days (90% CI 16-28 days, Martin et al., 2015; East et al., 2016) with around 30% probability that any single farm will report the disease. At a population level, the delay to a 95% confidence of detection of FMD within Victoria is estimated to be 34 to 40 days (East et al., 2016). Although early detection of exotic disease was not the primary objective of this system, similar timeframes were approached for both expected endemic diseases such as ewe mortality around lambing, as well as for 'outbreaks' of unexpected disease such as plant toxicities. This system was no less timely than existing systems and offers greater probability of positively identifying the presence of clinical syndromes on individual farms, making it a useful adjunct to passive reporting for exotic disease detection.

Reporting behaviour was not affected by time of year or whether farmers had disease events to report. Timeliness and response rate varied little between months, and the presence or absence of a disease event was not associated with timeliness in cases where a report was received. The lack of substantial variation in response rate throughout the year suggests that the sensitivity and timeliness of the system to detect unusual patterns of disease is unlikely to suffer during busy times on individual farms. This was evident in timely reporting continuing during late winter-spring (August to October), when most participating sheep farmers had lambing flocks. Furthermore, at least one disease event was reported in 69% of responses, with no association between timeliness and clinical syndrome presence or absence. This demonstrates that overall, these farmers were willing to report the clinical syndromes they were observing. Having disease events to report did not deter participants from timely reporting despite the increased effort required to provide the relevant case information. On the other hand, having syndromes to report did not appear to motivate farmers to report sooner; rather, factors related to the farmer rather than the content of the report were the main drivers of report timeliness. A lack of association between disease event status of the report and timeliness of the response overall means that early responses can be screened to give an indication of the total number of reports expected that month across all respondents, without those early reports giving an excessively 'rosy' or 'gloomy' view of what the full months' data are likely to show.

For the nine farmers that became consistent non-responders, the responses they did supply were also less timely, suggesting that delayed responders are more likely to

become non-responders over time. These farmers may require additional contact to understand the reasons for their delayed responses, or alternatively other participants recruited to replace them. During informal follow-up interviews for this system, several of the non-responding farmers indicated that their interest in providing data waned over time, in part because they were not receiving feedback about the data they provided. They suggested that access to summary data from the system, to be able to understand trends in the occurrence of clinical syndromes, benchmark their property against others, or receive early warning of potential disease outbreaks, might have been sufficient incentive for them to continue participating in the system (incentives are discussed further in Section 3.5.4). This was not feasible for the first two years of LANDI but is expected to improve participant retention in future systems.

This chapter has summarised the characteristics of preferred participants for this style of surveillance activity, based on the operation of the LANDI system. However, it is also worth considering whether the most timely and reliable responders are also the participants of interest for this kind of surveillance. It may be that disease events on very large farms (where there are many animals and possibly increased risk of disease spread), or on farms with multiple species (where an exotic disease may be introduced sub-clinically in one species but be transmitted and more clinically apparent in another species) should be priority farms for this kind of surveillance. In that case, the results of this study still guide the expected results of surveillance. For example, if multi-species farms are to be targeted for recruitment based on increased epidemiological risk, then response rate and timeliness of response may be reduced. Knowing this information up-front may inform engagement strategies to increase participation and timeliness, may increase the number of participating farms needed to account for expected non-response, or may mean the expectations and objectives of the system are adjusted to be more realistic. Because truly random recruitment of farmers for a system like this is rarely feasible, purposive recruitment along with prospective estimation of the associated biases is the preferred method for recruiting farmers for syndromic reporting.

3.5.3 DESIGN CONSIDERATIONS FOR LANDI SURVEILLANCE SYSTEM

3.5.3.1 RECRUITMENT AND TARGET POPULATION

Despite recruitment by convenience, careful consideration was given to what types of farms might be approached to participate in LANDI. Both sheep and cattle farmers were recruited to participate in LANDI. When the system was first conceived, it was recognised that of the Victorian sheep farmers that would be approached to participate in the system also grazed cattle on their farms. It seemed sensible to construct the system to allow reporting of clinical syndromes in both species, to capture a full ‘snapshot’ of livestock health on the participating farms. Once the system was built with the capacity to handle syndrome data for both species, the inclusion criteria for farms to participate allowed for farms with sheep, cattle or both species. There were, however, far fewer events reported in cattle (31% of reports positive) than in sheep (71% of reports positive). This may simply reflect the smaller number of cattle (median 141) than sheep (median 2908) on farms. However, it may also be that cattle receive more preventive and pro-active care than sheep, and that signs of disease in sheep are tolerated to a far greater extent. For example, the death of a single cow might initiate a greater response and intervention compared to the death of a single sheep. This also reflects the relative individual economic value of the animals. Nonetheless, the system’s ability to confirm lower rates of disease events occurring in cattle than sheep, as well as providing a means for doing useful surveillance of sheep—an often overlooked species—are useful benefits from LANDI’s operation.

The data collected by the system, and the analysis presented in this chapter, are limited by the recruitment of participating farms by convenience and willingness to participate. For example, farms that are clients of Mackinnon tend to be managed by pro-active, information-seeking farmers, and may have on-farm disease management practices above the industry average. Therefore, if anything, the rates of clinical syndromes occurring on farms in the wider population may be higher due to greater variation in farm management, although the probability of syndrome detection may be lower on the average farm with less ‘pro-active’ management. Recruiting via this existing farmer network, leveraging existing trust in the Mackinnon Project ‘brand’, was crucial to the feasibility of this surveillance system. Despite potential selection bias, the farms were considered broadly typical of the range of sheep and beef farms

in Victoria and were distributed throughout the major sheep and cattle production areas of the state. Although the sample size in our study was limited by resource constraints, the broadly representative nature of the participating farms and farmers means that our results are likely relevant to other grazing farms in southern Australia. Continued system operation with greater participant numbers will offer opportunities to repeat and refine these analyses, as will similar analyses in comparable systems for other types of livestock production or geographic locations. In a longitudinal study of sheep mortality in New Zealand, Davis (1974) concluded that the selection of collaborating farmers was “the single most important factor in ensuring success”. A similar conclusion is drawn by those directly involved in the operation of LANDI.

Recruitment of farmers for this system required substantial effort, with many hours invested in making contact with suitable farmers and following up to complete consent paperwork and demographic surveys, prior to commencing longitudinal data collection. Farmers who could not be contacted reliably or were unable to comply with the online submission of their demographic information were excluded from the study. The final sample of farmers participating in the surveillance system was therefore selected to maximise compliance with the data submission requirements of the system. Selection bias based on willingness to participate is present in many participatory surveillance activities (Charles-Smith et al., 2015). Furthermore, recruiting a truly random and representative sample to such a system is fruitless if the participants are subsequently unable or unwilling to provide the required data. In such a case, non-response bias replaces selection bias, while simultaneously increasing the administrative workload following up non-compliant participants.

3.5.3.2 SYNDROMIC DATA COLLECTION

When designing the data collection system for LANDI, acceptability was considered the most important attribute. Specifically, the system was set up for ease of use and to minimise the time required by the farmers to enter their data each month. Here, specific aspects of the design of the system tailored for acceptability will be discussed.

The syndromes used in the systems were derived from those used by Shephard (2006), but were substantially altered for three reasons related to acceptability. Firstly, farmers reporting their observations to LANDI would not receive detailed training on the syndrome definitions, so it was vital that the syndrome definitions were intuitive i.e. the syndromes matched how Victorian sheep and beef farmers

would observe different types of signs associated with disease. For example, Shephard's syndromes included four associated with the heart, circulation and blood. We believed farmers would rarely identify pallor, cyanosis or jaundice without the presence of other clinical signs. It was more likely that animals with circulatory disease would be noticed as weak or recumbent, and subsequently dead. Circulatory signs were therefore likely to be reported appropriately as 'deaths', and so the circulatory syndromes were not used for LANDI. Similarly, the distinction between an animal 'found dead' and a case of 'sudden death' was unclear, and so a single category of 'deaths' was substituted. The provision of free-text comments meant that any additional information not fully expressed by a single syndrome could still be captured by the system.

Secondly, Shephard's system was designed for one or more syndromes to be reported per case in real-time. We intended instead that each case would be reported under a single overarching syndrome summarising all cases in that month, so that a farmer would only need to enter data about several similar cases as a single disease event. Finally, we limited the total number of syndromes by aggregating clusters of similar syndromes. This was expected to reduce the amount of time (and cognitive effort) to complete each report, and also increased the simplicity of the system. To manage the risk that the nine specific syndromes might result in some events not being reported to the system, the 'other' syndrome option was included. This syndrome could be used if a farmer could not identify the relevant syndrome for the signs that they had seen, and was used in 4% of positive reports.

Monthly reporting was selected as a compromise between frequent reporting (with substantial time and energy required) and delayed reporting (with the risk of recall bias). Traditionally, other studies of disease on farms have used one count from a year as denominator data and then ask the farmer to remember disease events, estimate prevalence and self-prioritise the most important causes of the syndrome, such as diarrhoea in weaned lambs (Sweeny et al., 2012) or ewe mortality (Harris and Nowara, 1995). Monthly reporting offers two benefits, both more contemporaneous count data (especially to provide denominators for disease frequency measures), as well as reducing the likelihood of recall bias of the suspected causes of disease. Because increasing the frequency of reporting also increases the workload required by the farmer, and this system required the farmers to use a computer interface to enter their data manually, weekly reporting was considered unfeasible.

LANDI used a monthly summary report instead of a system of real-time event reporting, because monthly summaries were also considered sufficient to detect endemic disease events that may be ongoing and require further veterinary investigation. In a pilot of sentinel farms reporting, Black and Vujcich (2002) found that farmers didn't really have the time to complete data entry for each individual observation of a clinical syndrome. Summary reports were considered a viable alternative. Participating farmers were also encouraged to report disease events directly to a Mackinnon Project veterinary consultant if they felt investigation would be beneficial. The other advantage of a monthly summary is that by design, it captures negative reports. Each syndrome was either present or absent in each report. In a real-time reporting system, care would need to be taken to verify negative reports periodically, to differentiate 'present but not reported' syndromes from those that are truly absent. While confirming the true absence of disease is not always a simple activity for a surveillance system, confirming true absence in an observational syndromic surveillance system is both achievable and provides valuable data.

Free text fields were included in the report format for two reasons. The first was to capture additional relevant information about events, that might not fit neatly into the structured format of each syndrome report. These comments can also add important context to closed categorisation of disease events, particularly if individual records are being manually reviewed to identify unusual disease events (as was the case for LANDI). The second was because the farmers often had additional information about their disease events, that they perceived as important. If closed questions are not developed carefully, farmers may feel their observations are not being properly captured by the system, resulting in feelings of dissatisfaction with the system. Eliminating free-text comments altogether may leave many farmers feeling unheard and devaluing their opinions and careful observations. However, some farmers provided substantial amounts of information based on their observations of clinical syndromes that were not always relevant to the objectives of the project. This was also experienced by Black and Vujcich (2002) in a pilot farmer reporting system in New Zealand, who found open-ended questions often elicited substantial quantities of minimally useful information. It is important to design data collection to minimise the amount of time farmers spend entering data that will not be used, while simultaneously respecting the desire to provide their perspective on the disease events.

To simplify the appearance of the interface the farmers used to enter their monthly reports, the branching logic capability of RedCAP was used extensively. This meant that, initially, only the syndromes themselves were presented to the farmers, requesting a 'yes' or 'no' response to whether each syndrome had been observed that month. If 'yes' was selected, then the appropriate additional fields appeared to capture the relevant data about that disease event. This allowed the complex data structure of the system back-end to be presented to the farmers as a very simple system, again aiming to increase acceptability.

3.5.3.3 OTHER BENEFITS OF LANDI SURVEILLANCE SYSTEM

LANDI has proven useful for more than just the data it has generated. In an investigation of ways to improve surveillance in Australia, Wright et al. (2016) identified potential benefits from developing relationships between farmers, veterinarians and those responsible for surveillance, as well as making surveillance more transparent and highlighting how multiple stakeholders contribute to surveillance outcomes. Throughout the time LANDI was operational, efforts were made to engage both participating farmers and the broader Mackinnon Project farmer network in the concept of disease surveillance. Regular contact with participating farmers arose from both the monthly reports and contact to further discuss disease events. Presentations about LANDI were also made to farmer audiences at Mackinnon Project seminar days in 2015 and 2017. Reports about data aggregated from LANDI also featured regularly in articles in the Mackinnon Project farmer newsletter, with over 200 subscribers. A periodic summary report was also trialled as a regular engagement tool for participating farms, with positive feedback. Regular feedback of surveillance information relevant to the farmers supplying data would be beneficial for future similar systems. These activities, publicising the contribution individual farmers made to surveillance activities, help to make surveillance more visible, which may lead to increased perceived responsibility and more awareness of the importance of disease reporting. Australian beef farmers are known to often consider matters like emergency animal disease prevention and management, as well as biosecurity, as government responsibilities (Hernández-Jover et al., 2016). The more surveillance is perceived as an individual responsibility, the greater farmers' intentions to monitor will be (Wright et al., 2016). This is a cultural challenge, but systems like LANDI have potential to increase the 'ownership' farmers feel for effective surveillance.

Further, LANDI was designed with an escalation procedure to reduce delayed reporting, encouraging the farmers to report 'unusual' observations of signs of disease to a project veterinarian by phone in real-time rather than waiting to complete their monthly report. If an exotic disease were to occur on a participating farm, it is likely that this phone call would identify the potential problem and hasten formal detection of disease, likely faster than estimated for passive surveillance alone by East et al. (2016). Additionally, because participating farmers were recording their observations of clinical syndromes for their monthly reports, several reported anecdotally that they acted more quickly to respond to signs of disease in their livestock. These farmers sought veterinary advice more quickly about 'unusual' disease events, whereas previously they may have monitored the problem longer before seeking help, or not sought assistance at all. This was observed by the livestock consultants and confirmed in informal interviews with participating farmers. It suggests that the benefit of engaging farmers in syndromic surveillance can go beyond structured reporting, and can help drive change in farmers' disease management behaviour.

3.5.4 RECOMMENDATIONS FOR FUTURE SYSTEM DESIGN

There are three main areas of focus for improved design of future systems, based on lessons learnt from the operation of LANDI in 2014 to 2016. These are the selection of appropriate and sustainable incentives for participation; the importance of trust in the system, generated from effective follow-up of suspect cases; and finding a way to collect accurate denominator data so that case numbers can be expressed as incidence or prevalence estimates. Each will be discussed here, before proposing a system design concept that might overcome these real-world challenges to surveillance.

Ideally, a surveillance system should operate as a partnership between those generating data and those who can turn that data into information and communicate it effectively. Therefore, data partners should receive sufficient benefit from their provision of data to the system for the system to be sustainable. This benefit can be considered as incentive to participate, although ideally it is more than just compensation. For LANDI, the incentive was provision of subsidised veterinary investigations of unusual disease events. Not all participating farms experienced such an event, although the farmers did give feedback that knowing an investigation would be available if it were needed was sufficient incentive for ongoing participation. The veterinary investigation results were another major data output of LANDI, justifying

the substantial resources required to provide such a service. However, there were practical limitations to the provision of investigations, such as for farms that were large distances from the main pathology laboratory where investigations took place or when many disease events were occurring in a short time period and sufficient staff to conduct investigations were not available. There are also limits to the scalability of veterinary investigations as an incentive, especially where regional laboratory facilities are limited, such as in Victoria and other Australian states (Frawley, 2003). Therefore, it would be beneficial to trial alternative incentives.

Both financial and intangible benefits can be powerful motivators for ongoing participation (Barnes et al., 2015). One possibility is to leverage the data being generated by the system itself. Farms have the capability to generate large amounts of data, but farmers are typically not trained in data science or data visualisation. Therefore, to take farm data including syndromic observations, analyse it to produce information, and provide that information back to farmers in a useful format, has great potential as an incentive for observational syndromic surveillance. Specific applications of this information might be to allow farmers to benchmark disease occurrence in their animals against other similar farmers, or to generate alerts for subclinical or long-term disease problems like excessive cumulative mortality over an extended period of time. This would be particularly useful for chronic diseases where the total incidence or prevalence of disease is difficult to appreciate without reviewing historic data. The effectiveness of information communication as an incentive for farmers to provide observations requires further investigation.

Another important consideration is setting up the surveillance system so that farmers trust their data is being used, and used appropriately. A lack of trust has been repeatedly identified as a constraint to farmers reporting disease (Palmer et al., 2009a; Wright et al., 2016). This is particularly important for follow-up of veterinary investigations. Davis (1974) recognised that prompt reporting of results of post-mortems was “essential” to maintain the enthusiasm of farmers reporting ewe mortalities longitudinally, and it seems in this respect, little has changed over 40 years. A dedicated contact number was provided to all participating farmers, and they were encouraged to call that number whenever they noticed a disease event that they felt would benefit from investigation, to achieve a diagnosis or to guide treatment and control. The farmers were encouraged to report these ‘significant’ disease events actively, rather than waiting for their monthly report submission. In this way, disease

events could be investigated without delay. When farmers receive a satisfactory response to their first phone contact with a vet, they are more inclined to phone again. LANDI project staff therefore worked hard to provide a positive experience when the number was called to discuss an event, regardless of whether investigation was subsequently performed. Trust was also needed for farmers to feel safe reporting disease events to the system. The large number of events reported to the system suggests that, at least for the farmers who agreed to participate, they were comfortable that providing disease data was unlikely to adversely impact their farm or reputation.

A major challenge for LANDI was 'getting the denominators right', being able to identify the population at risk for each disease event and then accurately enumerating the number of animals in that population. Not all animals on a farm, or even all animals within a class, are at risk for a given disease event. For example, pasture toxicities (e.g. phalaris staggers) or infectious disease outbreaks (e.g. campylobacter abortions) may be confined to animals in a single paddock. If the affected class of stock are being managed as multiple mobs in multiple paddocks, not all animals in that class experience the same risk of disease. Similarly, some disease problems (e.g. infectious arthritis) are likely to only affect one class of stock on the farm rather than all animals of that species. These differences arise from the epidemiology of the disease, in terms of host-pathogen-environment interactions. Accordingly, during period B, farmers were asked to indicate for each event whether the problem was occurring in an individual mob/paddock, multiple mobs/paddocks or one or more whole classes of stock, and to estimate the relevant number of stock at risk. This allowed researchers to consider which denominator value might be appropriate to calculate measures of disease occurrence. This challenge is further explored in Chapter 4 using ewe mortality as an example.

The other denominator challenge faced was maintaining accurate stock count data for each farm, to be able to determine the size of the population at-risk. The farmers' routine on-farm activities tended to result in reasonable estimates of the number of animals affected by each disease event. However, few farmers routinely count the number of animals in every mob regularly as part of normal farm management. Rather, farmers verified their stock numbers at key times of year (e.g. scanning/marking/weaning for ewes and lambs, shearing, and for taxation purposes in June/July each year). The report format in period A was designed to capture these

strategically timed stock counts to verify the number of animals reported at risk for individual disease events. However, due to variation in numbers of purchases, sales and deaths, the stock counts did not always agree with the number of animals reported at risk for disease events. Increasing the frequency of total stock number reports was attempted during period B, but response rates were variable and farmers reported that generating these figures was time-consuming. Another solution to accurately estimating the number of animals on individual farms would add value to a syndromic surveillance system, as well as being crucial for emergency disease outbreak preparedness to rapidly ascertain the number of susceptible animals at risk.

It is worth considering a more sophisticated system that takes into account these three areas of recommendation. The features proposed here were not implemented in LANDI due to their additional complexity, but would provide great benefit for future systems. Syndromic surveillance of farmers' observations could be integrated with farm management software. If the farm management software managed the stock numbers and paddock allocations, then that information would be available to provide the required denominators needed for disease occurrence measures. Appropriate software for stock number and paddock recording is currently available in Australia, for example 'AgriWebb' (2018).

In combined farm management/surveillance software, along with observations of clinical syndromes, farmers would ideally be able to enter stock counts for specific paddocks or aggregated across classes, as well as record when mobs are moved around the farm. The software could also account for deaths allocated by paddock, so that at the next stock count the farmer can verify the number of live animals remaining in that paddock (or determine how many additional animals have 'gone missing' since their last count). An interface suitable for mobile or tablet use would allow the information to be captured in real-time in the paddock, with the farmer making a habit of creating these records as part of their daily farm activities. Such an interface could also use push notifications as farm management alerts, including notifications of disease patterns that may require intervention. These alerts could be generated by automated signal detection algorithms already developed for other syndromic surveillance systems (Dórea and Vial, 2016). Additional value to the farmer could also be provided, for example incorporating meteorological and pasture growth data to help them manage feed availability and paddock allocation. The surveillance data could be synced from within the software on individual farms to a central system,

for aggregated analysis and to provide benchmarking data back to individual farmers. Such a system would make collecting surveillance data incidental, with the software providing direct benefit to individual farmers. This may be more sustainable than relying on the industry-level benefits of surveillance information as the main motivation to participate.

While some LANDI participants expressed a desire for real-time reporting (rather than monthly summaries), others indicated reporting every event individually regardless of severity would prove too time-consuming. The proposal to integrate syndrome reporting into farm management software could reduce the perception of reporting as an extra 'activity' for farming. However, few farmers presently maintain electronic records of all disease events, although electronic recording of production information is slowly being taken up by Australian sheep farmers. Thus, even disease event recording integrated into farm management software would require behavioural change. Substantial investment would be necessary to develop such a sophisticated system, and then to deliver it with effectively to farmers to achieve good uptake. However, an integrated system like this has the potential to link farm management and surveillance into a single activity that has value for individual farmers as well as for government and industry. This has potential to help bridge the gap between the stakeholders of animal health surveillance.

3.6 CONCLUSION

Knowing which farmers to recruit to an observational syndromic surveillance system is challenging, but this study has provided some preliminary guidance to identify which farmers may be preferred participants. It can be difficult to fully understand the association between farm or farmer factors, and timeliness and response rate for syndromic surveillance, because causality can rarely be inferred and many measures are correlated. However, analyses such as those presented in this paper still provide a useful starting point for targeting syndromic surveillance to farmers who will participate effectively.

The syndromic surveillance system described in this chapter was operational for more than two years and may be a useful starting point for the design of similar systems. Care must be taken in the design and set-up of the system, because acceptability to farmers as data providers is crucial for sustainability. The system

presented here was not perfect, and several suggestions for improvement have been made. Nonetheless, this chapter has demonstrated that it is feasible to collect farmers' observations in a way that is useful for surveillance, on a scale that can provide new insights into disease occurrence. The next chapter will use ewe mortality as an example to demonstrate the potential value of farmers' observations as a data source to complement other, more traditional, surveillance activities.

Chapter 4.
EPIDEMIOLOGY OF ADULT EWE MORTALITY
IN SOUTHERN AUSTRALIA:
SYNDROMIC SURVEILLANCE FINDINGS

PREFACE TO CHAPTER 4

Building on the feasibility of collecting farmers' observations through syndromic surveillance described in Chapter 3, it is appropriate to test the usefulness and limitations of the data collected. Because it was unfeasible to investigate every syndrome in every class of stock recorded by the system, ewe mortality was selected as an example to demonstrate the utility of the information generated by the LANDI surveillance system. This chapter presents descriptive and analytical results generated from reports of ewe mortality collected by LANDI, aiming to establish the baseline frequency of ewe mortality on 31 participating sheep farms, and to quantify factors associated with increased risk of mortality .

4.1 ABSTRACT

The objective of this study was to use regular reports of farmers' observations to quantify ewe mortality on sheep farms in southern Australia. While some ewe deaths are inevitable on sheep farms, the number of ewes dying and the seasonal pattern of mortality are infrequently determined. Previous estimates are largely outdated and may not be representative of ewe mortality in a full farm system. Therefore observations of ewe mortality from 31 Victorian sheep farms were collected over 28 months (August 2014 to November 2016) through a prospective disease surveillance project. Observations were recorded as a monthly summary of the number of ewe deaths, ewe numbers at risk and descriptive causes of death (where known), and whether a veterinarian was consulted about the case (December 2015 to November 2016 only). Ewe deaths were reported in 540 of 612 reports, describing 2106 individual deaths, with a median of 4 deaths per positive monthly report. Farmers' descriptions of cause of death were evenly distributed between those associated with late pregnancy and lambing, and other causes. In a subset of reports where veterinary contact was recorded, only 15% of reported deaths involved a veterinarian. Almost half of the cases managed without a veterinarian had at least one death of unknown cause. Median mortality rates ranged between individual farms from 1 to 5 deaths/1000 ewes/month. The incidence rate ratio of mortality in two months preceding and three months sequent to start of lambing was 2.8 (95% CI 2.0 to 4.1) compared to the remaining seven months of the year. This quantifies the increased risk of death in ewes around lambing. Overall ewe mortality could therefore be reduced through strategies focussed on improving peri-parturient ewe survival. Further investigation of how and why farmers respond to ewe deaths without veterinary support is needed, to determine the best farm management strategies to reduce mortality.

4.2 INTRODUCTION

Ewe mortality is an important cause of economic losses on sheep farms in Southern Australia, as well as a potential animal welfare problem. Of the national sheep flock, 57% are adult breeding ewes (Meat and Livestock Australia, 2016b; Australian Bureau of Statistics, 2017a) and on many farms they represent the largest group of sheep to be managed. Despite this, there is surprisingly little information available on the causes or prevalence of ewe mortality. On individual farms, a one percentage-point increase in annual adult ewe mortality has been estimated to decrease farm gross-margin by 1.5% (Mackinnon Project, pers. comm.). Industry-wide, four of twenty-three priority diseases identified by Lane et al. (2015) are specific to deaths in adult ewes around lambing time: dystocia, mastitis, pregnancy toxaemia and hypocalcaemia. The combined cost of these diseases alone is estimated at over AU\$298 million per annum, while the total cost of ewe deaths to Australia's sheep industries is even higher. Accurately measuring ewe mortality and identifying common causes of ewe death are essential to reduce the overall losses, at both farm and industry levels.

Effectively reducing ewe mortality requires knowledge of the underlying cause of death. Consequently, it is difficult to give farmers generic advice to reduce ewe mortality. In the absence of a confirmed diagnosis, knowledge of common causes and risk factors for ewe deaths can direct management strategies to help reduce losses. In their comprehensive study, Harris and Nowara (1995) reported major causes of ewe deaths on 79 farms in the Mallee region of Victoria, including flystrike, photosensitisation (associated with a prevalent plant toxicity in the region), weight loss, and peri-parturient causes (primarily dystocia and pregnancy toxaemia). The farmers in that study reported greatest ewe losses in the autumn months, coinciding with the common time of lambing in that region in the 1990s. Reproductive causes were the main reason for death in 35% and 42% of farms running crossbred and Merino ewes, respectively. More recent data from the Victorian Sentinel Flocks Project confirms that, on the 18 participating farms, reproductive-related issues remain a major cause of death (Suter, 2013), with 58% (150/259) of all ewe deaths occurring in the 10 days preceding and following lambing (Agriculture Victoria, pers. comm.). More generally, the primary reason for ewe death near lambing has been reported by be dystocia, with additional losses associated with mastitis, hypocalcaemia and

pregnancy toxaemia (Davis, 1974; Harris and Nowara, 1995, Ghazali, 2007 #888; Suter, 2013).

Estimates of annual ewe mortality range between 3.1% to 10.8%, with examples of previous studies in Australia and New Zealand listed in Table 4-1. Despite the importance of ewe mortality and knowledge of common causes, studies that estimate the extent of losses have a number of important limitations. Information biases arise when studies use farm records to estimate mortality, as the quality and accuracy of those records may vary between farms (Harris and Nowara, 1995; Bush et al., 2006; Suter, 2013). Further information bias could be expected in prospective studies and surveillance activities requiring veterinary diagnosis, where the number of veterinarians and hours available to perform investigations as well as delays in the discovery of carcasses can influence both the types of cases that are detected and the accuracy of diagnosis in those cases (Davis, 1974; Suter, 2013). Dead sheep that are not discovered and investigated promptly can rapidly decompose to the point where a diagnosis is no longer achievable, as noted by Davis in New Zealand (1974).

Larger reported studies of ewe mortality (Davis, 1974; Harris and Nowara, 1995) were limited to a single geographic region and time period for practical reasons, resulting in selection bias. Other studies based on records generated during field trials or observational studies are biased due to the trial design, as the flock structure or management of ewes in those studies may not reflect that of the entire farm (Campbell, 2006; Ghazali, 2007; Kirk, 2016). Recruitment of farms for these studies may also have been purposive or based on convenience, rather than at random, resulting in further selection bias. Furthermore, the incidence of mortality between paddocks on a single farm may be confounded by environmental risk factors, so studying a subset of ewes may not reflect the overall pattern of mortality on that farm. The result is that estimates of ewe mortality in these studies may not reflect mortality on 'typical' sheep farms in the industry. In addition, each study's limited duration makes it difficult to detect changes in mortality over time, especially considering it may be inappropriate to directly compare mortality estimates from different geographic regions. It would be advantageous to be able to collect ewe mortality data longitudinally from a consistent sample of farms, to provide evidence for the presence or absence of changes in mortality levels over time. This could potentially be achieved through syndromic surveillance of farmers' observations of ewe mortality, although

not all biases will be eliminated through a change in methods (as discussed in Section 2.6.5).

While it is very difficult to estimate industry-wide losses, even determining the number of ewe mortalities occurring on a single farm is challenging. Few Australian sheep farmers can identify and record every ewe death occurring on the property, meaning a full account of all losses only occurs when examining farm records such as ewe numbers at shearing. In many of these cases, by the time significant mortality has been detected it is often too late to achieve a diagnosis and or determine appropriate changes to management to prevent repeated losses. The delay to detection of mortalities is often linked to the practicalities of farming, including other demands on farmers' time and geographic features of paddocks that may hide carcasses from view. Furthermore, at some times of year, environmental conditions such as heavy rainfall resulting in mud and groundwater may render direct access to particular paddocks unsafe for the farmer. These factors, alongside animal welfare standards that do not require daily close inspection of animals and large flocks managed with low labour ratios, mean that subtle, low frequency losses may not be detected in a timely manner, or even at all. Further challenges arise from methods of keeping farm records. Stock counts are usually conducted only at key management events, may not include every animal on the farm at a single time point, and can vary in accuracy. Individual sheep identification was introduced in Victoria in 2017 (Animal Health Australia, 2017), but animals are still not recorded with sufficient frequency to provide accurate, frequent counts of sheep from which mortality or other losses to follow-up could be readily inferred.

Due to the difficulty in conducting surveys of mortality for many species including sheep, several innovative approaches have been attempted internationally. These include analysing alternative data sources such as cattle registrations (Môtus et al., 2016) or fallen stock records for cattle (Ciaravino et al., 2012; Alba et al., 2015), horses (Tapprest et al., 2017), and sheep (Tongue et al., 2017). However, not all countries mandate animal registration or the collection of fallen stock, and in Australia farmers are responsible for the disposal of carcasses. Longitudinal reporting of deaths attended by dairy veterinary practitioners has also been reported (Fusi et al., 2017), but unless it is compulsory for veterinarians to conduct euthanasia and certification of found-dead cattle, substantial selection bias is likely. Where veterinarian attendance is less regulated, as in Australia, veterinarians will only be

able to provide data on the subset of animals they are actually engaged to treat. Just evaluating these cases will give biased underestimates of mortality and causes of death.

Data collected in new ways, such as through syndromic surveillance, could be used to verify existing mortality estimates, and to extend our understanding of ewe mortality. The cost-effectiveness of gathering observational rather than diagnostic data could facilitate the participation of a larger number of farms, compared to programs requiring veterinary or researcher attendance on-farm. Using a syndromic reporting approach to collect longitudinal data about ewe mortality has potential to increase the understanding of why ewes die and what can be done to reduce losses. If farmers recorded ewe deaths as they occurred, patterns of increased mortality could be identified sooner, allowing more timely intervention. Syndromic reporting by farmers can also offer a better indication of common causes of death and major risk factors, by capturing farmers' observations more regularly (or even in real-time). More accurate estimates of the causes and incidence of ewe mortality would also enable more objective ranking of the causes of mortality, compared to the anecdotal observations and expert opinion currently used (Lane et al., 2015). As discussed above, collecting farmers' observations can result in overall underestimation of mortality because not all deaths in the paddock will be identified by the farmer. However, assuming this underestimation is consistent over time, farmers' observations could also become an affordable way to monitor trends in mortality, both on individual farms and in groups of farms over time.

This study had three objectives. The first was to use farmers' observations collected by the syndromic surveillance system described in Section 3.4.1 to quantify adult ewe mortality occurring on 31 sheep farms in Victoria, Australia. The second was to determine the relative contribution of different causes of death to overall mortality, including quantifying the increased risk of death during the peri-parturient period. The third was describe the variability in ewe mortality between farms, to determine whether farm-level factors were consistently associated with the number of mortalities occurring. Together, these objectives aimed to provide an updated description of ewe mortality on sheep farms in Victoria, Australia.

TABLE 4-1. ESTIMATES OF ANNUAL ADULT EWE MORTALITY IN AUSTRALIAN & NEW ZEALAND FLOCKS.

Location	Data source	Year(s) ^a	Number of farms	Total number of mob-years ^b	Reported mortality ^c			Study
					All breeds	Merino	Non-Merino	
North Island, New Zealand	Prospective necropsy trial	1971-72	9 farms	All mobs on-farm (# not specified)	4.9%			Davis, 1974
Mallee region, Victoria	Farm production records	1987-88, 1988-89	79 farms	486 mob-years	7%	5.7%	10.9%	Harris and Nowara, 1995
Southern New South Wales	Farm production records	2002	12 farms	All mobs on farm (# not specified)	8.6%			Bush et al., 2006
Western district, Victoria	Observational study records (trial flocks only)	2001-02, 2002-03, 2003-04	1 farm	3 mob-years		10.8%		Campbell, 2006
North Island, New Zealand	Observational study records (trial flocks only)	2006 (3.5 months from pre-laming to weaning)	1 farm	1 mob			3.1%	Ghazali, 2007
Victoria, all regions	Farm production records	2009, 2010, 2011, 2012	18 farms	All mobs on-farm (# not specified)	3.5%			Suter, 2013
Northern tablelands, New South Wales	Observational study records (trial flocks only)	2007-08, 2008-09	6 farms	12 mob-years		10%		Kelly et al., 2014
Western district, Victoria	Observational study records (trial flocks only)	2012, 2013, 2014	4 farms	17 mob-years	4.6%	5.0%	4.5%	Kirk, 2016
Eastern wheatbelt, Western Australia	Syndromic surveillance ('sudden death' & 'found dead')	2014-15	4 farms	All mobs on-farm (# not specified)	3.1%			Butler and Loth, 2017

^a Where a range is given (e.g. 1971-72), this indicates a 12-month period beginning in 1971 and concluding in 1972; ^b The total number of mob-years is the cumulative number of ewe mobs monitored on all farms during each study. A mob is defined as a group of ewes that is managed together i.e. kept in the same paddocks, administered the same preventive treatments, etc. In studies of > 1 year duration, the same mob may be represented as multiple mob-years. Mobs of ewes < 2 years of age are excluded; ^c Where the study comprised only Merino or Non-Merino ewes, mortality figures are reported in the relevant breed columns.

4.3 METHODS

The data for this study was a subset of data collected by the surveillance system as described in Section 3.4.1. All reports received between August 2014 to November 2016 from the 31 participating farms that had adult ewes were examined, to understand the relative proportion of sheep mortality reports that involved adult ewe deaths (aged ≥ 2 years at the time of each report). Monthly reports that included ≥ 1 adult ewe death were then extracted and used for the rest of the analyses presented in this chapter, assuming zero ewe mortality in months where a report was received but no ewe deaths reported. These records included the month of the report, number of ewe deaths that occurred, number of adult ewes in the population at risk, and the cause(s) of death (entered as free-text comments during 'period A', from August 2014 to November 2015, and then by selecting one or more suggested causes of death with optional additional free-text during 'period B', December 2015 to November 2016). The level of veterinary involvement for each case was also included in reports in period B.

The ewe populations on these farms were dynamic, with farmers able to purchase and sell ewes throughout the year and with young ewes reaching 2 years of age and entering the adult ewe cohort, typically at the time of lambing. Within a month, the cumulative incidence of mortality was approximated using the number of ewes present at the start of the month as the denominator. Annual mortality rates were estimated, accounting for the dynamics of the population considering the extended time period. The denominator used to estimate annual mortality rates was approximated by taking the mean of the opening and closing flock count figures on each farm for the relevant 12-month period. This assumed that all purchases, sales and deaths occurred evenly distributed throughout the year, on average at the mid-point of the 12 month period of interest.

To identify common causes of death, all reported causes of death were categorised as follows. The free-text comments provided in period A were reviewed manually, classifying them by specific cause where this was provided in the comments, or otherwise 'unknown' cause or 'no comment'. Deaths were of 'unknown' cause when comments did not indicate any particular cause of death or specifically stated that the farmer did not know why the animal(s) had died, whereas 'no comment' was used

when no meaningful text was entered. Where a vague description of the cause of death (including weight loss, age, or sudden death) was given, the cause of death was coded as 'unknown'. In period B, the cause(s) of death selected were examined alongside the free-text comments to verify any specific cause reported by the farmer, with 'unknown' and 'no comment' categories used for deaths without a specific cause as described above. Deaths were then categorised as either reproductive or non-reproductive, based on the aetiology of deaths with a specific cause or on the time of year for deaths without a cause identified. For example, dystocia was always coded as reproductive, and Johne's disease was always non-reproductive. 'Unknown' and 'no comment' deaths were categorised as reproductive if they occurred in the periparturient period as defined below, otherwise were considered non-reproductive.

The 'periparturient' period was defined as extending 2 calendar months prior and 2 calendar months subsequent to the month of lambing start reported by each farm at enrolment. The remaining 7 months of the year were considered the 'non-periparturient' period for each farm. For example, a flock with a lambing start date of August 1st would have a periparturient period from June to October, and a non-periparturient period from November to May. The defined length of the periparturient period took into account the typical length of the lambing period on Australian sheep farms, (5-8 weeks after the lambing start date). The intent was to understand the relative contribution of causes of death associated with reproduction, which are expected to be mainly observed from late gestation (e.g. hypocalcaemia and pregnancy toxemia) through parturition (e.g. dystocia) and early lactation (e.g. mastitis).

The report format asked participating farmers to provide the number of ewes at-risk in each monthly report of ewe deaths, with the intention that this number would be the denominator to calculate the monthly cumulative incidence of ewe deaths.

However, at times the farmers found it difficult to determine the appropriate group of ewes to consider the population at risk, based on the cause of death reported. For example, in some cases where the cause of death was clearly environmental or isolated to one area of the farm, the farmers reported a subset of their ewes (e.g. a single paddock) as the number of ewes at-risk. Consequently, it was necessary to validate the monthly 'ewes at risk' denominator from the reports with periodic stock count figures collected throughout the project. The ewe count from the most recent

stock count in the three months preceding a mortality report was cross-checked against the number of ewes reported at risk in the report itself. Where the discrepancy between the two possible denominators—the routine stock count and the ‘at-risk’ figure given by the farmer for each report—exceeded 10%, and the stock count was greater than the ‘at-risk’ figure, stock count was used as the denominator. In cases where there was no stock count data reported in the three months preceding the mortality event, the population at risk was not corrected and the ‘at-risk’ figure was used to calculate monthly cumulative incidence of ewe deaths.

The annual incidence rate of mortality was investigated on participating farms in two 12-month periods: November 2014 to October 2015, and November 2015 to October 2016. Due to variation in response rate between farms, not all farms provided a report every month. Consequently, mortality incidence rate was only calculated for farms that had an overall response rate > 80%, and only calculated for that subset of farms in years where at least 11 of the 12 monthly reports in each 12-month period had been provided. Consequently, a single farm could contribute zero, one or two years’ data to the analysis of mortality incidence rate, with each farm-year treated as an independent observation for descriptive analyses.

The within-farm incidence rate of mortality aggregated over each year was calculated for 29 farm-years, with the median and range between farms used to describe the central tendency and variability in farm-level mortality. The same method was used to calculate the incidence rate of mortality in each farm-year during both the 5-month periparturient period and the 7-month non-parturient period. To allow comparison, all incidence rates were expressed as ewe deaths per 1000 ewes per month, with Wald 95% confidence intervals calculated to extrapolate to the reference population. Attributable fractions for both the periparturient period (attributable fraction in the exposed) and for periparturient deaths in the year overall (population attributable fraction) for each farm-year were derived from these incidence rate estimates, again described by the median and range.

The farm-year aggregations of mortality as described above were used to test the association between risk factors and mortality using count data regression models. The following farm demographics were included in all models as farm-level explanatory variables: whether cattle were also kept, the number of ewes on-farm at enrolment, the farm’s total winter stocking rate, the sheep production type (wool,

prime lamb, stud rams and stud ewes, including combinations), and geographic area (Gippsland, north-central, and the western district divided into eastern and western regions). A binary variable differentiating deaths in the periparturient and non-periparturient periods was also included in the model.

Poisson and negative binomial models were considered, both with and without correcting for zero-inflation. The raw data of mortality counts were over-dispersed but not zero-inflated, and so were treated as panel data in a random-effect negative binomial regression using the *xtnbreg* function in Stata 13 (StataCorp, 2013). All variables were initially included in the model, based on their univariable association with mortality at $p \leq 0.2$. Visual assessment revealed no substantial associations or collinearity between explanatory variables. Variable selection was then performed using a backwards stepwise approach, removing the least significant variable and assessing for any substantial change ($\geq 20\%$ change) in coefficients in other variables. After removal of all variables that were not statistically significant nor influential on other coefficients, all biologically plausible two-way interaction terms were added to the model. All multivariable analyses were performed using Stata 13.

4.4 RESULTS

4.4.1 PARTICIPATING SHEEP FARMS

The data used for these analyses were from 31 sheep farms with ewes participating in the LANDI project, as described in Chapter 3. The main sheep production types of these farms included 14 wool-producers, 9 prime lamb producers, 6 dual-purpose enterprises with wool and lamb as major outputs, and two stud farms. Two of the wool-producers and six of the prime lamb producers also had an additional 'minor' enterprise breeding rams (2 farms) or ewes (7 farms) for sale, including one that bred and sold both. Fifteen of the farms also grazed cattle.

Several breeds of ewes were represented, including Merino (12 farms), 'first cross' (Merino x meat breed, 4 farms), composite (purpose-bred dual purpose breeds, 4 farms), Poll Dorset (2 farms) and Dorper (one farm), with the remaining 8 farms grazing a combination of Merino and first cross ewes. All farms reported lambing in late winter or spring, except for three farms that reported multiple lambing periods throughout the year (due to stud activities or market considerations for lamb sales).

The median farm area was 500 ha (range 70 to 2900), with median 1500 adult ewes on farm at enrolment (range 65 to 7850 ewes). Five of the 31 sheep farmers had veterinary qualifications, of which two were practicing as veterinarians at the time of data collection and the remaining three retired.

4.4.2 DESCRIPTIVE ANALYSIS OF REPORTS OF EWE DEATHS

A total of 612 reports were received from 839 reports requested in the study period (28 months, from August 2014 to November 2016) from the 31 sheep farms, giving a 73% response rate. Complete records (100% of reports requested) were provided for 9 farms, with near-complete records (74 to 96% of reports) for a further 12 farms. The remaining 10 farms provided reports for <65% of months requested.

Of all reports received from these farms, 371/612 (61%) reported at least one sheep death in any stock class. One or more adult ewe deaths were reported in 240/612 (39%) of all reports with an estimated total of 2106 deaths in adult ewes, representing a median of 4 deaths per month per farm across all positive reports. A small number of reports indicated substantial mortality, with six reports describing the death of 60 or more ewes in a single month, and a maximum of 100 deaths in a single month. The median cumulative incidence of mortality in positive monthly reports was 0.3% (first quartile 0.1%; third quartile 0.8%; maximum 7.3%). Individual farms had only one or two high mortality months (> 1% ewe mortality per month) in a calendar year, with a maximum of 5 above-median months per individual farm and no farms having consistently high mortality.

Of the 240 reports of ewe deaths, the number of death events with reproductive and non-reproductive causes were similar. A death event could include one or more individual ewes. A death event due to reproductive causes was reported in 39% (94/240) of all reports, and a death event due to non-reproductive causes in 40% (96/240) of reports. In 31% (75/240) of reports, no cause of death was specified. Because the categories describing the causes of deaths were not mutually exclusive, the cumulative proportion of death events from reproductive, non-reproductive and unknown causes exceeds 100%. Reports with no specified cause of death included 58 reports where the farmer did not know the cause of death and 17 reports that had no comment provided. In some reports, both a reproductive and a non-reproductive

cause occurred in the same month (for example, some ewes ‘died lambing’ while others died from ‘grain poisoning’, a common term for ruminal acidosis).

The most common reproductive causes of deaths reported were dystocia (38 reports, 29% of all periparturient death reports), vaginal prolapse (18 reports, 14%) and hypocalcaemia (15 reports, 12%), general reproductive-associated deaths without specific cause (34 reports, 26%), and truly unknown cause in the periparturient period (28 reports, 22%), as shown in Figure 4-1. In 11 cases (8%) of deaths in the periparturient period, no comment on the cause of death was provided, so a total of 73 cases (56%) had no specific aetiological cause of death reported.

The most common non-reproductive causes of death reported were flystrike (16 reports, 13% of all non-reproductive death reports), Johne’s disease (16 reports, 13%), misadventure (15 reports, 12%) and toxicities (12 reports, 10%) primarily comprising plant-associated including phalaris toxicity, perennial ryegrass toxicity and facial eczema (Figure 4-2). In 25 reports (20% of reports in the non-periparturient period), the cause of death was reported to be unknown (25 reports), and in 6 cases (5%) no comment on the cause of death was provided.

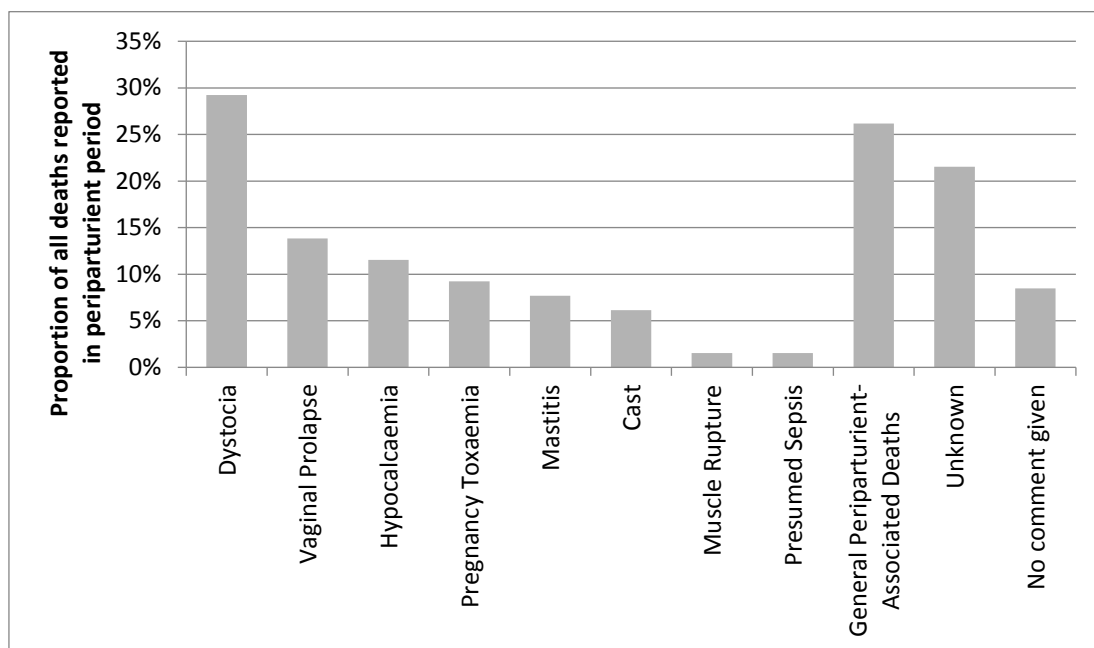


FIGURE 4-1. REPORTED CAUSE OF DEATH FOR ADULT EWE DEATHS IN THE PERIPARTURIENT PERIOD ON 31 SHEEP FARMS IN VICTORIA, AUSTRALIA (N=130 REPORTS).

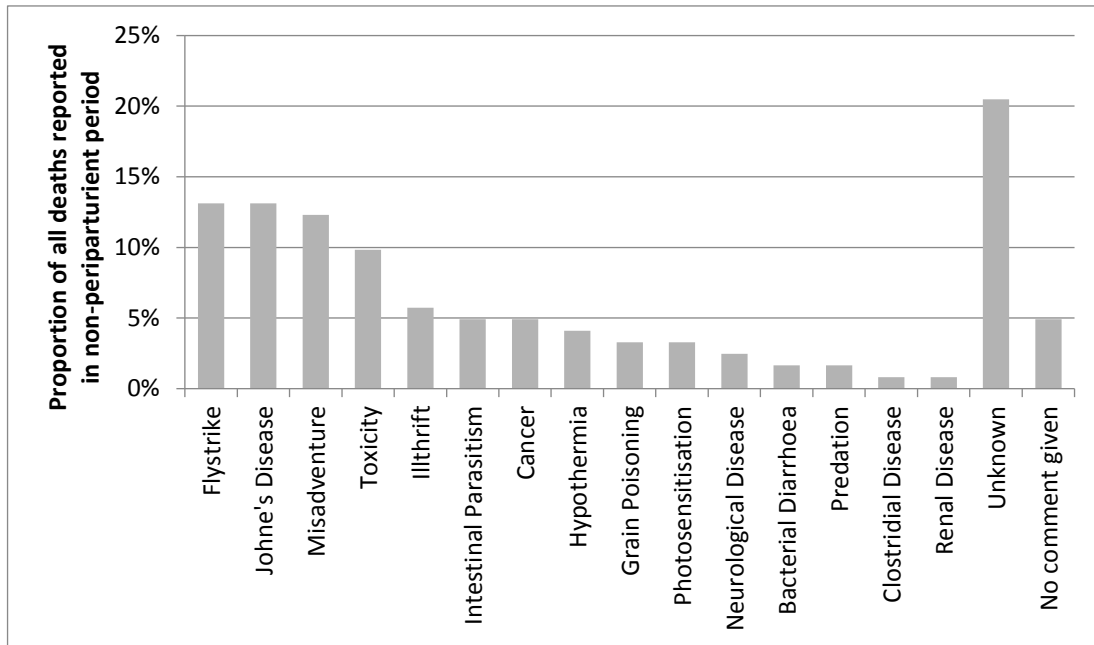


FIGURE 4-2. REPORTED CAUSE OF DEATH FOR ADULT EWE DEATHS IN THE NON-PERIPARTURIENT PERIOD ON 31 SHEEP FARMS IN VICTORIA, AUSTRALIA (N=122 REPORTS).

The level of veterinary involvement was recorded for 86 ewe mortality reports. 29/86 reports (34%) had any veterinary involvement, including 16 reports (19%) where the farmer was a veterinarian. This left just 13/86 (15%) where a veterinarian (other than the farmer) had been involved in the case at all, including seven property visits, two cases with phone advice only, and four where other veterinary involvement had occurred, typically through the provision of medication without a full property visit. The median incidence of ewe mortality in the 57 reports with no veterinary involvement was 0.3% of the farms' total ewe population (first quartile 0.1%; third quartile 0.9%; maximum 7.3%). Of these 57 reports, 27 had at least one death where the cause was either unknown to the farmer (17 reports), attributed to a general reproductive cause (8 reports) or where no comment was provided (3 reports). There were 13 reports with no veterinary contact where the monthly whole-farm incidence of ewe death was 1% or greater, including seven reported deaths of unknown or general reproductive causes, while the other six cases had known causes including fire, grain poisoning, dystocia, and misadventure.

The estimated incidence rate of ewe deaths overall, irrespective of cause of death, was calculated for 29 farm-years, while the estimated incidence rate of ewe mortality in the periparturient period specifically was calculated for 27 of those same farm-years.

Overall, the estimated incidence rate of ewe mortality was 1.8 (95% CI 1.7 to 1.9) deaths/1000 ewes/month, with an incidence of 3.3 (95% CI 3.1 to 3.6) deaths/1000 ewes/month in the periparturient period and 0.8 (95% CI 0.7 to 0.9) deaths/1000 ewes/month in the non-parturient period. However, there was substantial between-farm variation in the incidence rate of ewe mortality. The overall median ewe mortality rate was 2 ewe deaths per 1000 ewes at risk per month (ranging from 1 to 5 deaths/1000 ewes/month). In the peri-parturient period, the median incidence rate of mortality was 3 deaths/1000 ewes/month (range 1 to 10 deaths/1000 ewes/month). In periparturient ewes, a median of 80% of deaths were attributable to the periparturient period (range 14 to 100%). In all ewes, a median of 63% of deaths were attributable to the periparturient period (range 7 to 100%). On 17/27 farm-years examined, over half of all ewe deaths were attributable to the periparturient period.

4.4.3 MULTIVARIABLE ANALYSIS OF RISK FACTORS FOR EWE MORTALITY

The explanatory variables with significant univariable association with mortality rate included time of year (periparturient/non-periparturient), winter stocking rate, sheep production type, ewe numbers on-farm, the presence of cattle and geographic area. Only time of year and winter stocking rate remained statistically significant in the final model, and no interactions were statistically significant. In the resulting model (Table 4-2), the incidence rate of ewe mortality during the periparturient period was 2.8 times the incidence rate in the non-parturient period. Mortality was also significantly associated with the farm's winter stocking rate, with every 1DSE/ha increase in overall farm stocking rate associated with 1.22 times the incidence rate of mortality.

TABLE 4-2. RESULTS OF NEGATIVE BINOMIAL REGRESSION OF ANNUAL EWE MORTALITY, FOR 29 FARM-YEARS OF REPORTS OF FARMERS' OBSERVATIONS BETWEEN NOVEMBER 2014 AND OCTOBER 2016 IN VICTORIA, AUSTRALIA.

		Incidence rate ratio	SE	95% CI	P-value
Time of year	Non-parturient	Ref.			
	Peri-parturient	2.84	0.53	1.98 to 4.09	<0.001
Winter stocking rate	Per +1 DSE/ha	1.22	0.061	1.11 to 1.34	<0.001
Constant		0.18	0.087	0.066 to 0.47	<0.001

n = 58, degrees of freedom = 5, log likelihood (model = -204.3; null model = -224.3), AIC = 418.5. Ref. = reference category; SE = standard error; CI = confidence interval.

4.5 DISCUSSION

This study has estimated the frequency and volume of mortality events occurring in sheep farms in Victoria based on farmers' reports of their observations of clinical syndromes, with ewe mortality described in just under half of all reports received. It was unsurprising that two-thirds of all sheep mortalities reported overall were in adult ewes, as about two-thirds of sheep in a typical flock would be in this age class. Overall, ewe mortality on the participating farms ranged from 1 to 5 adult ewe deaths per 1000 ewes per month, which is equivalent to annual mortality of 1% to 6%. This range reflects typical values cited for annual ewe mortality in southern Australia, for example 3.1% in a comparable syndromic surveillance study in Western Australia (Butler and Loth, 2017) and 3.5% in a sentinel surveillance program on Victorian sheep farms (Suter, 2013). The agreement between these results suggests that the methods for collecting farmers' observations of ewe mortality reported here can produce valid mortality rate estimates.

The results of this study are important for both animal welfare and economic aspects of ewe mortality. Data collected using the reported clinical syndrome approach could help raise awareness of animal welfare and identify where reasonable mortality benchmarks are being exceeded, and therefore action is needed. Additionally, substantial losses in the largest group on-farm can have an important economic impact. Halving ewe mortality on a farm experiencing annual mortality of 5-6% could increase farm gross margin by several percentage points (Mackinnon Project, pers.

comm.), as well as improving ewe welfare on-farm. Depending on the cost and feasibility of intervention, this could represent a substantial benefit.

Overall, a median of 63% of all ewe mortalities were attributable to the periparturient period, with the incidence rate of mortality in the 5-month period surrounding lambing 2.8 times higher than the other 7 months of the year. Despite differences in the definition of the periparturient period, this figure broadly reflects the results of the Victorian sentinel flocks project, where 58% of ewe deaths occurred in the 20-day period around lambing (Agriculture Victoria, pers. comm.). Considering cases in a single month with one or more ewe deaths, parturient and non-parturient causes of death were reported in equal numbers, with just under a third of cases where the cause of death was attributed simply to 'lambing losses' or was unknown. While substantial losses were previously known to occur at lambing (Harris and Nowara, 1995; Ghazali, 2007), enumerating the mortality attributable to this time of year demonstrates the potential benefit of targeting management interventions to reduce ewe mortality at this critical point in the production cycle. Actions to reduce ewe mortality focussed on the months around lambing are likely to have the greatest production and welfare benefits.

Of all the farm-level factors investigated in the multivariable analysis, increased incidence rate of mortality was only associated with increased stocking rate. However, with only 29 farm-years of data available, the model may have been underpowered to detect other, lower magnitude associations. Based on these preliminary data, ewe mortality appears to vary between farms due to factors other than or in addition to scale of operation or enterprise type. The association between increased ewe mortality and increased stocking rate found in this study is well documented (Thompson et al., 2007). It is likely that closer attention to ewe nutrition preceding and during lambing and lactation would be a useful starting point to identify on-farm action to address ewe mortality on farms with above-average stocking rates.

Deaths of unknown causes are commonly reported in mortality studies. One third of deaths in this study were of undetermined cause, similar to figures found for unknown deaths in dairy cows (unknown deaths ranging from 16% to 46%, reviewed by Thomsen et al., 2006), and beef cattle (29.1% of deaths were due to 'other' and unknown causes based on farmers' observations, despite recruiting "better motivated and ambitious" farmers to report (Môtus et al., 2016). The proportion of 'unknown'

deaths from farmers' observations are expected, in part because subtle signs of particular diseases may be overlooked by farmers who are not specifically trained in disease diagnosis. Even surveillance projects administered by trained Agriculture Victoria veterinarians and animal technicians can have a fifth of cases where apart from ruling out exotic diseases, no diagnosis is reached, despite access to advanced diagnostics where required (Agriculture Victoria, pers. comm.).

Common reported causes of death included dystocia, vaginal prolapse and hypocalcaemia in the peri-parturient period, and flystrike, ovine Johne's disease, misadventure and toxicities in non-parturient ewes. These findings were similar to those of the Victorian Sentinel Flocks Project, where post-mortem examination was used to establish the cause of death (Suter, 2013). In that study, the most common causes of ewe death were obstetrical issues (mainly dystocia and vaginal prolapse) and metabolic diseases (hypocalcaemia and pregnancy toxaemia), alongside endemic infectious diseases including abscesses and generalised infections, mastitis, pneumonia, internal parasites and ovine Johne's disease. Both these studies had limited statistical power to detect differences between the prevalence of different diseases (240 cases from 31 farms in our study, and 330 cases from 18 farms in that project). However, the studies demonstrate the challenges of describing causes of livestock deaths on-farm due to the practical limit to the number of cases that can be investigated. Compared to increasing the number of post-mortem examinations performed over a short period of time, collecting farmers' observations could feasibly be scaled-up to increase the size and power of mortality studies within the resource limits available for the study of endemic diseases. Consequently, further investigation of the practicalities of working with syndromic and observational data is warranted.

It is difficult to know how representative the frequency of different causes of death observed in this study are of Victorian sheep farms in general. The proportion of cases of different causes of death in this study may reflect the numbers of these cases in the wider population, but may also indicate under-recognition of certain, less obvious causes of death. This leads to the question, how well does a farmer's diagnosis correlate with the true cause of ewe death? While no data are available for sheep, investigations in dairy cattle using necropsy examination as a gold-standard suggest that farmers correctly identify the cause of death in about half of cases (50-64% of cases in a study in Denmark (Thomsen et al., 2012), and 55% of cases on one farm in

the USA (McConnel et al., 2009)). Considering measures of diagnostic accuracy, observations by pen-riders in the USA monitoring feedlot beef cattle to detect cases of bovine respiratory disease were found to have sensitivity and specificity of 0.2 and 0.92 respectively. This indicates that the cases detected by pen-riders were usually true cases, but that many cases of disease that could be identified at post-mortem were not detected in the pen (Timsit et al., 2016).

The probability of detecting and reporting a cause of death by farmers likely depends on how easily the cause can be determined from inspecting a found-dead carcass. This was true in McConnel's study of a dairy farmer's observations (McConnel et al.), where accidental death was always correctly identified, locomotor causes of death correctly attributed in 83% of cases, but other causes of death were only correct in 41% of cases. Similar variation in accuracy is likely present the current study. For example, diseases with obvious clinical abnormalities prior to death are more likely to be correctly diagnosed, such as phalaris staggers. By contrast, differentiating between death due to hypocalcaemia or pregnancy toxemia is far more challenging, particularly because these two conditions can also occur concurrently. The common reporting of 'lambing losses' without specific diagnosis may have reflected the difficulty in determining the exact cause of death in these cases. To increase the specificity of reporting for causes of death, it may be possible in future to train participating farmers to collect, store and submit appropriate samples to confirm the presence of particular diseases, either in deaths of unknown cause or to look for additional diagnoses, such as the presence of metabolic disease in periparturient mortalities. In summary, information collected using the methods reported in this thesis are likely to provide useful data, but further investigation of the reliability of farmers' observations and potential methods to improve the accuracy of reports would help further enhance the value of the approach.

Farmers contacted a veterinarian in just 15% of cases of ewe mortality. This rate is low but similar to previous studies (Harris and Nowara, 1995; Frawley, 2003), although it has rarely been quantified. Harris and Nowara (1995) previously reported that only 10% of cases where annual mortality was >5% were reported to a veterinarian, with increased mortality associated with greater likelihood of reporting (26% of farms with >10% annual mortality). Unfortunately, in this study the low number of cases where a veterinarian was reported to be involved meant that any

association between the prevalence or causes of disease and veterinary involvement could not be detected. Although not seeking veterinary assistance would be reasonable in cases with an obvious cause to the farmer, such as dystocia and grain poisoning, there were also many cases with no veterinary involvement where the cause of death was unknown. This can be interpreted in several ways: farmers choose not to seek veterinary attention despite not being able to identify why their ewes have died (perhaps because deaths were not ongoing), or alternatively the farmer judged these cases were in unsuitable condition for a diagnosis to be achieved, even if a veterinarian did attend. Although conducted many years earlier, Harris and Nowara (1995) suggested likely reasons for low veterinarian involvement to include “sparse distribution of professional services” in the region and “farmers seeing losses as routine”. Farmers’ behaviour in managing disease, including contacting veterinarians, is investigated in greater detail in Chapter 6. It seems these factors are still influencing farmers’ reporting behaviour today.

This study identified the important challenge of accurately estimating the number of animals in the at-risk population to use as the denominator in cumulative incidence and incidence rate calculations. There were several considerations to these ‘denominator problems’: which animals to include in the population at-risk; inaccuracies determining the number of ewes present on-farm; and the dynamics of the ewe flock, including purchases, sales and the timing of young ewes’ transition to membership of the ‘adult’ ewe group, defined as ≥ 2 years old in this study. It was difficult to determine which animals to include in the population at risk because of the varying epidemiology of different causes of mortality. It was initially intended that the population at risk would be all adult ewes on the farm in the month of the report. However, some farmers felt this misrepresented mortality events that occurred within a single paddock. For example, acute phalaris toxicity can only affect ewes grazing phalaris species pastures, so ewes in paddocks with an alternative pasture species could justifiably be excluded from the population at risk. In this study, regular stock count numbers were used to estimate the total number of ewes on-farm as an alternate denominator where paddock-specific denominators were provided by the farmers. In future, researchers need to determine the group of at-risk animals of interest to meet the objectives of surveillance, including if they differ between different causes of mortality, and then clearly communicate which animals should be included to participating farmers. Even so, periodic or continuous monitoring of the

size of the population on-farm in different stock classes may still be necessary to validate the denominator values obtained.

Even when it is clear which denominator value is required for the purposes of surveillance, regular, accurate stock tallies are difficult to obtain on sheep farms because of the extensive management and typical flock sizes on Australian farms. Ewe numbers are usually determined only sporadically throughout the year, at key management events like shearing or lamb weaning. In the interim, there is no clearly established approach to estimating population size. The use of novel statistical approaches such as capture-recapture (El Allaki et al., 2015), random forest (Nicolas et al., 2016) or Bayesian approaches (van Andel et al., 2017), to estimate population size may assist in determining accurate denominators. However, while these approaches have proven useful for estimating farm numbers or the density of livestock over geographic areas, they have not been applied and optimised to provide sufficient accuracy for estimating populations on individual farms. In this study, because updated stock counts were only available periodically throughout the year, estimating monthly values for ewe-time at risk and using these to generate an overall denominator for each 12-month period on each farm to calculating mortality rates was not expected to substantially improve the accuracy of the mortality rate estimates generated.

The dynamics of the flock were a further challenge, because of variation in the timing of ewe purchases, sales and maturity of young ewes between flocks. This meant that it was not possible to estimate the number of ewes present at the start that were still present at the end of the two 12-month observation periods. Consequently, the number of ewes reported to have died throughout each year could not be compared to the decrease in population numbers over that time, to determine the sensitivity of the system to detect mortalities. The introduction of compulsory electronic identification of sheep in Victoria may enable better enumeration of the number of sheep on a farm (both at individual time-points and changes over time), but will take some years to have its full effect and may not overcome all of the obstacles described here. Further research to evaluate novel use of electronic identification, including the practicalities of automated in-paddock stock counting, would be an important contribution to improve reliability when estimating population size on extensive sheep farms.

The combination of these 'denominator problems' meant that annual incidence rates were estimated based on the average ewe-months at risk, calculated as the mean number of ewes present at the start and end of each defined 12-month period. This assumed that purchases, sales and deaths, as well as the transition of young ewes to adults ewes occurs either evenly throughout the year, or on average in the middle of the 12-month period. However, the periparturient period was in the second half of this period on all farms. Because deaths were more likely in the periparturient period, and young ewes became adults at the start of this period, this denominator approximation will slightly overestimate the incidence of mortality. However, the large number of ewes on most farms meant that small overestimations of the population at risk are unlikely to substantially alter the interpretation of the results of this study.

Using syndromic data to estimate mortality can overcome some, but not all, of the limitations of the other studies described in the introduction. This study takes a whole-farm view of ewe mortality, rather than just focussing on individual paddocks or trial mobs. Nonetheless, selection bias was still present with regard to the selection of farms, because this study was undertaken opportunistically based on the data generated by the LANDI surveillance system where farms were recruited by convenience and willingness to participate (described in Section 3.4.1). The power and precision of estimates in future investigations could be improved by expanding the coverage of the system by recruiting additional farms, both within and between geographic regions of interest. However, selection bias is unlikely to be avoided entirely, because only farmers willing to provide regular reports can be recruited to participate.

This study was also limited by the low response rate for some farms, resulting in an inability to aggregate data for those farms into 12-month mortality estimates or to compare their overall peri-parturient and non-parturient losses. With only 73% response rate and just 39% of responses reporting ewe mortality, it was also assumed that ewe mortality was truly zero on farms who provided reports of zero ewe deaths in a month. However, some deaths may go undetected by the farmers, especially where only one or two ewes succumb in a large mob over the course of the month of reporting. It would have been useful to verify any unrecognised deaths by monitoring changes in stock counts, but this was unfeasible due to the open nature of the adult

ewe population It was also not possible to assess correlation between missing reports and the presence or absence of ewe mortality, to understand how non-response may have affected the incidence of mortality. However, this does not necessarily invalidate the frequency of mortality reported in this chapter. 'Observed ewe mortality', rather than actual mortality, is the measure of interest for farmers who are interested in comparing the mortality they observe on their own farm to industry averages or targets. The type and magnitude of undetected deaths that bias this study are likely to be present when mortality observations are collected on a typical farm.

While the results of this study must be interpreted in light of its limitations, this work has demonstrated the utility of syndromic data to provide additional quantitative information about the occurrence of endemic diseases, including ewe mortality. It also gives evidence to support the observation of low levels of veterinary contact on Australian sheep farms, and estimating the substantial numbers of cases that are not currently captured by surveillance. Furthermore, quantifying the risk of mortality associated with the peri-parturient period highlights the losses associated with this time of year, and the potential benefit of focussing on this period to help farmers reduce overall on-farm mortality.

4.6 CONCLUSION

This chapter has shown that collecting periodic summary reports of sheep farmers' observations of ewe mortality can provide a substantial amount of useful information. Over a third of all farm-month reports indicated one or more ewe deaths, suggesting that ewe mortality tends to occur persistently at low prevalence on many farms. Most of these mortality events would not reach existing surveillance systems that rely on veterinary involvement, as a veterinarian was contacted in just 15% of ewe mortality events. The reasons for this lack of veterinary contact are only partially understood (as described in Section 2.5), but can represent a lost opportunity to improve productivity, sheep health and welfare. The peri-parturient period was a high-risk time for ewe mortality, being associated with 2.84 (95% CI 1.98 to 4.09) times the incidence rate of death when compared to the non-parturient period. No farm-level factors were found to be associated with ewe mortality, suggesting that mortality varies between individual farms rather than due to the farm characteristics that were included in this analysis.

These results demonstrate that structured reports of farmers' observations can give insights into, and quantitative estimates of, the occurrence of disease in livestock, with the added benefit that a sustained longitudinal approach could likely indicate changes in disease patterns over time. The farmers needed to provide only a small amount of data regularly to generate this information, making it feasible and sustainable if an easy-to-use reporting system can be designed and appropriate incentives are associated with participation. The advantages of this approach are its cost-effectiveness and potential to increase the number of farms providing data, especially if cases can be reported without requiring attendance by a veterinarian or other animal health staff. Potential limitations, such as misclassification and recall bias, could also be overcome by triangulating the information generated by farmer-reported syndromic surveillance with other appropriate information, such as smaller field studies and diagnostic laboratory submissions.

This chapter describes a case example that demonstrates the usefulness of data generated in the LANDI surveillance system described in Section 3.4.1. Further investigation of the most effective and sustainable methods for delivering such an approach on a larger scale is needed, as coverage of more farms will improve the quality of information that can be generated about endemic diseases from farmers' observations. This improved information could help to overcome the demonstrated underreporting and scarcity of veterinary contact in disease problems of sheep in southern Australia. The next chapter presents a close examination of this underreporting behaviour in Australian sheep farmers, to provide important context for the deployment of such a system.

Chapter 5.

HOW DO SHEEP FARMERS RESPOND TO SIGNS OF DISEASE IN THEIR LIVESTOCK? A QUALITATIVE INVESTIGATION OF FARMER DECISION-MAKING

PREFACE TO CHAPTER 5

Many disease events on Australian sheep farms are managed without contacting a veterinarian, as shown in Chapter 4. However, the reasons for this are not presently well understood. While barriers to disease reporting have been previously identified, these barriers alone appear insufficient to explain the low rates of veterinary involvement. This chapter presents an investigation of the disease response behaviour of Australian sheep farmers, including both when they seek assistance from a veterinarian, and how they manage disease in the absence of veterinary assistance. A qualitative analytical approach is used to interpret their decision-making process, recognising how the sheep farmers' perspectives and the context of their daily farming activities affect their decisions and actions.

5.1 ABSTRACT

Effective passive surveillance relies on the willingness of those in regular contact with livestock, such as farmers, to report unusual or important disease signs to animal health authorities or veterinarians. Australian sheep farmers infrequently contact veterinarians, which limits the sensitivity of passive surveillance. This study aimed to understand why Australian sheep farmers chose not to contact veterinarians when their animals showed signs of disease, and what alternative approaches they took to managing unwell animals. Established qualitative methods were used to investigate farmers' decision-making processes when facing unusual endemic disease situations. Data were collected during three focus group discussions with sheep farmers in Victoria, Australia. Transcripts of those discussions were analysed using a modified grounded theory approach to develop a preliminary theory of Australian sheep farmers' disease response behaviour. The theory sets the farmers' behaviour within the context of what it means to be a farmer, before describing their approach to 'dealing with the problem'. Critical steps in the decision-making process included the farmer recognising that action is needed and then deciding what that action would be. The farmers reported self-assessing to determine whether they would act independently based on their previous experiences, or alternatively whether they needed to seek advice. Veterinarians played a small but important role as potential advisors, alongside others including trusted farming friends and farmer discussion groups. Self-reliance and confidence in their own knowledge and skills was highlighted as the main reason the farmers often chose not to seek veterinary advice. The accuracy with which the farmers could self-assess their own knowledge and skills was beyond the scope of this study, but plays an important role in the decision whether or not to contact a veterinarian. Despite being described in previous literature, this self-reliance when facing disease has not received sufficient previous attention for its effect on farmers' contact with veterinarians. Rather than being seen as a barrier to effective passive surveillance, the actions that arise from farmers' self-reliance when facing disease should be taken into account when designing novel surveillance approaches.

5.2 INTRODUCTION

One of the major challenges of traditional surveillance methods in the Australian sheep industry is the low rate of veterinary contact. Sheep farmers often choose not to seek professional animal health services when managing disease in their animals, including some situations that a veterinarian may consider 'significant' and worthy of their attendance. Legislation requires suspect notifiable diseases in livestock to be reported to government, but other livestock disease is only reported to veterinarians at the farmer's discretion. The Frawley report (2003) suggested that only around 30% of Australian sheep farmers engage veterinarians each year. This low proportion of disease events that involve a veterinarian is supported by the results from LANDI presented in Chapter 4. This low rate of contact limits the effectiveness of the role veterinarians can play in passive surveillance, as well as having other important effects. The uptake of veterinary advice regarding animal health and farm management can increase farm productivity, leading to economic benefit (Lean et al., 1997). There is also scope to improve the financial sustainability of 'mixed' veterinary practices (those that service both companion animals and livestock) through increased livestock caseload (Frawley, 2003). In addition, Australia's capacity to respond to emergency situations involving farm animals, such as bushfires or exotic disease incursions, depends on veterinarians with experience treating livestock. It is therefore important to understand why farmers often choose not to consult a veterinarian when facing disease on-farm. Potential reasons for low rates of veterinary contact were explored in detail in the review at the start of this thesis (Section 2.5). Synthesis of these previous literature highlighted an important gap in the understanding of farmer's relationships with veterinarians: while barriers to disease reporting have been identified, there is little description of the decision-making process driving Australian sheep farmers' approaches to disease management.

Despite low rates of veterinary contact, Australian farmers generally hold veterinarians in high regard as sources of quality and trustworthy disease information (Palmer et al., 2009b; Hernández-Jover et al., 2016). Despite these positive perceptions, uncertainty remains around the value that veterinarians can add to a farm business, beyond emergency care for unwell livestock and routine disease accreditation testing and reproductive services (Frawley, 2003). Some farmers are also unconvinced that most veterinarians have sufficient knowledge of livestock to

assist in managing disease problems (Frawley, 2003; Wright et al., 2016). Nettle (2017) recently demonstrated that farmers are willing to be convinced of the benefit of farm advisory services. However, in the past Australian veterinarians have been criticised for lacking the ability to 'sell' their expertise in herd health and farm management sufficiently to increase their on-farm presence (Frawley, 2003). Nettle (2017) reported desirable characteristics for farm advisors to include being a trustworthy expert, and having an understanding of the whole farm as a system and a wider perspective beyond individual farms—all potentially fulfilled by a suitably experienced veterinarian. This presents an opportunity to increase veterinary contact, if veterinarians can better understand how their expertise fits into farmers' management approaches.

It may seem surprising that veterinarians are so well perceived and yet underutilised. Several barriers that prevent farmers from reporting disease and, by extension, engaging veterinarians, have been identified in previous studies. These barriers include the stigma of being known as a farmer with a notifiable disease, fear of the consequences of reporting (such as farm quarantine or inadequate compensation for necessary disease control measures), concerns that the cost of a veterinarian outweighs the benefit of a diagnosis, and practical constraints including the distance of the farm from a suitable veterinary practice, and the time and labour involved in having a veterinarian visit (Frawley, 2003; Palmer et al., 2009b; Wright et al., 2016). However, Palmer (2009b) found that the practical barriers to seeking veterinary contact would be overcome if a problem was perceived to be severe enough: "most farmers said they would consult a veterinarian if symptoms were worrying enough, regardless of distance". Higgins et al. (2016) confirmed this attitude, describing how cattle farmers assessed whether a problem was within or beyond their experience to manage. Additionally, in another study of Australian cattle farmers, Lanyon et al. (2015) found there was often "no barrier" to contacting a veterinarian, but simply a question of whether veterinary assistance was considered to be needed. Furthermore, farmers interviewed by Wright et al. (2016) suggested that the stigma attached to having disease was no longer a disincentive to report disease. Perhaps, then, it is not a matter of barriers that prevent farmers from contacting veterinarians, but rather the limited perceived role of the veterinarian in managing most animal health problems.

The role of veterinarians on Australian farms is linked to what farmers see as appropriate ways to manage their land and their animals. Both beef and sheep farmers have reported that vigilantly monitoring their animals for signs of disease is considered an important part of good farm management (Hernández-Jover et al., 2016; Higgins et al., 2016; Butler and Loth, 2017). Farmers also report confidence in their ability to manage disease themselves (Frawley, 2003) and to know when a veterinarian is needed (Palmer et al., 2009b), while recognising that their disease knowledge has a limit (Higgins et al., 2016). Wright et al. (2016) describe farmers considering both the severity and duration of clinical signs to make these judgements.

Australian farmers seem to consider only severe disease problems (those that are ‘unusual enough’) to require a veterinarian’s assistance. This may be partly attributed to farmers’ low perceived risk of exotic disease outbreaks (Palmer et al., 2009a; Hernández-Jover et al., 2016), because of Australia’s strong national biosecurity policies (Animal Health Australia, 2017). Existing Australian studies do not describe what ‘unusual enough’ looks like from the perspective of farmers. Furthermore, it is likely that the threshold for what kind of disease problems require a veterinarian will vary between farmers, based on their previous experiences of endemic disease and their attitude to risk. Understanding how farmers judge whether a problem is unusual enough to require veterinary attention would be useful for the design of new systems or programs to increase veterinary contact on-farm. Although it would be possible to establish farmers’ thresholds for contacting veterinarians in terms of prevalence or specific clinical signs, these are unlikely to be generalisable between farmers or to all disease presentations. It would be useful instead to understand how farmers judge disease situations in general, including contextual factors like previous experiences and how they aspire to manage their farms. This could allow us to understand why farmers rarely contact veterinarians, and to determine whether scope for behaviour change exists.

To describe how farmers decide what action to take in response to disease in their livestock, it is appropriate to consider their responses to endemic diseases, rather than just reporting unusual or notifiable diseases. Some farmers may not have personally faced a problem they deemed ‘unusual enough’ to contact a veterinarian for some years, or even in their entire farming careers. In these cases, questions that focus on disease reporting tend to yield information about what farmers would

hypothetically intend or aspire to do, and may not reflect what they would actually do when faced with an unusual disease problem; intentions are only partially correlated with actions, especially when investigated prospectively (Ajzen, 1991; McEachan et al., 2011). In addition to considering how farmers respond to common, endemic disease situations, it would be beneficial to recognise the influence of broader farm management and farmers' general approaches to decision-making when investigating farmer behaviour. Higgins (2016) suggests considering farm management and decision-making as contextual factors that underpin current behaviour, rather than as barriers to behaviour change. By accepting the broader context of current farm management, strategies that are compatible with that context can be devised, potentially increasing the role veterinarians can play to assist farmers facing disease problems in their livestock.

Further investigation of sheep farmers' decision-making around endemic disease in their livestock is needed, to establish the perceived role of veterinarians on-farm and to understand how the context of farming affects how farmers behave. The studies described above used a variety of quantitative and qualitative approaches to investigate farmer behaviour. In contrast to quantitative research, which typically aims for inference of study findings to a wider population of interest, qualitative research can offer deep insights into the opinions and behaviours of individuals within a population. Qualitative research is useful for exploratory studies, to provide depth of understanding as the basis for future quantitative and inferential research. Because the application of qualitative approaches in veterinary research is presently emerging, a brief overview of approaches and their rationale is presented here.

5.2.1 REVIEW OF QUALITATIVE METHODS

There are a variety of specific approaches which can be described as qualitative research methods. The range of options available may be one of the reasons veterinary epidemiologists have only recently begun using qualitative approaches. When considering any qualitative study, the method of data collection and the method of analysis are two defining features that must be considered. Some examples of recent qualitative work relevant to farmer behaviour and animal health are listed in Table 5-1, identifying how data were collected and the analytical approach taken. This table is intended to be illustrative rather than exhaustive.

Data collection for qualitative research can take several forms including individual interviews, focus group discussions, and questionnaires with free-text fields. Individual interviews are typically conducted using a semi-structured approach. This is where a small number of questions or areas of focus, based on the research questions or a socio-psychological theory, are determined *a priori* to guide the interview. Then, during the interview process, these key questions guide the conversation, with follow up 'probe' questions used to encourage the interview participant to offer greater depth or breadth when describing their experience or opinion throughout the conversation. Examples of probes include 'can you tell me more about...' or 'can you give me an example of that?'. Other less common interview approaches include structured interviews (all questions are asked of all interviewees, with no follow up probes to increase depth) and unstructured interviews (where interviewees are asked to comment on a topic with little guidance to the direction of their commentary). Interviews can be conducted in person, or alternatively by phone or over the internet (for example, using Skype or similar software). Because participants' responses to qualitative interviews are affected by the way questions are asked, and by the rapport between the interviewer and interviewee, how interviews are conducted should be carefully considered.

Focus group discussions are an alternative to individual interviews, especially where it is advantageous to capture the discussion of attitudes or issues within a group as well as individuals' opinions or experiences (Krueger and Casey, 2014). While a group setting can reduce the intimacy and confidentiality of the interview if sensitive topics are raised, if groups are carefully selected and facilitated, they can provide rich data for qualitative analysis. Focus groups are typically conducted in-person, with the quality of the data generated dependent on careful control of group dynamics and contributions by a facilitator. Data generated by either individual interviews or focus groups are often recorded and transcribed for analysis, although the conversation can also be captured through written quotes, notes and impressions (termed 'field notes') made by the interviewer or an observer where recording is not possible or appropriate. Finally, data can be collected by questionnaire, either paper-based or electronically. Qualitative data generated in this way typically relies on free-text fields, and the quality of data generated by a questionnaire depends heavily on careful question wording and piloting of the survey. Questionnaires are less commonly used for detailed qualitative enquiry, as there is limited opportunity to clarify ambiguities

in participants' comments, and no way to elicit elaboration on important points raised during survey completion. Each of the methods of data collection described here may be appropriate for several types of qualitative analysis. However, the intended analytical approach will influence the types of questions and how they are asked, regardless of the method of data collection. Thus, the methodological approach to the research should be planned before any data collection occurs. As with any good research, the specific choice of data collection and analytical methods should be appropriate to the research question under investigation.

Qualitative approaches common in the investigation of farmer behaviour in relation to livestock health include thematic analysis, socio-psychological theories (for example, the theory of planned behaviour) and grounded theory. Each of these will now be briefly discussed, highlighting their defining features, advantages and disadvantages for investigating complex behaviours like farmers' responses to disease in their livestock.

5.2.1.1 THEMATIC ANALYSIS

Thematic analysis is a common method in qualitative research. As described by Braun and Clarke (2006), thematic analysis approaches qualitative data and seeks to identify a number of 'themes' that describe patterns within the data. Braun and Clarke describe six phases to thematic analysis: familiarisation with the data, generating initial codes, searching for themes, reviewing themes, defining and naming the themes, and producing the report of the analysis. Working from initial 'codes' that describe interesting features of the data systematically across the dataset, the researcher clusters related codes together to form themes that structure the notable features of the data in a way that is suitable for reporting. This creates clearly defined themes that tell the overall story of the analysis, illustrated through direct quotes from the participants' responses. Thematic analysis is an approachable and flexible method, being easy to learn and relatively quick to perform. However, the results are typically a detailed description and summary of the data, and tend not to provide a detailed explanation of the underlying causes of the observations, beyond those explicitly identified by the participants themselves. Therefore, thematic analysis may provide a broad but shallow description of the topic under investigation. This does not mean that it is not a useful approach, but does limit its application to understanding the underlying drivers of disease reporting behaviour.

TABLE 5-1. EXAMPLES OF QUALITATIVE METHODS USED TO INVESTIGATE FARMER BEHAVIOUR RELATING TO ANIMAL HEALTH.

Topic	Data collection approach	Analytical approach	Reference
Western Australian farmer disease reporting behaviour	Individual, semi-structured face to face interviews	Grounded Theory	Palmer et al., 2009a
Dutch pig farmer disease reporting (specifically related to classical swine fever)	Focus group sessions, individual, semi-structured face to face interviews, electronic questionnaire	Grounded Theory	Elbers et al., 2010a
Dutch poultry farmer disease reporting (specifically related to avian influenza)	Focus group sessions, individual, semi-structured face to face interviews, electronic questionnaire	Grounded Theory	Elbers et al., 2010b
French organic farmers' relationships with veterinarians	Individual, semi-structured face to face interviews	Grounded Theory	Duval et al., 2017
English sheep and pig farmers' attitudes to disease risk management	Individual, semi-structured face to face interviews	Thematic analysis	Garforth et al., 2013
Australian beef farmers' biosecurity and risk management practices	Individual, semi-structured face to face interviews	Thematic analysis	Hernández-Jover et al., 2016; Higgins et al., 2016
Influence of economic figures for Danish dairy farmer decision-making	Individual, structured phone interviews	Thematic analysis	Anneberg et al., 2016
Australian horse owners' response to Hendra virus	Individual, semi-structured face to face interviews	Thematic analysis	Wiethoelter et al., 2017
French dairy farmers' antibiotic use for mastitis	Individual, semi-structured face to face interviews	Thematic analysis	Poizat et al., 2017
Texas cattle farmers' intent to participate in foot-and-mouth disease detection and control	Individual, semi-structured face to face interviews	Theory of Planned Behaviour	Delgado et al., 2012
English pig farmers' disease control decisions	Individual, semi-structured face to face interviews	Theory of Planned Behaviour	Alarcon et al., 2014
British dairy farmers' cattle disease control and prevention beliefs and attitudes	Individual, semi-structured phone interviews	Theory of Planned Behaviour	Brennan et al., 2016

5.2.1.2 AN EXAMPLE OF A SOCIO-PSYCHOLOGICAL THEORY: THE THEORY OF PLANNED BEHAVIOUR

Socio-psychological theories are also commonly used in qualitative research, particularly when attempting to understand human behaviour. The selection of a theory suitable for a particular study is somewhat subjective. While there are many theories available, this section will focus on the Theory of Planned Behaviour as an example, given that several recent studies related to farmer behaviour have reported this theory as their basis (Delgado et al., 2012; Alarcon et al., 2014; Brennan et al., 2016). The Theory of Planned Behaviour (TPB) was developed by Ajzen (1991), as an extension of their previous Theory of Reasoned Action. The TPB provides a framework to understand decision-making around activities that an individual can plan for – such as whether a farmer will contact a veterinarian about a disease in their livestock. This behaviour will be used as an example to demonstrate the application of the TPB.

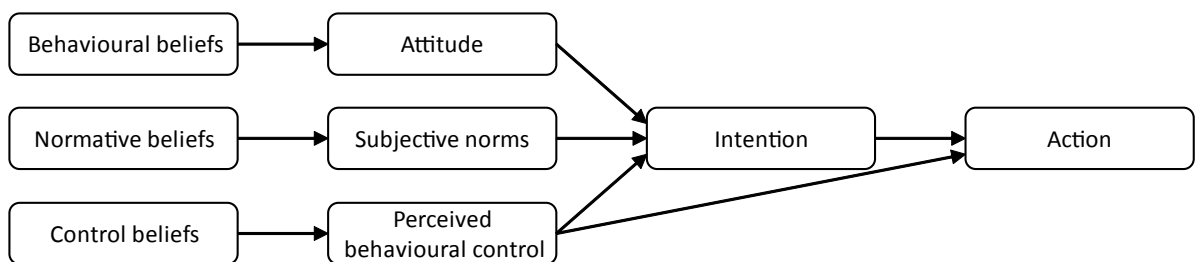


FIGURE 5-1. THEORY OF PLANNED BEHAVIOUR, ADAPTED FROM ARMITAGE AND CONNER (2001).

The TPB describes the farmer’s decision-making process principally through the effect of three factors—attitude, subjective norms (explained below) and perceived behavioural control—on intentions, and subsequently the effect of intentions on actual behaviour (Figure 5-1). The three factors each contribute to the overall intention, and the farmer implicitly compares and weighs these factors as they decide whether or not to contact a veterinarian. The three factors in context are: the farmer’s attitude toward contacting the vet, including both the disease severity and the likelihood of different possible outcomes, if they do or do not call the vet; their subjective norms (perceived social pressures) about how to respond to disease, with the farmer considering how others would expect them to behave, weighted by how influential they perceive those other people’s opinions to be; and the farmer’s perception of their own behavioural control or ‘self-efficacy’, namely the feasibility of

actually contacting a vet, including practical considerations such as time and money. This last concept of self-efficacy is where the 'barriers' to contacting a veterinarian (as described previously) fit into the TPB. Each of the three factors are influenced by the farmer's beliefs: behavioural beliefs, normative beliefs and control beliefs, respectively. All three factors influence the farmer's overall intention to contact a vet, while behavioural control also influences the farmer's ability to convert that intention into action and actually initiate veterinary contact. Of course, when focusing on attitudes and intentions, intention is not a perfect predictor of behaviour – for various reasons, we may not follow through on what we intend and plan to do in a given situation. However, decision-making processes can be better understood through knowledge of decision-makers' attitudes and subsequent intentions.

In general terms, the TPB can be applied in either a qualitative or a quantitative way. The ideal application of the theory combines both approaches, using qualitative investigation to identify the underlying beliefs that drive the farmer's attitudes, subjective norms and perceived behavioural control, and then measuring the effect of those beliefs to determine the quantitative contribution of each to overall intention and behaviour. However, it is also appropriate to use the TPB as a framework to structure a wholly qualitative investigation, to give rich insights into the beliefs of farmers without implying the relative influence of those beliefs on intention and behaviour. In this way, the TPB can be used as a starting point for the design of key questions for qualitative data collection and as initial codes in a deductive analysis of the subsequent data. Other socio-psychological models can be applied to qualitative research using a similar approach (Denzin and Lincoln, 2011). However, there are limitations to socio-psychological models when applied in this way. Frequently, not all of respondents' attitudes or opinions fit neatly into the model, which often leads to authors presenting a 'modified' theory with added factors, such as presented by Delgado et al. (2012), or combining factors from multiple models to more fully explain behaviour, as demonstrated by Garforth et al. (2013). This does not invalidate deductive analysis using a socio-psychological model per-se, but may mean that other influential elements present in the data may be overlooked or not given sufficient attention by the analyst.

5.2.1.3 GROUNDED THEORY

Grounded theory was originally documented as a method of qualitative enquiry by Glaser and Strauss (1967), and has been developed and expanded substantially by many authors in the decades that followed. There are now multiple perspectives on grounded theory, including the 'constructivist' approach described by Charmaz (2014), which is the approach that will be used in this thesis. At its core, grounded theory seeks to take qualitative enquiry to a higher level of abstraction than simple thematic analysis, seeking to make explicit a theory that explains the deep content and implications of the data that is analysed (Glaser and Strauss, 1967). The resulting theory is 'grounded' in the data and the experiences reported by the research participants. It is built using an inductive analytical approach by examining the data for recurring actions and processes described by the participants, rather than imposing factors selected *a priori* on the data, as occurs when a socio-psychological theory is used as a framework for thematic analysis.

Several principles or elements are traditionally employed when grounded theory is used to gather and synthesise information that explains how people experience the world around them. Grounded theory is constructed as a number of 'categories' that explain a concept, rather than simply 'themes' present in the data. Charmaz (2014) describes nine actions that are common to many grounded theory studies, but emphasises that not all studies must undertake all actions. These actions are to:

- Conduct data collection and analysis simultaneously, in an iterative process
- Analyse actions and processes rather than themes and structure
- Use comparative methods (comparing different parts of the data to discover similarities, differences and contradictions)
- Draw on their data to develop new conceptual categories
- Develop inductive abstract analytic categories through systematic data analysis
- Emphasise theory construction rather than description or application of current theories
- Engage in theoretical sampling to achieve theoretical saturation (seeking additional data from both the same and new informants, until additional data ceases to add to the developing theory)
- Search for variation in the study's categories
- Pursue developing categories and a concept, rather than covering a specific empirical topic

Grounded theory is frequently used in an incomplete form, without applying all nine of the principles listed above. Charmaz (2014) views the first five actions as necessary for grounded theory. Such 'modified grounded theory' studies are still considered valid and can represent important contributions to knowledge. For example, when a theory is developed alongside iterative data collection, it is ideal to continue collecting data until further interviews cease to contribute anything additional to the development of the theory (theoretical saturation is reached). However, if it is not possible to continue data collection to this point, a preliminary theory developed from whatever data can be collected may still be a substantial and novel contribution to knowledge, although care should be taken to interpret and use a preliminary theory appropriately.

A defining feature of data analysis using grounded theory is the kinds of codes used to categorise the qualitative data during analysis. Rather than using descriptive codes to identify *what* participants say, grounded theory seeks to apply analytical codes that describe *how* participants experience and respond to a topic (Charmaz, 2014). This is achieved by using gerunds (verbs that function as nouns) in the codes used to categorise the data, for example 'being', 'feeling' or 'responding'. This kind of coding allows the analyst to move beyond description and into conceptualisation, eventually aggregating codes into concepts to then create theory from the data.

The advantages of grounded theory as an analytical approach are its flexibility and the depth of analysis possible. Grounded theory seeks not only to describe the semantic content of the data, but to synthesise both explicit and latent attitudes and opinions, creating an abstracted theory that explains and explores the topic of interest, including how categories arise and why they occur. It is not limited by a preconceived theory being applied to the data. Instead, it can generate a new theory that more comprehensively explains the idea or experience under investigation. This makes it useful for investigating complex behaviour and decision-making processes, when applied with care. However, grounded theory requires skill, is time consuming, and demands researchers to maintain a close working knowledge of the data throughout the analysis so that participants' responses are authentically represented in the resulting theory.

5.2.1.4 SELECTING THE MOST APPROPRIATE METHOD

The most appropriate method for qualitative investigation of human behaviour depends on the depth of understanding that is desired, as well as the agreement of the data with any theory that will be imposed as part of the analysis. The aim is to allow space for the richness of human experience, and avoid projecting pre-conceived ideas or premature conclusions onto research data. In practical terms, it is impossible to be entirely neutral approaching any qualitative study, because the researcher's existing ideas can rarely be kept in complete isolation from data collection and qualitative analysis (Charmaz, 2014). However, these existing ideas should be recognised and challenged throughout the research process, and a method selected that will minimise their effect. Where the drivers of the behaviour of interest are poorly understood, imposing the structure of a socio-psychological theory onto a qualitative investigation risks focussing the researcher's attention on the factors explicit in the theory. If care is not taken, unexpected findings in the true experiences of the participants can be overlooked if they do not fit neatly into the theory being applied. Alternative approaches that allow more space for unexpected influences or concepts will allow a richer perspective to be documented, which can then be used to inform quantitative work when inference to a broader population is desired. For this reason, to better understand the behaviour of Victorian sheep farmers when responding to disease in the investigation, grounded theory was the final analytical method used for this study.

The objective of this study was to describe how Australian sheep farmers decided when to contact a veterinarian about disease problems in their flock, and how they manage disease when a veterinarian is not involved. The study aims to generate deep understanding of the reasons why veterinarians are presently engaged to assist with sheep health problems on Australian farms so infrequently. A better understanding of farmer behaviour will provide the basis to review present strategies and devise new approaches to increase the rate of veterinary contact on sheep farms. While increasing veterinary contact is a challenging goal, it has substantial potential benefits for farmers, livestock industries and government as stakeholders in livestock health.

5.3 METHODS

5.3.1 QUALITATIVE APPROACH

To investigate how sheep farmers respond to disease problems in their animals, a qualitative pilot study of how farmers respond to disease problems in sheep was conducted. In this study, a qualitative approach was expected to give insight into how farmers decide what to do when faced with a disease problem, and why they would choose one approach over another. It was hoped that these insights would help highlight the perspectives of farmers as important actors in surveillance design. This study has been reported in line with recommended standards for qualitative research (Tong et al., 2007). All aspects of this project received human ethics approval from the University of Melbourne (Ethics ID 1545921).

Because this study aimed to understand the different approaches sheep farmers take when dealing with disease, focus group discussions were used for data collection. The interactions between participants that are possible during focus groups make them useful for investigating the range of opinions or perceptions held by research participants, especially when attempting to uncover motivations and behaviours related to complicated topics (Krueger and Casey, 2014). For this study, the group setting was anticipated to help highlight the different approaches farmers take when managing disease problems (Kitzinger, 1994). It would also provide context for discussing why different approaches were chosen by participants. Investigating the diversity of approaches using alternative methods such as in-depth individual interviews was unlikely to produce such rich content for analysis.

5.3.2 INTERVIEW GUIDE DESIGN

The theory of planned behaviour was used as a basis to develop the interview guide for the study. We hypothesised that farmers' behavioural beliefs, particularly the likelihood and severity of different disease outcomes depending on their actions, would inform their attitude to disease response. The opinions of others, including family, friends, professionals and the general public, would provide the basis for the subjective norms the farmers held – those whose opinions they valued would influence their behaviour. Finally, the perceived ability of the farmers to undertake different disease response options, and particularly the barriers to contacting a

veterinarian, would affect both their intent and final behaviour when responding to disease.

The interview guide used for data collection (provided in Appendix D2) was designed as an open discussion with a series of semi-structured prompts. Two types of prompts were used to stimulate the discussion during focus groups: direct questions discussing the sheep farmers' experiences and opinions about responding to disease and contacting veterinarians, and hypothetical disease scenarios. This allowed the farmers to speak both from their own experiences as well as give their opinion of how disease situations should be approached. The hypothetical scenarios (Appendix D3) were designed to reflect uncommon presentations of endemic diseases, where contacting a veterinarian or taking some other approach would both be reasonable actions for the farmer to take. As we expected some farmers to have rarely encountered situations that they felt would warrant a veterinarian's assistance, the hypothetical scenarios used to elicit the farmers to describe how they would likely behave when responding to a disease situation slightly outside their normal experiences. Exotic disease situations were not included, as it has been previously established that most farmers would intend to report rapidly when faced with an exotic disease (Palmer et al., 2009a; Wright et al., 2016).

5.3.3 RECRUITMENT OF PARTICIPANTS

Key farmers, who were known have contact with other farmers in the region through existing farmer groups, were approached to assist in identifying potential participants in the three target geographic areas. These key farmers were not themselves recruited to the study, but were asked to suggest other farmers in the area that might willing to participate in the focus groups discussions (i.e. single-stage snowball sampling). The key farmers first contacted their suggested farmers, to gain permission to supply contact details to the researchers. Potential participants were then contacted by the author phone and/or email and invited to take part in the focus groups. A relationship between the participants and the author was therefore established during recruitment, and participants were informed that the study was about how sheep farmers responded to disease problems in their animals. Recruitment continued until six farmers were available for, and agreed to attend, each of the three proposed sessions.

5.3.4 DATA COLLECTION

Based on the study design described above, three focus group sessions were held with sheep farmers in three major Victorian sheep production regions (Victoria's western district, north-central Victoria and Gippsland). The sessions took place on weekdays in October and November 2016, with one morning group (10am start), one afternoon (12.30pm start) and one evening group (6.30pm start). The timing of the meetings attempted to accommodate the farmers' schedules but also reflected the travel time of the facilitators and the availability of venues. The sessions took place at community meeting rooms in towns central to the participating farms.

Each focus group discussion session was led by a female trained facilitator with extensive experience facilitating farmer groups including for qualitative research. The author also attended the sessions as assistant facilitator, after being explicitly identified as a veterinarian and consultant with the Mackinnon Project during recruitment and this identity reiterated at the beginning of each session.

The sessions were each of 2-3 hours' duration with refreshments provided as thanks for the farmers' participation. No other incentive to participate was provided. On arrival and before the beginning of the discussion, each farmer was asked to complete a consent form and a preliminary questionnaire (Appendix D1) collecting data including age, postcode, major farm outputs, stock numbers and asking the farmers to list their three biggest constraints to production and the most important recent animal health problem they had faced.

The discussion sessions lasted between 1.75 to 2.5 hours. The interview guide included preliminary questions asking the farmers to describe past experiences with responding to disease events and with veterinary involvement on their farms. The farmers were then presented with each of the three disease scenarios, and each was discussed amongst the group, focussing on what actions they would take, why they would choose those actions, and what the potential outcomes could be. Next, the farmers were asked to discuss how the opinions of others influenced their decision-making. Finally, they were asked to list incentives and barriers for sheep farmers to contact veterinarians, and then each farmer was given 5 votes each to rank the most important incentives and barriers based on the list the group had generated.

The discussions were audio recorded and the assistant facilitator also prepared comprehensive field notes during and immediately following each session in parallel with the recordings. A debrief between the two facilitators was conducted after each session with the assistant facilitator taking notes. The audio recordings of each session were transcribed by the author in the week following each session, prior to the next discussion.

One of the purposes of debriefing after each session was to evaluate the thematic saturation of the data. Thematic saturation occurs when the main themes arising from each interview session are being repeated and there is little additional information arising from later groups. In this study, there was little additional material arising in discussion during the third session that had not already been raised by prior groups, and strong agreement between the key themes in all three groups. For this reason, conducting further focus groups drawn from a similar population was considered unlikely to reveal more detail about farmers' approaches to managing animal health problems. Therefore, no additional groups were deemed to be required and data collection was considered complete after the third discussion group.

5.3.5 SHIFT OF THEORETICAL APPROACH

From early stages of data collection, it was clear that the emergent themes influencing farmers' decisions about responding to disease and contacting veterinarians did not fit neatly into the Theory of Planned Behaviour. Specifically, self-reliance was a core driver for not contacting a vet, but could not be adequately described within the behavioural belief or perceived behavioural control elements of the TPB. This was unsurprising, as it is common for many socio-psychological models including the TPB to incompletely explain intentions or behaviour (Conner and Armitage, 1998). However, in this case the themes observed were so discordant with the author's conceptualisation of the TPB that an altered methodology was deemed necessary. Therefore, following preliminary thematic coding of the data, a constructivist grounded theory approach was used for the final data analysis.

The grounded theory analysis conducted in this study undertook all but one of the actions common to grounded theory studies (listed in Section 5.2.1.3, from Charmaz, 2014), with the exception of theoretical sampling. Theoretical sampling requires interviews with additional participants or repeat interviews with the same

participants to be conducted as the analysis progresses. This allows the developing theory to be verified and refined, based on these further discussions, until theoretical saturation is achieved. Theoretical saturation occurs when iterative data collection no longer reveals new dimensions to the developing theory (Charmaz, 2014). Due to practical limitations, it was not possible in this study to return to the participants or to conduct further focus groups to test the developing theory. However, all the remaining actions of grounded theory were undertaken during the collection and analysis of data for this study.

5.3.6 DATA ANALYSIS

All data generated from the focus groups (transcripts, field notes, results from the pre-discussion questionnaire and rankings of incentives and barriers to contacting veterinarians) were imported into Nvivo 11 Pro software (QSR International) for analysis. It was beyond the practical constraints of this study for coding to be completed by multiple researchers. As the author attended and subsequently transcribed the audio recordings for all three discussion sessions, it was appropriate that the author also conducted the analysis due to familiarity with the content and context of the data. To increase validity and reliability of coding, codes and quotations from the transcripts were reviewed periodically by an additional researcher.

Preliminary thematic coding was undertaken to explore the content of the transcripts, reported in Section 5.4.2. This was followed by grounded theory analysis, with data were coded according to the two-stage process described by Charmaz (2014): initial line-by-line coding to reflect the actions and responses of participants, followed by focussed coding to identify all incidents of each code. Concurrent memo writing was undertaken throughout the coding process, to define and clarify the emerging codes. Those codes were then explored for commonalities and variation using a process of constant comparison between groups and between participants, to finally elicit a theory that sufficiently explained the farmers' rationale for deciding when a veterinarian was required. Particular focus was given to themes that had not already been identified in prior literature, or were contrary to previous research findings (reviewed in Section 2.5), as these themes represent the novel contribution of this study to existing knowledge on farmers' disease management and decision-making.

5.4 RESULTS

The results of this study are presented in three sections: descriptive characteristics of the participating farmers, core themes emerging from thematic coding regarding veterinary contact on sheep farms, and a preliminary theory of sheep farmers decision-making when facing disease in their livestock which resulted from the grounded theory analysis.

Quotes presented in these results are taken verbatim from the transcripts of the discussion sessions, and are accompanied by a non-consecutive participant identification code designating the session and individual participant (e.g. A1 meaning participant 1 from session A). The term 'vet' is a common Australian abbreviation for veterinarian and appears in several quotes from the transcripts.

5.4.1 PARTICIPATING FARMERS

In total, 33 farmers were identified to be invited to participate in the focus groups (western district 13, Gippsland 6, north-central 14). Of these, 3 could not be contacted by the phone numbers provided, 3 were not interested in participating, and 9 were not available on the day/time the groups would be run. Six farmers agreed to attend each of the three sessions giving a total of 18 farmers, but at late notice 5 were unable to attend, including three female participants. A total of 13 farmers therefore participated in the groups (five in the western district group, four in the north-central group and four in the Gippsland group).

All participating farmers were male sheep producers (prime lamb and/or wool), and ten also ran cattle. Sheep numbers on their farms ranged between 1000 and 14,000 (median 3,200 sheep), on properties of 215 to 1700ha in area (median 640ha). All participants were male, with an age range between 36-79 (median age 57). The geographic distribution of the participants' farms by shire is shown in Figure 5-2.

When asked to list their three biggest issues or constraints to farm production as part of the pre-discussion questionnaire, ten of the thirteen farmers cited weather/seasonal variability (7/13 farmers) or pasture production and feed availability (4/13) as major issues. Other common issues reported were labour availability (4/13) and input costs (4/13). Only three farmers identified animal health

problems in their three biggest issues, with two specifically referring to intestinal worms of sheep rather than any other health problem.

During the discussion sessions, the farmers were asked to describe their most recent contact with a vet. Five reported farm visits by veterinarians in the preceding 2-3 years for routine veterinary work (such as brucellosis accreditation or prescriptions for sedatives for shearing rams), and five others reported they had only spoken to a veterinarian by phone in that period (including submission and reporting of worm egg count testing). Only two of the thirteen farmers reported having a veterinarian visit the farm to investigate or treat a sheep health problem in the preceding 2-3 years, with one other farmer having delivered a sick sheep to a veterinary practice in that time.

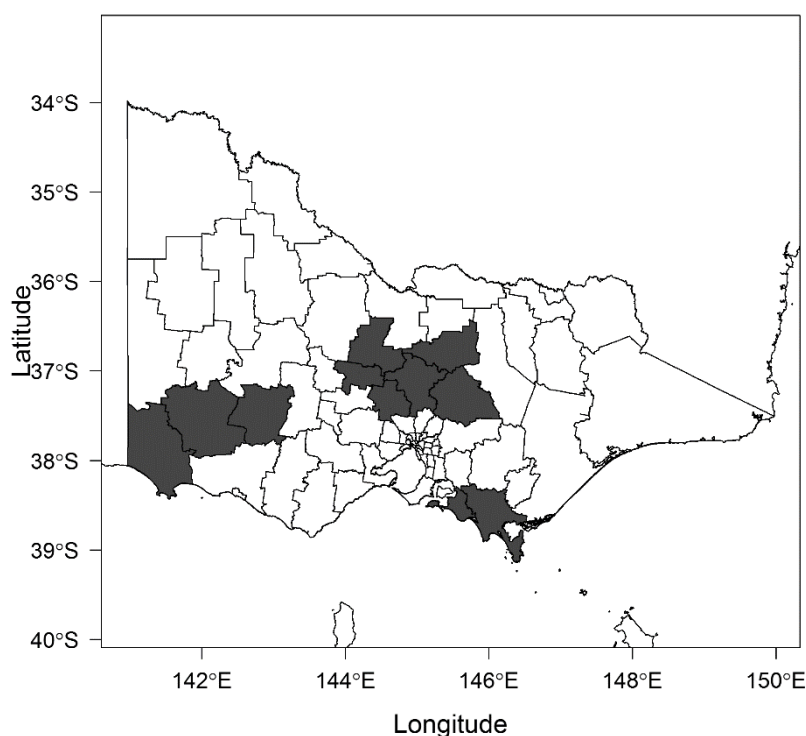


FIGURE 5-2. SHIRE LOCATIONS OF FARMS FOR VICTORIAN SHEEP FARMERS PARTICIPATING IN FOCUS GROUP DISCUSSIONS OF DISEASE RESPONSE BEHAVIOUR.

5.4.2 MAJOR THEMES REGARDING VETERINARY CONTACT

Preliminary thematic coding identified five important themes related to veterinarians throughout the three discussion sessions: that veterinarians are needed when the cause of illness is unclear, the value of veterinarians for sheep farms, the complexity of

'barriers' to contacting veterinarians, the effect of cost when farmers consider contacting veterinarians, and the farmers' preference to contact veterinarians by phone rather than requesting farm visits.

5.4.2.1 VETERINARIANS NEEDED WHEN CAUSE OF ILLNESS IS UNCLEAR

The farmers in all three focus groups reported that the main reason to contact a veterinarian was when the cause of illness was unclear. This was evident in their comments during the discussion and was reinforced when they were asked to list and rank motivators for contacting a vet.

"It's when we can't work it out ourselves, that's when we're gonna say, 'ok, we've got, the sum total of [local] sheep knowledge in the car, and we can't figure out what's going on, we're gonna call in a vet.'" (B5)

The converse was also true; the main reason the farmers would not contact a veterinarian was because the cause of illness was clear. They reported confidence in their ability to diagnose common problems and did not need assistance in these cases, based on their previous experiences and knowledge. In many cases, this knowledge has been accumulated and passed down through generations of family farming the same land.

"I grew up in a situation where the vets weren't skilled in sheep anyway, so... well, I started to pick up, every time I read something, I tried to store it away, and draw back on it." (B6)

If new disease problems were similar to the farmer's past experiences, they would simply deal with the disease themselves, using the same actions as they had taken in the past.

5.4.2.2 VALUE OF VETERINARIANS FOR SHEEP FARMS

The farmers felt veterinarians were trustworthy sources of animal health information. It was seen to be worth contacting a veterinarian if the cause of a problem was not clear. Prompt veterinary advice when facing an unfamiliar or unusual disease was expected to minimise losses.

"If his diagnosis is quick enough, and correct, that's a good outcome. You can deal with the problem, or hopefully deal with the problem." (C4)

A veterinarian's professional diagnosis also offered peace of mind in the face of a stressful disease situation, which was seen as a valuable contribution to farmers' wellbeing.

"It's a real worry when you don't know what's, what they're dying of. I think we've all had a lot of experience and usually you can diagnose it, but when it baffles you, you know, it's really good for [the vet] to come back and say, 'well you're right, it wasn't worms, it was such-and-such', you know what I mean. That's very reassuring." (C5)

The broader perspective of veterinarians was also valued. Veterinarians were recognised as having district knowledge of disease patterns which the farmer would not otherwise have access too. Knowing what diseases were occurring in the area was seen as valuable for confirming a diagnosis and determining what treatment or action would likely be efficacious in dealing with the problem.

"While you're sort of got your own myopic focus on your patch of land, [the vet] will be getting calls from sort of all over the district." (A7)

"Generally when something like that's happening, it's not just generally a one-farm problem. I think it's probably more of a district problem and the vet would be on top of it, he'd probably say, well this is, what you tell him the symptoms are, and he'll say "well that's very similar to, there's a fair bit of this, such and such, happening" and that's probably what it is." (A1)

The farmers suggested that 'good vets' also understand the complexities of farming enterprises. While not expected to advise on agronomy or farm economics, veterinarians were valued when they were able to refer farmers to other professionals to help manage the underlying causes of disease from a whole-farm perspective.

"Treating those ones that you've got, then going, well look, what's your fertiliser regime, what's your pasture growth... farmers that might not be up to snuff with those sorts of issues, [vets] can just quickly, maybe steer them in the direction of people they need to talk to, or just give them a quick overview." (B2)

Overall, veterinarians were perceived positively by the participating farmers.

5.4.2.3 'BARRIERS' TO USING VETERINARIANS ON FARM

Potential 'barriers' to contacting a veterinarian were discussed in all groups, including the cost of veterinary visits as well as fear of harm to their enterprise or reputation. However, the farmers did not identify these individual barriers as major influences when deciding which problems required veterinary attention. They did recognise that stigma or fear around reporting a disease problem could influence the decisions of other farmers, but that overall this attitude was reducing over time and did not apply to themselves.

"The really bad [potential disease situations] are they find something disastrous and quarantine you... I think most people now are aware enough that you can't hide these things, so you've just got to bite the bullet, call the vet or call the authority." (A3)

"I suppose like those, Johne's or those sorts of diseases, do you get it diagnosed, or do you just shoot them and bury them, and pretend you haven't got it I guess. And a lot of those diseases people talk about, like footrot I think in the old days, you probably used to hide that."

"Bit of a social disease."

"But I think we're all over that, and it's just the reality of, it's just something you deal with and you get on with life." (B4, B5)

Importantly, veterinary advice did need to be timely for it to be of value. Being able to act quickly was critical, so the farmers could minimise their losses from a disease problem. If a consultation could not take place for several days after the farmer's initial enquiry, farmer must still act in the meantime, reducing the value of the veterinarian's visit. If the farmer anticipated the veterinarian would be unlikely to attend or advise in a timely manner, they were less likely to make the effort to contact them, opting instead to take whatever action they felt was most appropriate.

5.4.2.4 FARMERS' PERCEPTIONS OF THE COST-BENEFIT OF VETERINARY SERVICES

While not strictly a 'barrier' to using veterinarians, the farmers did report consideration of the cost of a veterinary visit against the likely benefit it would bring. The benefit they could identify was determined by their previous perception of what the disease problem was costing them. Not all farmers recognised the sub-clinical or

production losses that may be occurring alongside clinical cases or deaths. Nonetheless, in cases where a problem affected or was likely to spread to multiple animals, the cost of a veterinarian was often justified by the benefit of early diagnosis and effective treatment.

"I'm happy to [pay for a vet] if it means that there's, there is an issue and it could potentially spread to the ones that are actually ok at the moment." (B2)

"If you save a couple of ewes you'll pay for the vet." (A3)

The farmers also recognised the intangible benefit of a veterinarian's assistance to give them peace of mind.

"And it's potentially a threat to your whole enterprise... if 20% here are suddenly are lost, it's a significant financial outcome, so the relatively small cost of the vet, hopefully successful encounter with the vet is a big payback, and it's sort of mental reassurance for me as well" (A5)

The combination of likely economic benefit as well as reassurance meant that the farmers generally held positive attitudes to calling a veterinarian, despite what it might cost.

"I think if I've made a decision to call a vet, I'm not really worried about the cost." (A4)

It seemed that, rather than being deterred from contacting a veterinarian by 'barriers' or practical constraints, the decision to contact a veterinarian had often already been made before these factors were considered.

5.4.2.5 FARMERS' PREFERENCE FOR TELEPHONE CONSULTATIONS

Once the farmers had decided to contact a veterinarian, they distinguished two types of contact: calling a veterinarian by telephone to discuss their observations, or calling to requesting the veterinarian to visit the farm.

"Can I just clarify, when I said ring the vet, I wouldn't ring him to get him to visit. I'd just ring him and say, what do you think, this is what I'm looking at." (B4)

"If I was going to, I wouldn't go and get the vet, I'd just ring him, say this is happening, say, he can just confirm what I suspect." (A7)

In most cases, farmers preferred phone calls as the way to receive veterinary advice. A call could also be accompanied by submission of diagnostic material such as faecal samples or delivery of a carcass for post-mortem examination.

"We are in constant contact [with our vet] with worm egg counts, but that's mainly done over the phone, so we take samples and then... yeah, [they] give us feedback on that." (A5)

Physical visits to farm by veterinarians were generally reserved for sporadic routine work such as health certification, brucellosis screening tests or prescribing drugs such as sedatives for shearing rams. The farmers rarely saw the need to have a veterinarian actually attend the farm to investigate a disease problem in their sheep.

"We've had just about every disease known. Like mostly these metabolic things, ryegrass staggers, phalaris sudden death, phalaris staggers, phalaris everything – and all have been identified more or less over the phone." (A3)

Phone calls were advantageous because they were affordable (often free) and provided immediate advice for the farmer to act on. Speaking to a veterinarian on the phone could increase the farmer's confidence in their own suspected diagnosis and the course of action they were choosing. This related to the findings, above, that farmers sought peace of mind and needed to act quickly to control disease. The main attraction appeared to be in helping farmers to sort out their problem rapidly over the phone, rather than just because a phone consultation was usually free.

5.4.3 THEORY OF SHEEP FARMERS' DISEASE DECISION-MAKING

The thematic findings above described several aspects of the role of veterinarians on farm, but did not explain the way the farmers actually made the decision to either contact a veterinarian or not. To extend these findings, a theory describing the general decision-making process of the participants was derived from the data. The theory, set in the context of what it means to be a farmer, describes the general process the farmers used to work out how to respond to disease, or 'deal with the problem'. Importantly, not all occurrences of disease are considered 'problems' by farmers, and not all disease 'problems' on-farm are recognised or detected.

For diseases that were seen as problems, the farmers' decision-making process had several distinct steps (Figure 5-3). First, the farmer needed to recognise action was

needed, which would prompt them to determine what that action would be, leading them to assess whether the problem was within or beyond the limits of their experience and knowledge. Based on their self-assessment, the farmers chose between two options: either taking a self-reliant approach to deciding what action was needed, or seeking advice on the action required from others including veterinarians. Either option led the farmer to identify and take action that they judged was appropriate. After acting, they re-evaluated whether the action had been effective or not in resolving the disease problem. If the problem was not resolved, the farmer would return to the beginning of the process, recognising that further action is needed.

When the decision-making process recurred, the likelihood that the farmer would choose to seek advice increased. Dealing with a disease problem that was not resolved with the first action taken could become an iterative process, eventually resulting in a veterinarian becoming involved if the farmer could not resolve it independently. Each of these steps will now be described in greater detail, using quotes from the focus group participants to illustrate each stage of decision-making.

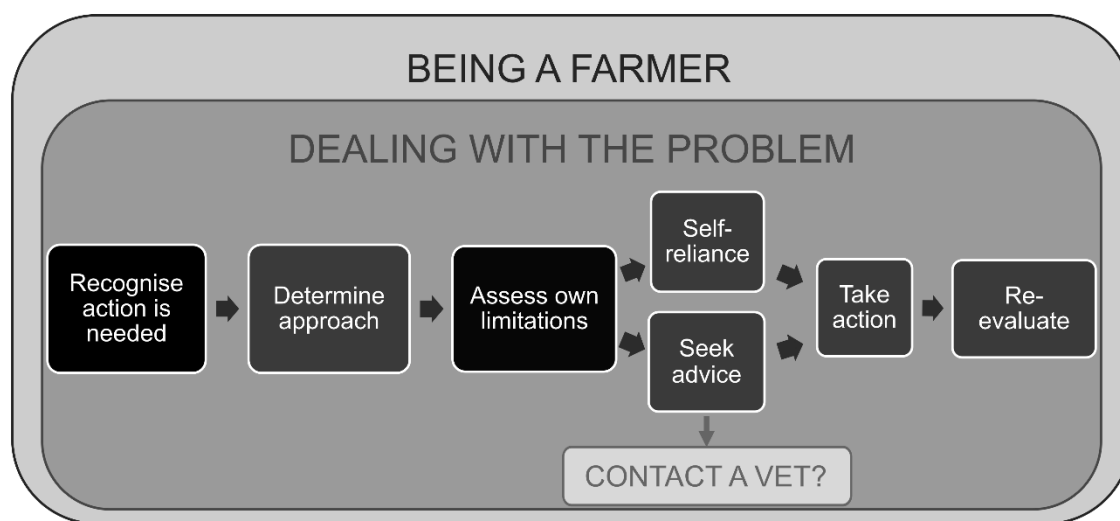


FIGURE 5-3. SCHEMATIC REPRESENTATION OF SHEEP FARMERS' GENERAL DECISION-MAKING PROCESS WHEN FACING DISEASE PROBLEMS.

5.4.3.1 CONTEXT: BEING A FARMER

The disease response behaviour of the farmers was underpinned by their own ideas of what it means to be a sheep farmer. This context included 5 elements: having history on their land, responding to environmental unpredictability on their land, the importance of getting farm management right, seeing problem-solving as part of farming, and managing risk.

Their history on the farm contributed to the farmers' approach to understanding and managing disease problems. The cumulative knowledge of years on their land, along with knowledge passed down from older generations of their families who may have farmed that land, was the basis for their knowledge of how to respond when common diseases occurred.

"You have that instinct, you've been with it all your life which most farmers generally have, there's not many people just go out and buy a farm and start farming, and if you're the second, third generation brought up and taught this since they can walk and they have that intuition, they quite often know [the cause of a common problem] themselves." (A7)

The environment, including climate, rainfall and weather events such as fire or storms, was recognised as a strong contributor to disease occurrence. These environmental conditions were known to vary between years, and were out of the control of the farmers.

"It's very, very wet country, lake country, I don't know why you farm there sometimes but – especially in the years like this we're underwater, but that's part of the things that happens with farming I suppose, one of the elements we can't control, and if we could we'd be really happy." (A1)

They reported that many cases of disease were triggered by environmental conditions such as flood or drought, which were unlikely to recur in the following year.

Therefore, for disease problems associated with these weather events, there was little need to develop a preventive strategy for the future and therefore limited value in follow-up investigation of these cases.

The farmers' comments also demonstrated how their years of experience farming has led them to identify links between environmental conditions and disease occurrence.

When discussing common disease scenarios, the farmers readily suggested likely causes of disease based on their interpretation of presenting clinical signs, time of year and recent weather events.

"If you see a sheep limping, you mentally go through... wonder what's causing that, and nine times out of ten it's abscess this time of year. Different times of the year it can be different things." (C4)

"And those sort of conditions, where it's dry feed, then a green pick, summertime, warm conditions, moisture, it's a recipe for barber's pole [worms]." (B6)

The farmers emphasised how important it was to get farm management right to avoid disease, especially when managing sheep. They recognised that disease was likely to occur if they neglected basic animal management such as nutrition, vaccination against clostridial diseases and gastrointestinal worm control.

"...sheep are a lot less forgiving than cattle, and you've gotta have those basics right with sheep. You can't afford not to have your minerals up or your worm tests done." (B5)

As well as being important for avoiding losses, good farm management was also described as a basic responsibility for farmers. It was the farmer's duty to take actions to reduce disease occurrence in their animals, even if the economic benefit was likely to be marginal.

"I don't know that [the value of individual animals] really matters, like, you're in charge of your sheep, you're responsible, so you've gotta address [disease problems you identify]. If you're not, you're failing." (C1)

Problem-solving was also described as an important aspect of farming. Minor problems were commonly faced on-farm, and these problems had to be dealt with effectively to minimise their effect on productivity. The farmers recognised that people who do not enjoy problem-solving are unlikely to be motivated to keep farming long-term. Some participants emphasised problem-solving as a major part of their enjoyment of farming sheep.

"I'd like to work it out myself. Not can, I don't know whether I can work it out myself, but I like to." (B6, participant's emphasis)

By contrast, others reported their desire to simply get problems such as disease solved, so they could focus their energy on other parts of farming they found more enjoyable.

"I just see [sheep disease] as a bloody headache, [call the vet,] 'what've I gotta do?' Give me a solution and we'll just move on, we'll treat it and we'll get on with life." (B4)

Risk appetite and the desire to engage in problem-solving can vary between individual farmers, and will be reflected in their farm management decisions such as how they source replacement stock. The farmers recognised that, while risks can rarely be eliminated entirely, the decisions they made and the way they managed their farm could effectively reduce the risk of disease introduction.

"I'd be more cautious if I was, sort of, trading sheep, bringing in sheep, but most of my sheep are all born on-farm, so we're sort of, like a restricted flock. Only thing I'd have to worry about is what, if something's come through the fence from a neighbour or something." (C1)

When facing an issue on-farm, the farmers were motivated to 'deal with the problem', to look for corrective action that can eliminate the identified issue. This applies to both general problems encountered in farming, but also specifically to livestock disease problems. The following sections will describe each step in the process farmers take to deal with disease problems in their sheep.

5.4.3.2 RECOGNISING ACTION IS NEEDED

Before a farmer decides how to deal with a disease problem, the farmer must first identify the problem and decide that action is needed and worthwhile. There are three elements to recognising the need to act:

- The disease must be recognised and detected by the farmer (problem identified)
- The disease must be judged as unacceptable and requiring action (problem worthy of action)
- The farmer must feel it likely that they can take action to improve or resolve the problem (likelihood of efficacy)

Only when all three elements occur will the farmer then consider and decide what action to take. If any of the elements does not occur, the farmer will (knowingly or unknowingly) tolerate the disease in their animals.

If the farmer does not recognise that a disease is occurring, they are not able to act on it. Diseases that have subtle clinical signs or where losses are not visible to the farmer may not be detected by the farmer. Routine observation and monitoring of their sheep was seen as part of good farm management, but the farmers recognised that it was still possible for disease to be overlooked, especially if it occurred at low prevalence or sporadically. The size and topology of paddocks and the presence of predators could also make it hard for every case to be detected for some diseases.

“[Other farmers] live with [infectious abortions], I don’t think they really realise the production losses that’s happening... and then if you don’t see [the sheep] every day, the foxes and crows pick up the foetuses, so you’re not actually seeing it” (B6)

Once the farmer recognised that disease is occurring, they would then judge whether the disease is a ‘problem’. They felt that a very low incidence of diseases or deaths could be a normal part of farming sheep. This was especially true when illness or deaths were isolated to single animals.

“You’ll go into a paddock and pick up a dead sheep, and everything is running around looking healthy, and then a week later you go and then there might be two dead ones. So, I just put it down to sheep being sheep.” (B4)

If the problem was unlikely to affect the rest of the flock, it was also unlikely to trigger investigation or preventive action. However, when disease began to affect multiple animals or had potential to spread between individuals, the farmers would begin to consider it a problem where action was likely needed.

“Identifying whether the problem’s a problem of that sheep or a problem of the flock, is the challenge.” (C3)

The farmer’s judgement of the magnitude of a disease problem could be constrained by their record-keeping practices. If isolated cases were occurring but not recorded, the farmer might overlook a disease problem that they would otherwise judge as

needing action. This was described as a practical limitation, linked back to how busy farmers are managing the many other activities of running the farm.

“Unless you keep a record of how many ewes you take away, you’re that busy doing other things, and you could drag two away one day and three another day, and you wouldn’t sort of, remember it, if you know what I mean.” (C5)

After the farmer identified the disease and determined that it was a problem, they would then assess their ability to influence the disease problem—estimating the likely efficacy of actions they could take. The farmers reported experiencing situations where they were confident of the cause of illness or deaths in their sheep, but their past experiences suggested that there was no effective action that could be taken to treat affected animals or prevent further cases.

“I guess the most frustrating thing is, that twin lamb disease. Your sheep are often in really good nick, and it doesn’t matter what you do, they just don’t get any better. You can’t, you know, pump stuff into them. You can’t fix ‘em.” (C4)

If they believed that there was no effective action that could be taken, the farmer would not proceed to the rest of the decision-making process, but rather tolerate the disease problem in their animals. By contrast, if they felt that there might be something that they could do, they would proceed to the next stage of the decision-making process, which focussed on determining what the most appropriate action would be.

5.4.3.3 DETERMINING APPROACH

Having recognised unacceptable disease problem and judged that they might be able to do something about it, the farmer must then determine what is going on and what action they might take. The farmers emphasised that their approach to the disease problem must be established as quickly as possible. Prompt action is valued, both to resolve the farmer’s concern about the problem and to minimise losses.

“If you’ve got something that you think’s critical, and you can see a way forward, you want to try something straight away. You want to resolve your problem as quickly as possible.” (C4)

Getting an exact (aetiological) diagnosis for the disease problem was not intrinsically valued by the farmers. Rather, they wanted to understand the cause of the problem

sufficiently to identify the most appropriate action needed to 'deal with the problem'. If the appropriate action could be determined based on a provisional diagnosis, further investigation was seen to have limited value.

5.4.3.4 ASSESSING OWN LIMITATIONS

To determine what action should occur in response to the disease problem, the farmers first assessed how the problem aligned with their previous knowledge and experiences. This was primarily to determine whether they needed additional assistance to deal with the problem, or whether they could independently determine an appropriate course of action.

"You've gotta work out what you know and what you don't know." (A3)

For common disease presentations, the farmers often felt confident that they knew the cause of the disease problem and the necessary course of action, and could take a self-reliant approach.

"Yeah, like, ewes die, that happens. But you can usually, 'oh yeah, that's what it was'." (C3)

However, if the cause of the problem was not clear to the farmer, they were motivated to seek advice from others to help determine what they were dealing with.

"I guess number one [reason to seek advice] is, you don't know the cause or you don't, you can't identify what the problem is." (C1)

The farmer's perception of whether the disease was similar to their previous experiences or knowledge was the main driver to choose between being self-reliant or seeking advice.

5.4.3.5 SELF-RELIANCE

The farmers reported feeling capable of dealing with many sheep disease problems themselves. When the farmer could confidently identify the likely diagnosis for the disease problem, and knew some appropriate action to take in response to that diagnosis, they would go ahead and act. Again, there was perceived value in acting promptly to deal with the problem. The benefit of fast action was a major reason not to seek advice unnecessarily when the farmer was confident in their own knowledge and experience.

"I'm gonna open their mouths and look at their gums, push in on their gums and see what sort of response I get to the blood rushing back into the gums, and probably from that I'm gonna assume it's barber's pole worm. But I wouldn't call a vet, I'd drench them with cydectin, or another 'mectin.'" (B5)

When managing disease in a self-reliant approach, the farmers drew on the cumulative understanding of disease and experiences of treatment efficacy they had gained over their farming career. The farmers suggested therefore that farmers with less experience might be less likely to rely on their own knowledge and would be more likely to seek advice and additional knowledge before taking action. By contrast, very experienced farmers would readily recognise the cause of the problem and be able to determine whether, and what, action was needed.

"It depends where you are in the learning curve. If you've been going for 5 or 10 years you might think, like my son is, and he'd be out there googling and ringing everyone and checking things out, I'd just say, 'oh, crap year', you know, we've had it before and probably better next year." (A3)

When diagnosing disease problems in their own sheep, the farmers assumed that they had the necessary information to make an accurate diagnosis. They felt that their experience and intuition would be sufficient to recognise the important aspects of the case, and that they would observe affected animals closely enough to recognise both the clinical signs and any changes or progression of the disease problem.

"Your senses would be heightened anyway, and you wouldn't be just observing then, you'd be more constant, particularly with those mobs and also with your other mobs as well." (A6)

There was no mention of the possibility that they might overlook subtle clinical signs or risk factors that would differentiate between multiple possible diagnosis, or that there might be possible diagnoses that they were not aware of.

Each farmers' self-reliant approach had been developed over decades or even multiple generations of farming. Several farmers attributed the development of this approach, at least in part, to a historical lack of sheep veterinary services in their area.

"This is the whole problem we came up right against at the start, it's that lack of veterinary experience with sheep in this area, you know?" (B5)

Some farmers also described building their approach through reference to veterinary textbooks and experimentation with different treatment approaches to recurring problems over some years.

"I grew up in a situation where we had to sort of lean on other farmers' experiences, and I got the Hungerford vet book when I was twenty or twenty-one, and I used that a heck of a lot to read what was happening. I grew up in a situation where the vets weren't skilled in sheep anyway." (B6)

They felt that the combination of these activities gave them the knowledge, experience and confidence to deal with familiar disease problems independently.

5.4.3.6 SEEKING ADVICE

As an alternative to the self-reliant approach described above, the farmers could decide seek advice about the signs of disease they were observing. The farmers were motivated to do so when they recognised they had reached the limit of their own knowledge and experience. Through seeking advice, the farmers primarily sought to increase their confidence in their interpretation of the disease problem, and gain peace of mind about the actions they were considering taking in response. There was also intrinsic emotional value in sharing the problem with someone else.

"Probably, if you couldn't get to the bottom of it... I'll often run an idea past... somebody like-minded that's got similar sheep to you, talk about it. I think it's good for yourself too, because if you're feeling perhaps a bit down about it, you know, a load shared is often a good thing." (C5)

Advice could come from a variety of different sources. Although this study did not comprehensively investigate farmers' animal health information sources, several respected sources of advice were discussed. Respected farming friends or neighbours with similar production systems in the same district were helpful for support and sharing their experiences.

"You know, I do ring up a couple [of farmers] that I know, we share ideas about, if we've got any problems, you know, this is what's happening. Another head is always handy." (C5)

“When we first started getting selenium deficiencies and white muscle disease in lambs... we all got together, the neighbours, people that farm in a similar way and had the same sorts of problems, due to the year.” (C4)

The farmers sought out these individuals based on the relevance of their experience and similarity to themselves, rather than proximity; not all neighbours were considered useful sources of advice.

Farmer discussion groups were also a useful place to talk about disease problems. However, several farmers raised the challenge of time constraints related to day-to-day farming activities that limited their farmers’ availability to attend groups. These farmers still recognised the value of the discussions that took place in those groups, but saw it very difficult to find the time to attend.

“You’ve got things to do on the farm, so that’s why I probably don’t go to the lamb group, ‘cause it’d be on at 10 o’clock in the day, it goes till two... and I think they’re fantastic, but it’s just timing for me.” (B5)

Not all discussion groups provided opportunities to discuss problems to do with animal health, with some focussing more on profitability or marketing aspects of farming. Nonetheless, the farmers recognised the potential value of these groups for discussing their disease problems with others, especially to gain additional perspectives on what the cause or appropriate action might be.

“When you’re a farmer by yourself, you don’t always think about the obvious sometimes either.”

“That’s where discussion groups are good, because it’s just broadening the way you look at it, and you’re not on your own.” (A4, A1)

Agricultural extension consultants, agronomists and pharmaceutical sales representatives (specifically ‘drench reps’ for anthelmintic medications) were also recognised as valuable sources of advice for problems specific to their area of expertise.

“If it was worm related, there’s a rep for one of the [pharmaceutical] companies, he’s pretty good on worms, so he can talk to you about that sort of thing.” (C3)

The farmers tended to contact experts that they had established relationships with, rather than seeking unknown advisors. For example, some knew consultants or

agronomists who were facilitators at farmer groups or field trials the farmers had been previously involved with. Disease problems the farmers felt arose from farm management, rather than just disease per-se, were particularly directed towards these types of consultants.

“Not necessarily with the vet, ‘cause this is a sort of a more a total management thing, because there’s a whole series of things that have probably gone wrong, rather than just a veterinary issue.” (A7)

Stock agents, by contrast, were seen to have no role advising on any disease problems in sheep, because their area of knowledge was not related to animal health.

“I would be reluctant to take the word of the neighbour, or the stock agent who might have just inadvertently been on the scene at the time I’ve discovered this problem, and I just find that background noise distracts you.” (A4)

Finally, veterinarians were seen as valuable and trustworthy sources of advice on disease problems in sheep (as described in Section 5.5.2.2). The farmers varied in whether the veterinarian would be the first or sole source of advice, or alternatively whether they would first discuss the disease problem with others, usually trusted farming friends. How quickly a veterinarian would become involved related to the perceived severity of the problem or how far beyond the farmer’s experience it was. While simple or slightly unusual disease problems might be informally discussed with friends, a major problem or a disease with presenting signs unlike anything the farmer had previously encountered would be referred promptly to a veterinarian.

“If you’ve lost two and you’ve got others lagging behind, and you’ve already drenched them—”

“I’d be going straight to the vet, I wouldn’t be going over to the neighbours’ for a cup of tea.” (A3, A4)

Veterinary contact is discussed further in the next section (5.4.3.7).

When seeking advice from all the above sources, the farmers mainly wanted to ‘talk through’ the possible explanations for the disease problem they have observed.

“I’d probably like to just collect a bit of advice, before I did it.” (B4)

They were not looking for someone else to diagnose and fix the disease problem for them, but rather to discuss what the diagnosis was likely to be, and therefore what action the farmer themselves should take. The farmers were also seeking peace of mind through these conversations—to know that they were doing the best they could to manage the disease problem, given their current circumstances.

“In that first 24 hours when you go to bed at night, and think, ‘I don’t quite know what’s happening, and I hope that it’s gonna work’. For me anyway, you’ve got experience and confidence to back your judgement. For me, I’m feeling good that I’ve sought some really good, top advice.” (B4)

5.4.3.7 CONTACTING A VET

While the farmers did not always decide to contact a veterinarian, the option to do so was an important part of the farmers’ decision-making process about how to respond to a disease problem. Veterinarians were primarily contacted when the farmers couldn’t determine the diagnosis and treatment approach without assistance, and were highly valued in these situations.

“It’s basically if you’ve got a problem that you don’t know, you’ve got not a clue.”
“Rely on their experience and their knowledge.”
“Yeah.”
“Getting the right diagnosis and therefore the right treatment.”
“And the process, how to do something.” (A4, A5, A6)

The farmers reported being able to judge what kinds of disease problems would benefit from a veterinarian’s input, based on their past experiences.

“You generally with a fairly high certainty, pretty good accuracy, you know whether a vet’s gonna be able to help you or not... It’s part of a bigger picture of where you’re at with vets in general over history, we just probably don’t have... historically the good outcome with the vets to warrant calling them very much.” (B5)

The farmers mainly sought advice from veterinarians whom they believed were experienced with sheep disease, and whose advice they trusted. This often meant contacting a veterinarian with specialist sheep knowledge, who may be located several hundred kilometres away, rather than their local mixed-practice vet.

"I know the [local vets], you probably lose a day or two by the time they work out what's going on. So you're probably better to talk to [a sheep specialist], where, someone'll be onto it, probably already seen a couple of times per year whatever's going on... doesn't have to work it out.." (C3)

Once they had decided to contact a veterinarian, the farmers valued being able to discuss the disease problem with them promptly. Consequently, they tended to prefer phone calls rather than property visits (discussed in Section 5.5.2.5). In addition, as the farmer was usually looking to discuss the disease problem rather than expecting the veterinarian to fix it for them, there was little perceived need for the veterinarian to physically visit the farm. If the veterinarian would be substantially delayed in providing advice about the disease problem, or if diagnostic results would take some time, the perceived value of the veterinarian was reduced.

"Well, they can take a blood test, and that can take a long time to get a result, and then you've got all these stock that unwell, and you're waiting for this result. So, it's not necessarily bad, but it's just, you've gotta deal with this problem until you know the outcome." (C5)

Veterinarians were therefore most likely to be contacted when it was likely they'd be able to help quickly, assisting the farmer to determine and take action to 'deal with the problem'.

Typically, once the farmer received advice from a veterinarian they considered had good sheep knowledge, the farmer would endeavour to enact their advice. The value of this service, where a good outcome was likely, was considered worth the potential cost of engaging a veterinarian.

"If you get good advice and successful outcomes I don't think [cost is] an issue, and I've sort of found that that's been the case. So, you know, I think, I think it's probably depends a bit on the quality of the vet." (A5)

5.4.3.8 TAKING ACTION

Once the farmer had identified some appropriate action to take and was reasonably confident that it would reduce or eliminate the disease problem, they implemented that action. Whatever activity was needed was seen to be the responsibility of the farmer. Consequently, the outcome of the action was also their responsibility. As

described above, the farmers described wanting to minimise the time delay between deciding action was needed and taking action, to reduce the overall effect of the disease problem on productivity and animal welfare.

5.4.3.9 RE-EVALUATING

Finally, the farmers re-evaluated the response to treatment, to determine whether their action had achieved the desired outcome—whether the disease problem had been ‘dealt with’. They allowed some time for treatment to have its effect before re-evaluating the situation.

Facilitator: “You’d drench ‘em and you’d wait to see a response, and you’d expect to see a response in how much time?”

“Oh, a week.”

Facilitator: “And if you haven’t got a response in a week?”

“I’d be ringing the vet.” (A4)

While there was some variation in the specific amount of time the farmer would wait before deciding there was further action needed, all groups reported the need to allow time for a response to treatment.

“Cause you’re, if you’ve hit the right drench, they’ll improve very quickly.”

Facilitator: “How quickly is very quickly?”

“Oh, within three or four days.” (C4)

If the farmer sees a response to treatment, they will usually be satisfied that their diagnosis of the problem had been correct, and that further investigation or identification of further actions to take were not required.

“[A good] outcome is your observations are correct, and the things you put in place work.” (A7)

However, if the response to treatment is not satisfactory, the farmer would return to the start of the decision-making process, recognising that further action was needed. Each iteration of the process increases the probability that they will decide seek advice, and within seeking advice, also increases the probability that the necessary advice will be sought from a vet.

The farmers recognised that with each iteration of the decision-making process, time passes and any associated losses are likely to increase. If they misjudged the situation in the first instance, a poorer outcome was likely, both financially and for animal welfare.

"I suppose the response hasn't worked, so then you have to find another response, so that's all time, so you've probably wasted a week, and you'd imagine that there's probably more dying in that period of time." (A4)

Alternatively, the farmer may reach a point where they feel that there is no action that would allow them to control the disease, and consequently may decide not to take further action. These experiences may then lead that farmer to tolerate similar disease problems in future, because they do not perceive effective action to be available.

5.5 DISCUSSION

This study aimed to clarify how Australian sheep farmers respond to disease problems in their livestock, and to explain the reasons for low rates of veterinary attendance on-farm. The farmers in this study often took a self-reliant approach when facing common disease problems, drawing on their own experience and knowledge to identify appropriate response actions rather than contacting a veterinarian in the first instance. They tended to only seek assistance from others, including veterinarians, for unusual disease problems outside the range of their experiences. It was unclear exactly how the farmers judge their own abilities and breadth of knowledge when deciding whether to seek advice about disease problems. Nonetheless, the farmers felt this self-reliant approach was suitable for many disease problems, meaning that low rates of veterinary contact were seen by the farmers as rational and appropriate. When a disease problem was beyond their experiences, the farmers tended to seek advice for the purpose of talking through how they might manage the problem themselves, rather than seeking for someone else to come and deal with the problem. This meant that a veterinarian physically attending the farm was rarely needed, because the farmer's requirement for advice could often be satisfied over the telephone. These findings add new depth to the 'tolerance' veterinarians may perceive farmers having for some types of disease problems. These insights into sheep farmer behaviour when managing disease problems suggest that removing 'barriers' to reporting for reporting of both endemic and exotic diseases to private and

government veterinarians are unlikely to substantially increase the rates of veterinary contact with farmers. Rather, new models for veterinary service provision and new surveillance approaches that better align with farmers' existing disease response behaviour are likely needed to increase the effectiveness of passive surveillance in the Australian sheep industry.

Self-reliance was a key feature of the approach to dealing with disease problems taken by the participants in this study. If the farmer felt confident that they had identified the diagnosis and knew what action as required, there was little need to contact others including veterinarians for assistance. While self-confidence in managing disease problems has been reported in previous studies (Frawley, 2003; Palmer et al., 2009a; Garforth et al., 2013; Lanyon et al., 2015; Wright et al., 2016), its substantial impact on farmer contact with veterinarians has received little attention. The converse situation was also described: if the farmer believed they could not determine the diagnosis or cause of a problem and therefore the action needed, there was little that would stop them from contacting a veterinarian. This was reported both by farmers with established relationships with vets, as well as farmers who had not dealt with veterinarians for many years.

The consequences of the farmer's tendency to be self-reliant were driven by how accurately the farmers could assess their own limitations. If the farmer's knowledge and interpretation of their observations was accurate and relevant to the disease problem, their presumptive diagnosis and empirical treatment would likely be appropriate, and their self-reliant approach effective in dealing with the problem. For mild cases of endemic disease, this approach could be argued to be entirely valid, making it unnecessary to spend additional time and money to engage a veterinarian. However, the success of a self-reliant approach relies on the farmer accurately discriminating between disease problems they can manage themselves and disease problems beyond their experience, and requires the farmer to realise their need to seek advice in the latter cases.

Direct evaluation of how accurately farmers could determine the limits of their knowledge was beyond the scope of this study, but the potential consequences of inaccurate self-assessment can be considered. If a farmer overestimates the relevance of their knowledge and experience or their observational skills, they may take a self-reliant approach when it would be more beneficial to seek advice. In such cases, when

the farmer re-evaluates the situation, they may recognise that the problem has not resolved and will then be more likely to seek advice, while having to accept increased production losses or mortality associated with delayed or ineffective treatment. The participants in this study indicated they often evaluated the effectiveness of their own actions, and thus past experiences of misjudged self-reliance may make the farmer more likely to seek advice in similar future situations. By contrast, it is also possible that a farmer may not recognise that their self-reliant approach was ineffective. For example, treatment may have resolved the obvious clinical cases but not or sub-clinical cases or the underlying cause, or the disease may have resolved despite ineffective treatment, or all affected animals may have died or been euthanised. In these situations, ineffective treatment may be perceived as effective, or the disease problem might 'disappear' without explanation. Farmers will add these experiences to their knowledge base for dealing with disease, potentially developing ineffective treatment approaches that they will draw on as part of their knowledge base for future disease problems. These ineffective approaches can lead to further economic loss and potential threats to animal welfare, and also reduce the likelihood that a veterinarian will be engaged early, or at all, if similar disease problems occur in the future. Based on the frequency and potential consequences of the self-reliant behaviour reported by the participants in this study, it would be valuable to further investigate of how farmers assess their own limitations when dealing with disease problems, including whether there would be interest in interventions or technology to support farmers to increase the accuracy of their self-assessments.

When the participants in this study decided they needed to seek advice, their main objective was usually to 'talk through' the disease problem (identifying the likely diagnosis, and therefore the appropriate treatment) with someone they trusted and who had relevant previous experience. Sources of advice included trusted farming friends, farmer groups, extension officers and veterinarians. Veterinarians were identified as a trustworthy source of animal health information, as reported in previous studies (Heffernan et al., 2008; Garforth et al., 2013; Toma et al., 2013; Hernández-Jover et al., 2016). Farmer groups, in particular, were also recognised as useful forums for both sharing their own experiences with disease problems, and for gathering information from the experiences of others. However, it was difficult for many participants in this study to attend these groups, due to inconvenient meeting times and the need to prioritise their on-farm responsibilities.

The main reason the farmers sought advice from a veterinarian was to talk through their observations and the likely diagnosis or differential diagnoses. This was to ensure the farmer's proposed treatment approach was likely to work, and to gain reassurance and peace of mind that they were making the best decision for their farm. It was therefore unsurprising that the farmers felt this could be achieved over the telephone, rather than requiring a farm visit from the veterinarian. Furthermore, because the farmer was usually looking to act quickly to address the disease problem in front of them, receiving the right advice by phone was often the fastest way to determine what action was needed. The emphasis on phone calls also reflected farmers' preference to seek advice from veterinarians with known expertise in sheep health, who may not be located in the local area of their farm, rather than the closest veterinarian who could provide a farm visit. There was some uncertainty about whether local mixed practice or cattle veterinarians had sufficient knowledge of sheep disease.

The appropriateness of the advice provided to farmers in a telephone consultation is dependent on the quality of information provided by the farmer to the veterinarian. If the farmer's observations are thorough and correctly interpreted, a veterinarian can often provide suitable and relevant advice. However, if the farmer has overlooked some crucial detail of the epidemiology or clinical presentation of the case, or have misinterpreted a clinical sign and jumped to an inappropriate conclusion, it can be difficult for the veterinarian to provide the appropriate advice for the true disease situation on the farm. There is some potential for the use of technology to supplement a farmers' observations and improve the accuracy of a diagnosis made by telephone, for example by providing relevant photos or videos of the affected animals. However, further investigation to better understand how essential veterinarians' physical presence is to achieve a diagnosis on sheep farms is needed, both for the benefits to the farm including productivity and animal welfare, as well as more broadly for effective passive surveillance.

To an outside observer such as a veterinarian, a farmer progressing through the decision-making process described in this study (Figure 5-3) could appear to be 'tolerating' a disease problem. There were four situations where tolerance of disease may be perceived by an outsider: the farmer's initial self-reliant approach has not resolved the problem; the farmer believed there was no efficacious treatment; all sheep affected by the problem have died; and a problem that is perceived to affect

only a single sheep. In the first situation, a farmer may appear from the outside to be tolerating a disease problem when are in fact taking a self-reliant approach to manage a disease problem. If the farmer is unsuccessful in the process of taking action and re-evaluating based on their own knowledge, there can be substantial delay before the farmer seeks advice. It is important for veterinarians to understand that, in these cases, the farmer rarely accepts the disease situation they are facing. Rather, time is passing as the farmer attempts to 'deal with the problem'. The presentation of a disease problem when it is first reported to a veterinarian should not be misinterpreted as the first time the farmer has identified the problem, but in many cases may be the point to which the disease problem has escalated when the farmer has misjudged their abilities to deal with it independently.

In the three other situations, there is indeed some level of tolerance of disease. In the second case, a disease problem may be truly tolerated if no effective treatment or preventive strategy is known or practically available to the farmer. For diseases where the farmer feels there is no helpful action available, for example pregnancy toxemia in lambing ewes, or anaemia due to infection with *Mycoplasma ovis*, the farmer may tolerate a disease at a prevalence beyond what they would otherwise be comfortable with because they believe there is nothing they can do. How frequently this occurs depends on both the true availability and the farmer's awareness of effective treatment or prevention strategies. For these kinds of disease problems, it is critical that new or little-known treatment or prevention approaches are effectively communicated to the farmers, or disease may be tolerated unnecessarily. Tolerance of these endemic diseases may also result in excessive tolerance of an emergency disease that has a similar clinical presentation (for example, tolerance of foot abscess in ewes during winter, which may be clinically appear similar to lameness due to foot-and-mouth disease in sheep). In the third situation, if all affected sheep have died and the remaining live sheep appear to be unaffected, there is no longer a need for action to resolve the problem, and so a confirmed diagnosis is not required and not worth the farmer's time and expense. Similarly in the final case, if the disease problem appears to be isolated to a single sheep, especially if it is only detected at the point when an animal requires euthanasia or has already died, the farmer may perceive little value in obtaining a diagnosis and therefore make a cost-benefit judgement not to seek advice or have the animal examined by a veterinarian. By better understanding the different situations that may appear from the outside as 'tolerance'

of disease, we gain a more nuanced picture of why rates of veterinary contact might be low on sheep farms.

When considered together, the results of this study have several important implications for the detection of sheep diseases by surveillance systems. Notably, because the decision to contact a veterinarian was often made before potential 'barriers' such as the cost of a veterinarian were considered, subsidisation of veterinary services for surveillance purposes may not substantially increase the number of cases brought to the attention of a veterinarian. Considering emergency diseases, it is likely that traditional passive surveillance activities in Victoria would detect a disease with very unusual clinical signs occurring with high prevalence, because the farmer is likely to judge the disease problem to be beyond their experience and therefore decide to seek advice. This supports Butler and Loth's (2017) assertion that sheep farmers observe their animals frequently and therefore are likely to report an unusually high occurrence of disease cases rapidly. However, if the farmer observes a 'subtle emergency', for example common clinical signs occurring with increased prevalence, or unusual clinical signs with low prevalence, there is less certainty that the farmer will recognise the problem is beyond their experience and determine that they should seek advice, especially when they first identify the problem. Detection (and particularly early detection) of these types of disease problems by traditional passive surveillance is less certain.

To increase the probability of detection of disease problems that could be 'subtle emergency' cases, as well as providing increased data collection about routine endemic diseases, there are several possibilities. While increasing the likelihood that a veterinarian will be contacted about disease problems may seem the ideal solution, an alternative approach would be to collect data about disease on-farm without requiring the direct involvement of a veterinarian. In the first case, if the perceived role of veterinarians on sheep farms were broadened to include a more preventive approach focussed on increasing productivity in the face of endemic diseases (especially if this approach were demonstrated to be economically worthwhile), this could increase the rate of veterinary contact with sheep farms. If veterinarians were more closely associated with sheep farms, farmers may be more inclined to seek advice, even for disease problems they would usually manage with a self-reliant approach. If a major shift in the role of veterinarians on sheep farms is not possible, involving farmers more directly in surveillance data collection is a viable alternative, for example using a

syndromic surveillance approach as described in Chapter 3. In either case, improving passive surveillance on Australian sheep farms will require a surveillance approach that is a good 'fit' for the farmers' existing approaches to disease management as described in this study, rather than trying to 'convince' farmers to comply with a reporting system imposed upon them that may not align with their current behaviour and farm management practices.

Alongside its practical implications, this study has also demonstrated the usefulness of moving beyond a socio-psychological theory when investigating farmer behaviour related to animal health surveillance. The depth of the insights offered by the results of this study were possible because of the shift in analytical method described in Section 5.3.5. As self-reliance emerged as a central driver of behaviour during the focus group discussions, simply adding it as an additional element to an existing model or incorporating it into the concept of 'self-efficacy' seemed to obscure its importance. Because the focus group discussion sessions were facilitated to allow farmers to tell their stories and perspectives at length without substantial re-direction, the content of the transcripts prepared from the sessions were suitable for an adapted grounded theory approach to be used instead of the intended Theory of Planned Behaviour. As a result, the findings of this study are less constrained by the initial expectations of the researchers, and are intended to more accurately reflect the farmers' decision-making process. This study has shown how moving beyond existing socio-psychological theories to methods such as grounded theory is a valuable approach to qualitative studies in veterinary epidemiology, especially for studies where a deeper understanding of the drivers of behaviour are needed.

There were several limitations to this study, particularly related to the generalisability of the results. These included the types of farmers that were recruited, the geographic areas where the groups took place, the presence of a veterinarian at the discussion groups, and the inability to achieve theoretical saturation in line with the traditional actions of grounded theory. Each of these limitations is briefly discussed below.

The participants in these focus groups were recruited by convenience, but were considered broadly typical of Victorian commercial sheep farmers. Several female farmers were approached to participate in this study but were unfortunately not available to attend the group meetings as scheduled, despite the best efforts of the researchers. Due to the method of recruitment, participating farmers may have been,

on average, 'information-seeking' types who were more likely to have previously participated in farmer groups. Many of the participants reported knowing and trusting one or more veterinarians, whom they could contact by phone for animal health advice and to talk through the possibilities when dealing with a disease problem in their sheep. Consequently, their behaviour likely represent the 'best case scenario' for disease reporting behaviour by sheep farmers. Despite this, all participants reported low frequency of veterinary visits to their farms. Other farmers may be even more reluctant to contact veterinarians, which may reflect higher thresholds for self-reliance or the stronger influence of disincentives to contacting veterinarians. Nonetheless, many elements of the theory generated in this study are likely to also be applicable for farmers who are less 'information-seeking'.

The geographic areas where the discussion groups took place were selected as three examples of different sheep production regions of Victoria. These regions were selected to investigate potential variation in the farmers' responses to disease between regions, as well as to include farmers whose primary enterprises were both wool (predominant in the north-central region) and lamb (the major type of sheep production in Gippsland). Overall, the sheep farmers in the group recruited from the western district were slightly more pro-active in contacting a veterinarian than the other two groups, likely because have been more veterinarians with sheep-specific knowledge in that region over recent decades, compared with the other two regions. Apart from this minor difference, the decision-making processes reported by the farmers were remarkably consistent between the three groups.

The presence of the author, a veterinarian, at the discussion sessions may have influenced the willingness of the farmers to report truthfully about the frequency or reasons they contacted veterinarians. At the beginning of each session, the facilitator (who was not a veterinarian) emphasised the value of truthfulness rather than the farmers altering their comments to the 'right answers' they perceived a veterinarian might like to hear. As discussion progressed in all groups, the farmers became increasingly candid about their actions and decision-making, and freely described many situations where they did not seek veterinary assistance. Nonetheless, there may be further influencing factors around disease response behaviour that were not discussed, that may be attributable to a veterinarian's presence at the discussion sessions.

The decision-making process described in this study may not be directly generalisable to all Victorian sheep farmers, both due of the qualitative nature of the study and because it was not possible to achieve theoretical saturation (as defined in Section 5.2.1.3). The key themes discussed in all three focus group sessions were consistent and no additional key themes were raised in the third session, indicating thematic saturation of the results presented in Section 5.4.2. The lack of theoretical saturation occurred because it was not practically feasible to return to the participants or to conduct further focus groups to test the developing theory. Therefore, the theory presented in Section 5.4.3 is presented as preliminary, and may not completely describe all factors contributing to farmers' behaviour when deciding how to respond to disease problems in their sheep. Conducting further group discussions or individual in-depth interviews with additional sheep farmers, especially with farmers who have little previous involvement in farmer groups or who do not have established relationships with veterinarians, would be useful to verify the completeness, consistency and applicability of the theory. This further research may identify additional influences or decision-points that should be added to the theory. Furthermore, a quantitative approach (such as a structured survey) could determine the extent to which this decision-making process or its key drivers are generalisable to a wider population of sheep farmers. Despite these limitations to generalisability, this study has provided new insights into the disease response behaviour of sheep farmers and can still be used to improve the design of surveillance activities and models for providing veterinary services to sheep farms.

In addition to validation of the preliminary theory, additional research to extend this study could include focussing on sheep farmers' decisions around preventive health activities, as well as determining whether similar farmer decision-making processes in other livestock industries contribute to limited veterinary contact. This study has provided insight on how sheep farmers respond to disease problems at the time when the problem is detected, but did not specifically investigate how farmers' experiences of disease problems influence decisions about ongoing farm management or preventive health strategies. Further research would be useful to understand farmers' decision-making processes subsequent to the immediate response to disease problems, describing how farmers decide whether and how to change their farm management to avoid recurrence of the same problem. Elements of the theory presented in this chapter may also be applicable to other animal owners or managers

in Australia, for example beef or dairy cattle farmers, horse owners or small-scale pig farmers. Further work to investigate the relevance of this theory and its implications for surveillance and veterinary service provision to other industries would be a useful extension of this work.

5.6 CONCLUSION

This chapter has presented a preliminary model of farmer decision-making behaviour, describing the process Australian sheep farmers use to decide whether, and how, to respond to disease problems in their livestock. A tendency to draw on their own experiences and knowledge to manage many disease problems independently was the primary reason for low rates of veterinary contact with sheep farms. While further validation would be beneficial, this model adds substantially to the existing knowledge of farmer behaviour and the reasons why veterinarians are infrequently contacted about sheep health events. It has demonstrated that there are rational reasons for farmers' sheep health management decisions, and that the perceived role for veterinarians on sheep farms is presently limited.

For these reasons, a surveillance approach that can detect cases of livestock disease without relying on a veterinarian could be appropriate in the short-term to increase the volume of sheep health data that can be collected and used for surveillance purposes. Such a system was described in Chapter 3 and the utility of the data collected demonstrated in Chapter 4. However, the longer term prospect of redefining the role of veterinarians on sheep farms should remain a priority, as veterinary contact is useful for livestock health surveillance as well as for farm productivity, animal health and welfare more generally.

The implementation of a syndromic surveillance system to overcome low rates of veterinary contact depends on recruitment of appropriate farms to provide data. While Chapter 3 described recruitment based on favourable participation, an alternative approach is to target syndromic surveillance to farms that are at increased risk of acquiring or disseminating disease. One way to identify such farms is through network analysis of livestock movement records, such as the NLIS sheep movement data collected in Victoria, Australia. However, because those data are a targeted subset of all sheep movement in and through the state of Victoria, the potential effect of missing or incomplete data on network analysis should be considered, as presented in the next chapter. This will allow the results of subsequent network analyses to be interpreted with appropriate care.

Chapter 6.

SAMPLE SIZE CONSIDERATIONS FOR LIVESTOCK MOVEMENT NETWORKS

PREFACE TO CHAPTER 6

Consideration of sample size or data completeness is an appropriate precursor to analysis of livestock movement data for the purposes of targeted surveillance, such as farm-based syndromic surveillance as described in this thesis. This chapter is an investigation of the effect of sample size and missing data on livestock movement network analysis, and is presented as a peer-reviewed article that was published in Preventive Veterinary Medicine in 2016. This chapter is in three parts. The introduction section supplements the introduction to the paper, adding publications not available at the time of manuscript writing and other relevant background that was omitted. The manuscript for the published paper is then presented. Finally, the conclusion section seeks to situate the results and discussion of the manuscript within this thesis, and to indicate further research specifically relevant in the context of targeted on-farm surveillance.

The manuscript (DOI: <https://doi.org/10.1016/j.prevetmed.2015.07.009>) presented in this chapter has been reproduced in accordance with Elsevier copyright policy for the use of published articles in research theses. The supplementary materials to this manuscript are provided in Appendix F.

6.1 ABSTRACT

The movement of animals between livestock holdings contributes to infectious disease spread in farm animal populations, and is increasingly investigated with social network analysis methods. Tangible outcomes of this work include the identification of high-risk premises for targeting surveillance or control programs. However, knowledge of the effect of sampling or incomplete network enumeration on these studies is limited. In this study, a simulation algorithm is presented that provides an estimate of required sampling proportions based on predicted network size, density and degree value distribution. The algorithm may be applied *a priori* to ensure network analyses based on sampled or incomplete data provide population estimates of known precision. Results demonstrate that, for network degree metrics, sample size requirements vary with sampling method. The repeatability of the algorithm output under constant network and sampling criteria was found to be consistent for networks with at least 1000 nodes (in this case, farms). Where simulated networks can be constructed to closely mimic the true network in a target population, this algorithm provides a straightforward approach to determining sample size under a given sampling procedure for a network metric of interest. It can be used to tailor study designs of known precision, for investigating specific livestock movement networks and their impact on disease dissemination within populations.

6.2 INTRODUCTION

Records of livestock movement between farms can be a rich source of epidemiological information, including for targeting surveillance activities (Christley et al., 2005a) such as on-farm syndromic surveillance. Network analysis methods can unlock this valuable information. However, throughout past network analysis studies of livestock movement data, there is little mention of the impact of sampling or completeness of data. Data completeness is not always a valid assumption for livestock movement data. Indeed, for some countries it is presently unfeasible to have census network records, for reasons of privacy or due to informal or illegal movement of farm animals (Lindström et al., 2013; Amaku et al., 2015; VanderWaal et al., 2016). An appreciation of the level of incompleteness required to impact network descriptions and analyses, and the likelihood that such an issue exists in a given dataset, is thus warranted.

Considering the effect of missing data on different network analysis measures, more ‘global’ network measures tend to be more robust to measurement error such as missingness, compared to node or local metrics (Wang et al., 2012). Overall, networks with a low global clustering coefficient and less positively-skewed degree distributions are generally more resistant to missing data (Wang et al., 2012). In the context of livestock movement networks, many have a low clustering coefficient despite their strongly skewed degree distribution, which suggests that for these datasets, the consequences of missing data may be modest. Nonetheless, the consequences of missing data on inferences that can be drawn from network studies should at least be considered. For node level measures, the rank order of nodes for degree centrality is generally less affected by missing nodes or missing edges than other measures such as clustering coefficient or eigenvector centrality (Wang et al., 2012). Similarly, Smith and Moody (2013) found that, across twelve empirical networks, in-degree and closeness were more robust in the face of missing data when compared to betweenness.

Smith et al. (2017) demonstrate that not all nodes contribute equally to the effects of missing data. In particular, the strongest bias due to missingness is seen when more central nodes are missing. Dawson et al. (2015) give a similar result, showing that only 15-20% of the most highly connected nodes need to be present in the data to give an accurate estimate of mean degree and degree standard deviation. Accordingly, Wang et al. (2012) suggest that, where data quality or completeness limit the

precision of analyses, data cleaning and validation should be focussed on nodes that are highly influential for the measure of interest. In most cases, these will be the most central (most highly connected) nodes.

To detect missing edges in a livestock movement network, an alternative data source detailing movements that have occurred but are not present in the data is needed, but is rarely available. It is perhaps more feasible to detect missing nodes, where lists of registered farms could be used as comparison data. However, it may not be reasonable to assume that every registered farm must have purchased or sold livestock in a given timeframe. Hence even detecting missing nodes can be challenging.

A small number of studies have previously identified the effect of incomplete network data in their network analyses. For farm characteristics such as geolocation or demographic data, missing data may be readily recognised, for example as reported by VanderWaal et al. (2016) when describing Uruguayan cattle movement. By contrast, León et al. (2006) recognise that missing edges and therefore potentially missing nodes may be present in the Argentinian cattle movement database, but make no attempt to quantify or account for it. Going one step further, Martínez-López et al. (2009) found a significant difference in temporo-spatial clusters identified in the full network of pig movement in Spain and a geographically-restricted sub-network. This demonstrates that the results of analysis of an incomplete network may not approximate those expected from the full network dataset – and therefore that any potential missing data must be recognised and, if possible, addressed either in data collection or analysis.

In considering a range of empirical networks, Smith and Moody (2013) demonstrated that the effect of missing data is dependent on the type of network and the question being posed (or which measure(s) the study is attempting to estimate). However, the general similarity of many livestock movement network studies, both in terms of the global characteristics of the networks as well as the types of questions being asked, means that approaches to missing data for livestock movement should be reasonably generalisable across different network datasets. This does not, however, mean that sample size estimates from one empirical dataset, such as reported by Dawson et al. (2015) based on cattle movement in the United Kingdom are immediately valid for other countries' data. Despite common network features, there may be important

differences in trade patterns between countries, such as the influence of livestock markets or how animals are traded for ‘finishing’ (fattening) prior to slaughter on the movement of animals between farms.

While these factors are useful to consider when approaching network analysis of livestock movement, they do not offer a practical approach to assessing whether a given number of missing nodes or edges will negatively affect the results of network analysis. Knowing when to be concerned about bias due to missing data will help future studies to account for its effects more appropriately.

This article proposes a simulation algorithm for estimating the required sample size to assess the degree values of a network given assumptions about the true network’s degree distribution, number of nodes, number of edges (or density), sampling method, and the power and precision required. Further, a descriptive sensitivity analysis is presented, demonstrating the robustness of the sample size predictions made by the algorithm between simulated networks with variations in degree distribution, number of nodes and sampling method.



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Sample size considerations for livestock movement network data

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ABSTRACT

The movement of animals between farms contributes to infectious disease spread in production animal populations, and is increasingly investigated with social network analysis methods. Tangible outcomes of this work include the identification of high-risk premises for targeting surveillance or control programs. However, knowledge of the effect of sampling or incomplete network enumeration on these studies is limited.

In this study, a simulation algorithm is presented that provides an estimate of required sampling proportions based on predicted network size, density and degree value distribution. The algorithm may be applied *a priori* to ensure network analyses based on sampled or incomplete data provide population estimates of known precision.

Results demonstrate that, for network degree measures, sample size requirements vary with sampling method. The repeatability of the algorithm output under constant network and sampling criteria was found to be consistent for networks with at least 1000 nodes (in this case, farms).

Where simulated networks can be constructed to closely mimic the true network in a target population, this algorithm provides a straightforward approach to determining sample size under a given sampling procedure for a network measure of interest. It can be used to tailor study designs of known precision, for investigating specific livestock movement networks and their impact on disease dissemination within populations.

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1. Introduction

Understanding the pattern of animal movements between livestock holdings presents an opportunity to target surveillance and control activities to premises with increased risk of infectious disease spread (Christley et al., 2005), a valuable approach when jurisdictions are required to maximise their impact with limited resources. Social network analysis (SNA) provides a means for quantifying networks of animal movements, and has been used increasingly in the context of preventative veterinary medicine, with applications ranging from studies of tuberculosis transmission in possums in New Zealand (Porphyre et al., 2008) to factors influencing equine influenza spread in Australia (Firestone et al., 2012).

Early applications of SNA in livestock movement networks followed the 2001 UK foot-and-mouth disease (FMD) outbreak (Webb, 2005; Woolhouse et al., 2005; Ortiz-Pelaez et al., 2006). As traceability and network analysis has become a priority in many countries, the legislated requirement to declare movements of livestock from one geographical location to another has become commonplace, and the analysis of such data has been pursued across the world (Bigras-Poulin et al., 2006; Baptista and Nunes, 2007; Natale et al., 2009; Volkova et al., 2010; Rautureau et al., 2011; Aznar et al., 2011; Rautureau et al., 2012; Smith et al., 2013).

However, throughout this literature there is little mention of the impact of sampling or completeness of data obtained from such sources, and *a priori* sample size calculations are notably absent from analytic approaches. Although for some data sources such as the UK cattle tracing system (Dawson et al., 2015) completeness may be a valid assumption, this is not always the case. Farm-level records of livestock movements may be incomplete or absent altogether if, for example, compliance is poor or a recording system is under-resourced. An appreciation of the level of incompleteness required to impact network descriptions and analyses, and

Abbreviations: SNA, social network analysis; FMD, foot-and-mouth disease; CV, coefficient of variation; SD, standard deviation; R₀, basic reproductive number.

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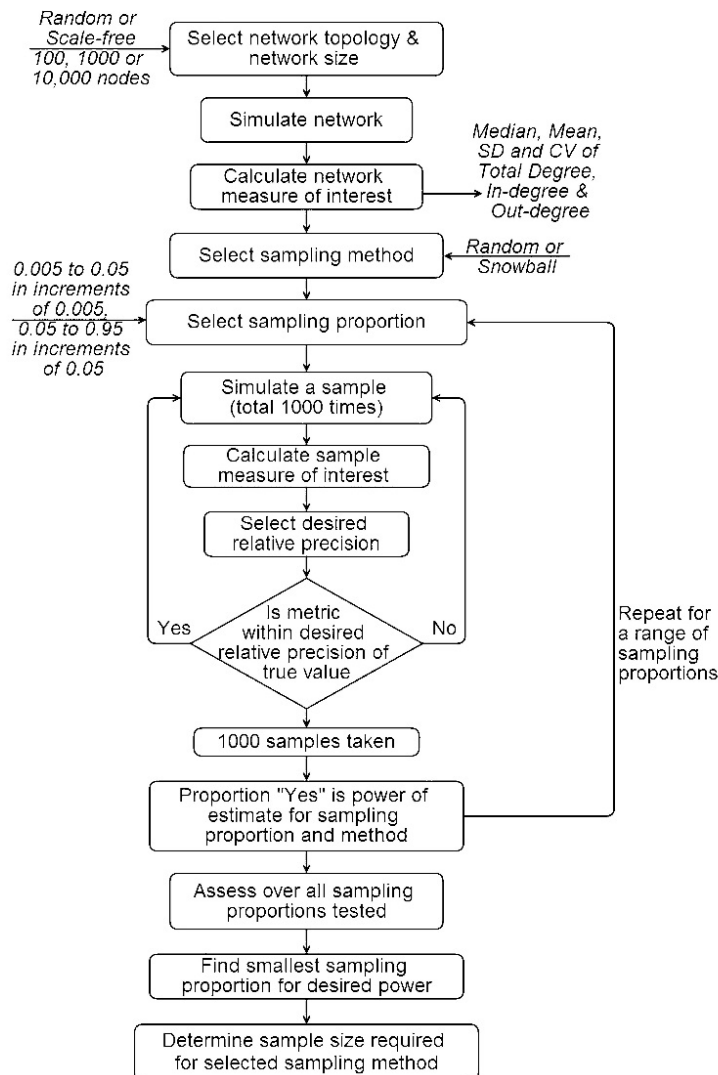


Fig. 1. Sampling algorithm for estimating animal movement network parameters with specified precision. Italics indicate values or categories used for each variable in this paper.

the likelihood that such an issue exists in a given dataset, is thus warranted.

1.1. Network characteristics and terminology

Before discussing the impact of sampling on the precision of network metrics, it is prudent to consider the key network measures applied to describe livestock movement networks. The network comprises premises where the species of interest are kept (*nodes*, such as farms or saleyards), and movements of animals between a pair of premises (*edges*). Most livestock movement networks are directed, in that edges represent a one-way movement from a unique source farm to a unique destination. Edges can be reciprocated where trade occurs in both directions between a pair of nodes. Comprehensive reviews of SNA concepts and their application to preventative veterinary medicine are available elsewhere (Dubé

et al., 2009; Martinez-Lopez et al., 2009). Many structural indices are available to describe network characteristics, measuring, for example, a node's network position (*centrality*) or connectivity (Butts, 2008). A simple but powerful node-based centrality measure is the degree value, the total number of incoming and outgoing edges for a given node (i.e. the total number of other premises each individual farm trades with). In a directed network, the total degree value for each node can be categorised into in-degree (incoming movements), and out-degree (outgoing movements).

A network's topology can be described at a basic level by the distribution of degree values. While early theoretical work on network analysis focussed on random networks with normal degree distributions, many real-world networks have a highly skewed power-law distribution of degree values, denoted a "scale-free" network topology (Barabási and Albert, 1999). These scale-free networks are typified by most nodes having small degree values, but a

small subset of nodes having very high degree values. Such heterogeneity in degree values has been repeatedly identified in livestock movement networks (Bigras-Poulin et al., 2006; Natale et al., 2009; Aznar et al., 2011), where most farms trade with few others, but a small number of farms have many trading partners.

The effect of this degree heterogeneity on disease transmission is intuitive; a farm with many trading partners could greatly amplify the spread of an infectious disease through a population. Furthermore, a distinction between the effects of in- and out-degree can be made, as high in-degree premises are more likely to acquire infection from trading partners, while premises with high out-degree can infect a higher number of other farms. If in-degree and out-degree values are positively correlated, “superspreader” nodes (those at higher risk of both acquiring and disseminating an infectious disease) emerge (Galvani and May, 2005). An example of this phenomenon occurred during the 2001 epidemic of FMD in the UK, where livestock saleyards widely disseminated disease prior to the onset of effective control measures (Ortiz-Pelaez et al., 2006). The impact of degree heterogeneity on disease spread is quantified by adjusting the basic reproductive number (denoted R_0 , the average number of new infections caused by each infected individual in an entirely susceptible population, whereby if $R_0 > 1$, an outbreak will be perpetuated through the susceptible population, while if $R_0 < 1$ the outbreak will die out). The coefficient of variation of degree values (Eq. (1), where σ and m are the standard deviation and mean of degree values in the network, respectively) is the measure of interest to adjust R_0 .

$$CV = \frac{\sigma}{m} \quad (1)$$

$$R_0 \propto 1 + CV_{in} CV_{out} r \quad (2)$$

CV_{in} and CV_{out} are the coefficient of variation for in-degree and out-degree respectively for the full network, and r is the correlation between in- and out-degree values for all nodes in the network. R_0 will increase according to the relationship in Eq. (2) (Woolhouse et al., 1998), if CV_{in} and CV_{out} are positively correlated. A negative correlation between degree values will lower R_0 , while if there is no correlation the effect is indeterminate.

For the special case where $r = 1$ and therefore in- and out-degree are equal for all nodes, Eq. (2) can be simplified to use CV_{total} , the coefficient of variation for all degree values in the network, to give Eq. (3) (May et al., 2001). The magnitude of CV is heavily influenced by high-degree nodes within the network.

$$R_0 \propto 1 + (CV_{total})^2 \quad (3)$$

In many infectious diseases in human populations, roughly 20% of infectious individuals are responsible for 80% of disease transmission (Galvani and May, 2005), and this phenomenon has also been identified in livestock movement networks (Woolhouse et al., 2005). If premises with the highest degree values can be identified, they can be targeted for surveillance or control strategies to reduce their effect on R_0 (Christley et al., 2005), with evidence suggesting focussing half of control resources on the most infectious 20% of cases is up to three-fold more effective than random control (Lloyd-Smith et al., 2005). But how are these nodes identified? While declared livestock movement data may be available, records are often incomplete. Thus the question arises, what proportion of the network must be completely enumerated to give accurate estimates of the degree distribution?

1.2. Sampling network data

The search for a simple, practical method for determining sample size for network investigation has been previously unrewarding, largely due to the complexity of network data. The number of edges in a network is dependent on several factors

including the number of nodes, and most network measures combine node- and edge-level data. As such, deriving mathematical approaches to determine sample size and confidence intervals have proved challenging (Frank, 1988). Many sampling investigations have focussed on effects in networks with random topology (Granovetter, 1976; Frank, 1978; Galaskiewicz, 1991; Borgatti et al., 2006), and so their findings cannot be directly applied to real-world networks with scale-free characteristics. More recent work has assessed a broader range of topologies, and indicate the important parameters to consider when sampling a network, namely true network topology (Albert et al., 2000), sampling method (Leskovec & Faloutsos, 2006), network density and sampling proportion (Galaskiewicz, 1991).

Sampling methods for network data include random node sampling, as well as targeted approaches that utilise the connections in networks, particularly useful when a sampling frame is not available. A common targeted method is snowball sampling (Goodman, 1961), where one node is chosen to sample at random (the *ego* node), and then all directly connected nodes (first-degree neighbours, or *alters*) of that *ego* are also sampled in the first “wave” of the snowball. Second and subsequent “waves” can also be included if desired, with each wave sampling all alters of the nodes in the previous wave. Snowball sampling has been shown to provide robust estimates of in-degree with relatively small sample sizes and wave numbers (Johnson et al., 1989). Further targeted approaches include random walk (where a single alter is chosen at random for each wave), or forest fire (where each alter’s inclusion in a wave is determined by a set probability). Dawson et al. (2015) more recently explored the effect of imperfect data on network model construction for prediction of epidemics, using cattle movement data from the UK. For fast-spreading diseases, targeted sampling methods yielded more accurate epidemic spread outcomes compared to random sampling, and appeared robust at small sampling proportions (around 20% of the network). No practical approach is given, however, to determine the required sampling proportion for a specific analytical objective.

Degree has repeatedly been shown to be more tolerant of the effects of sampling than other centrality measures (Borgatti et al., 2006; Costenbader and Valente, 2003). In livestock movement data, the total, in- and out-degree values for a node (how many sources and destinations they trade animals with) can be determined from information collected from that node alone, independently of whether the source or destination nodes are included in the sample. This is in contrast to sociological networks, where sample based estimates of in-degree and especially out-degree are dependent on both individuals connected by an edge being included in the sampled network, although in-degree remains robust and the effects of sampling appear repeatable (Galaskiewicz, 1991). The ease with which degree can be sampled, its reported robustness to error and missing data, and its relevance for animal disease control, make it a useful measure to illustrate sampling strategies. However, it should be noted that obtaining a precise estimate of a network measure does not guarantee the overall network topology will be consistent between the full and sampled networks. In other words, subnetworks of scale-free networks are not reliably scale-free (Stumpf et al., 2005). Thus, the choice of network metric as well as its desired precision are important factors in determining sample size to describe a network.

This paper proposes a simulation algorithm for estimating the required sample size to assess the degree values of a network given assumptions about the true network’s degree distribution, number of nodes, number of edges (or density), sampling method, and the power and precision required. Further, a descriptive sensitivity analysis is presented, demonstrating the robustness of the sample size predictions made by the algorithm between simulated net-

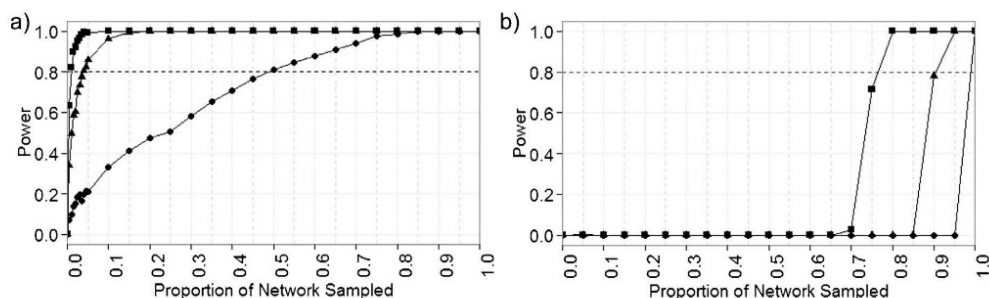


Fig. 2. Sample proportion required to determine the coefficient of variation of total degree when applying (a) random sampling, and (b) snowball sampling, in a 10,000 node random network. Circles (●), triangles (▲) and squares (■) indicate results for $\pm 1\%$, $\pm 5\%$ and $\pm 10\%$ precision respectively, dashed horizontal line indicates 80% power.

works with variations in degree distribution, number of nodes and sampling method.

2. Materials and methods

2.1. Simulation algorithm

The proposed approach (Fig. 1) takes a theoretical, simulated network, constructed to replicate the real-world network of interest, simulates sampling of that theoretical network multiple times, and assesses the agreement between degree metrics from the samples with the true measure in the full network at a desired level of precision.

2.1.1. Network simulation

Networks with two distinct topologies were generated, random and scale-free. Directed random networks were simulated with the Erdos-Renyi model (Erdos and Renyi, 1959), with edge probability equal to the inverse of the number of nodes. Scale-free networks were simulated with the Barabasi-Albert model (Barabási and Albert, 1999). To simulate a more realistic variation for in- and out-degree, the scale-free networks were generated with undirected edges, each edge then being converted to two reciprocal directed edges and 50% of the edges removed at random. A total of 20 networks of each topology were generated with 100, 1000 and 10,000 nodes in turn, altogether giving $20 \times 2 \times 3 = 120$ networks. The networks were divided into 12 sets for comparison, each set containing 10 networks of equal size and equivalent topology. Network density, D (the proportion of edges (e) present from the number theoretically possible based on the number of nodes present (n), as in Eq. (4)), and global clustering coefficient (also known as transitivity, an indicator of the level of local clustering present in the network (Butts, 2008)) were calculated to describe the simulated networks.

$$D = \frac{e}{(n \times (n - 1))} \quad (4)$$

2.1.2. Calculation of true network measures

For each of the 120 networks, the distributions of total degree, in- and out-degree were assessed by calculating the median, mean, standard deviation (SD) and coefficient of variation (CV) for each distribution, giving a total of $3 \times 4 = 12$ measures for each network.

2.1.3. Simulation of sampling

Six of the 12 network sets, each representing one combination of network size and topology, were sampled with random node selection, while the remaining six sets underwent snowball sampling.

Snowball sampling was simulated in a single wave, whereby a random node was selected, all alters (first-degree neighbours) of

that node were identified, and all of these nodes then included in the sample. A second random node was then selected, and that second node and its alters were also included in the sample, excluding any nodes that had already been sampled. This sampling method was repeated until the total number of nodes sampled was equal to the required sampling proportion. The true total, in- and out-degree values for the sampled nodes were then calculated.

Sampling proportions from 0.05 to 0.95 in increments of 0.05 were tested in every network, as well as sampling proportions from 0.005 to 0.05 in increments of 0.005 in networks with 1000 or 10,000 nodes. Sampling at each proportion was repeated 1000 times in each network.

2.1.4. Precision and determination of power

Precision values of $\pm 1\%$, 2.5%, 5%, 10% and 20% were tested. The results of the 12 measures were calculated for each sample. These sample values were then compared to the true network value, and whether the sample value was within the specified relative precision of the true network value was evaluated. This was repeated for each of the 1000 samples at a given sampling proportion and sampling method, and the proportion of samples within each relative precision of the true value determined, equivalent to the power of the estimate at that sampling proportion. A power of 80% was used as the cut-off to determine the minimum sample proportion required, for a given measure at a particular level of relative precision.

2.2. Sensitivity analysis of measures

The sample size required to estimate each measure (mean, median, SD and CV) within $\pm 5\%$ relative precision at 80% power was calculated for all ten sets of networks with common size and topology. The variability of the required sampling proportions that achieved this power and precision was described by the minimum, mean and maximum sample sizes that obtained this outcome within the simulation run for each network size/sampling strategy set. These investigations aimed to verify the consistency of the following effects over multiple distinct iterations of the algorithm:

- The repeatability of the algorithm, specifically whether simulating different networks with the same size and topology would give similar sampling proportion outcomes.
- The effect of network topology on required sampling proportion.
- The effect of sampling method on the necessary proportional sample size.
- The consequences of varying network size for sampling proportion, at the level of an order of magnitude.

Table 1

Network measures for 6 hypothetical livestock movement network topology and size combinations, with 20 simulated networks per combination. Where measure was not equal for all simulations, mean measure is given with range in parentheses.

Topology	Number of nodes	Number of edges	Density	Global clustering coefficient
Random	100	103 (89–114)	0.010 (0.009–0.012)	0.017 (0.000–0.032)
Random	1000	991 (940–1061)	0.001	0.002 (0.000–0.007)
Random	10,000	9980 (9701–10119)	0.0001	0.0002 (0.000–0.001)
Scale-free	100	99	0.010	0
Scale-free	1000	999	0.001	0
Scale-free	10,000	9999	0.0001	0

Network generation and sampling simulation were performed using R v3.1.1 (R Core Team, 2014) using the igraph (Csardi and Nepusz, 2006) and incursion (Stevenson and Sanson, 2013) packages. A parallel computer cluster using R v3.0.1 was used to carry out the snowball sampling in the networks comprised of 1000 and 10,000 nodes (Victorian Life Sciences Computation Initiative grant VR0277).

3. Results

3.1. Characteristics of simulated networks

A descriptive summary of the 120 simulated networks is presented in Table 1. These large networks with low density are typical of livestock movement networks previously reported, such as the cattle movement network in Denmark with approximately 30,000 nodes and density <0.0001 (Bigas-Poulin et al., 2006) or sheep movement in Scotland with approximately 15,000 nodes and density 0.0003 (Volkova et al., 2010). The true total degree measures for each set of networks is summarised in Table 2.

3.2. Sampling algorithm results: 10,000 node networks

As an illustration of the algorithm, results from four 10,000 node networks are presented in Figs. 2 and 3, representing the combination of the two network topologies and two sampling methods, for three relative precision levels ($\pm 1\%$, $\pm 5\%$ and $\pm 10\%$ precision), giving the sample size required to estimate the CV of total degree.

The effect of sampling proportion on power using random sampling in a random network is shown in Fig. 2a. At $\pm 5\%$ precision, a sampling proportion of 4% of this network (representing 400 nodes) is required to estimate CV of total degree with 80% power. If $\pm 10\%$ precision is adequate, the sampling proportion drops to 1% of the network under the same conditions. For the same network, assuming 80% power and $\pm 5\%$ precision, the median, mean and SD of total degree can be estimated by sampling 0.5%, 3.5% and 4% of nodes, respectively (data not shown). Thus, if all four measures were required, a total sample size of 400 nodes would be sufficient in this network.

In contrast, snowball sampling in a random network is demonstrated in Fig. 2b. Snowball sampling with a single wave to estimate

CV of total degree requires 95% of nodes to be sampled for 80% power and $\pm 5\%$ precision. With the same power and precision assumptions, the median, mean and SD of total degree of this network can be estimated by sampling 15%, 95% and 30% of nodes, respectively (data not shown). The lack of precision in estimates of the mean at smaller sample sizes drives the need for such a large sample to estimate CV. If all measures were required, 9500 nodes would need to be included in the sample. This indicates that, if a snowball sampling approach was used, almost the whole network must be enumerated, and an alternative sampling method or network census should be considered. If no feasible alternative were available, up to 500 nodes missing at random would be tolerable.

The outcome of random sampling in a scale-free network can be seen in Fig. 3a. To estimate CV with 80% power and $\pm 5\%$ precision, 90% of nodes must be randomly sampled. For the median, mean and SD of total degree at the same power and precision, sampling proportions of 0.1%, 20% and 90% are required, respectively (data not shown). In this case, lack of precision in estimates of the SD at smaller sample sizes means a large sample (9000 nodes) is needed to estimate CV. If up to 10% of nodes are missing at random, the estimate of CV will still have $\pm 5\%$ precision with 80% power.

Finally, Fig. 3b shows the effect of snowball sampling in a scale-free network. To estimate CV with 80% power and $\pm 5\%$ precision, snowball sampling with a single wave from each randomly selected node will require a sampling proportion of 50%. The median, mean and SD of total degree for this network can be estimated with the same power and precision with sampling proportions of 70%, 95% and 90% respectively (data not shown). Interestingly, in contrast to random sampling, with snowball sampling the CV can be estimated with the desired precision at a lower sample size (5000 nodes) than SD or the mean. This was observed in all 10 replications of this simulation with different 10,000 node scale-free networks, with consistent findings of 95%, 90% and 50% sampling proportion for the mean, SD and CV, respectively, with 80% power and $\pm 5\%$ precision.

Sample size results for the in- and out-degree measures were similar to the total degree results described above.

3.3. Descriptive sensitivity analysis

The repeatability of the algorithm, as well as the impacts of network topology, sampling method and network size on required

Table 2

Range of total degree measures for 6 hypothetical livestock movement network topology and size combinations, with 20 simulated networks per combination.

Topology	Number of nodes	Total degree							
		Median		Mean		SD		CV ^a	
		min	max	min	max	Min	max	min	max
Random	100	2.00	2.00	1.78	2.28	1.30	1.66	0.60	0.79
Random	1000	2.00	2.00	1.88	2.12	1.34	1.45	0.67	0.74
Random	10,000	2.00	2.00	1.94	2.02	1.39	1.44	0.69	0.72
Scale-free	100	1.00	1.50	1.98	1.98	1.91	3.55	0.96	1.79
Scale-free	1000	1.00	1.00	2.00	2.00	2.63	4.50	1.32	2.25
Scale-free	10,000	1.00	1.00	2.00	2.00	3.28	4.28	1.64	2.14

^a Coefficient of variation (Eq. (1)).

sample size can be assessed by comparing the mean and range of metric results for each of the 12 sets of networks. Results for required sampling proportion to give 80% power and $\pm 5\%$ precision for the four total degree measures are provided as supplementary materials.

For a set of 10 networks of equivalent network size and topology, the same sampling method produces highly consistent sampling proportion estimates (with a range <0.15 for most measures investigated). Median measures in small networks (100 nodes) are the exception, where wide ranges of relative sample sizes were returned under all four combinations of sampling method and network topology. For example, in a scale-free network with snowball sampling, estimates of the required sample proportions from 0.55 to 0.95 were produced, indicating a single iteration of the algorithm may not reliably determine required sample size. The range of sample proportions for all measures in larger networks (1000 and 10,000 nodes) demonstrated far less variation, with most producing sample proportions within 0.15 of each other across the 10 replications.

Snowball sampling in random networks gave increased variation in sample proportion results for networks of 100 or 1000 nodes. The same issue was not detected when snowball sampling was used in scale-free networks. Agreement between the 10 replications was particularly high for total degree measures in the 10,000 node networks of both topologies, with the range of sample proportions within 0.1 for all measures except SD in random networks with snowball sampling (range = 0.15).

4. Discussion

Differing sampling methods in networks with common features returned different required sample size estimates, particularly for the scale-free networks. In scale-free networks using snowball sampling, while large sample sizes are required to estimate mean and SD of total degree, a far smaller sample size is required to estimate CV. This demonstrates that sampling methods should be selected taking into account the particular network measure of interest. If investigating the effect of a scale-free network on R_0 , and in- and out-degree are known to be strongly positively correlated, then only 50% of the network is required to accurately estimate the CV and therefore adjust R_0 accordingly. This is an important finding, and shows that a simulation-based approach can be useful in providing a way to select the network sampling method best suited to estimate a specific network measure of interest.

With an increased requirement for precision in degree metrics, comes an increase in required sample size. However, there are other important influences on sample size estimates for SNA: network density, topology, and sampling method as previously

highlighted. Reliable estimates of sampling proportion are dependent on valid assumptions of a network's structure. Livestock movement networks are commonly scale-free with some clustering, and so topology is relatively straightforward to predict. Density can be estimated from the mean total degree of the network, and we have found that in large networks of low density (approximately 10,000 nodes), this can be estimated with a random sample from approximately 20% of nodes. The challenge here is that the sample proportion of 20% is based on an assumption of low density, while attempting to estimate a variable that influences density. Thus, the quantifiable impact of network density on the sampling proportion must be further investigated to assess the validity of this approach.

It is important to consider the impact of the relative precision of metric estimations when applying this algorithm, and to set this value in the context of the particular research question at hand. The measure of interest might be estimated on the basis of results in other similar networks, and the desired absolute precision quantified. If a relative precision of $\pm 10\%$ is determined to be sufficient, this can markedly reduce the sample size required compared to $\pm 5\%$ precision. This advantage can have practical implications and may be the deciding factor in feasibility of a particular investigation.

Further, consider that this simulation algorithm addresses the effect of chance in sampling networks, but does not necessarily eliminate systematic error in sampling. Where random sampling is called for (including in selecting the initial nodes for snowball sampling), true randomisation is critical to maintain the power of the degree measure estimates determined from the investigation. Identifying and attempting to control all biases is as critical in network data as in other epidemiological datasets.

The results presented indicate that the proposed algorithm for determining sampling proportion in typical livestock movement networks is repeatable in networks of moderate size (≥ 1000 nodes). An upper confidence level could be applied to sample size estimates to account for minor variation that can occur between simulations. For networks similar in topology and density to those presented here, a confidence level of sampling proportion of ± 0.1 would be appropriate, such that if the required sample proportion from a single simulation gave a result of 0.4 (40% of nodes), one might sample 50% of nodes to ensure the requisite power and precision were achieved.

This paper has aimed to assess the effect of sampling method on the proposed simulation algorithm, rather than validating particular sampling methods for livestock movement network analysis. Consequently, the complexities of snowball sampling have not been completely investigated, such as the number of waves of sampling from each randomly selected node. This algorithm could, however, be used to compare snowball sampling with different numbers of waves, as well as other related sampling methods (including random walk and forest fire methods).

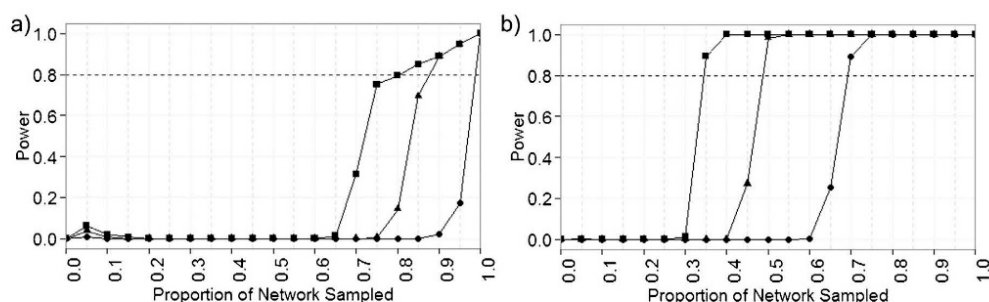


Fig. 3. Sample proportion required to determine the coefficient of variation of total degree when applying (a) random sampling, and (b) snowball sampling, in a 10,000 node scale-free network. Circles (●), triangles (▲) and squares (■) indicate results for $\pm 1\%$, $\pm 5\%$ and $\pm 10\%$ precision respectively, dashed horizontal line indicates 80% power.

The simulation of a “typical” network based on underlying assumptions about network topology, density and size is dependent on the availability of a model for simulating such a network. Several such models are available in existing software, but these have their limitations and an understanding of how the model creates the network and whether it is truly representative of the real network of interest is critical to the validity of sample size results. Furthermore, many network models fail to incorporate a realistic level of clustering, the models presented in this paper notwithstanding, and this may also influence the validity of sample size results produced by this approach. Investigating other models that accurately replicate livestock movement networks that might be used in this algorithm would be a valuable direction for future work. Therefore, this algorithm should be validated by testing it with real network data, and with other network metrics of interest.

5. Conclusions

While in the past network sampling has been largely neglected in veterinary applications of SNA, this study and the simulation algorithm presented demonstrate that it is possible to estimate the sample size required for network investigation. Based on a small number of assumptions, this simulation approach can be used by investigators to design valid studies that give precise estimates of meaningful network metrics for investigations of specific livestock movement networks and their impact on disease dissemination within populations.

Conflicts of interest

None.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.prevetmed.2015.07.009>.

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6.4 CONCLUSION

This article has described an approach to estimate the loss of precision of network degree measures suffered when livestock movement network data are incomplete, using a simulation approach. The algorithm presented can be used by investigators to design valid studies that give precise estimates of meaningful network metrics for investigations of specific livestock movement networks and their impact on disease dissemination within populations.

This approach is more adaptable than that proposed by Dawson et al. (2015) who found that 30% and 90% of nodes need to be sampled for snowball sampling and random node sampling, respectively, to retain network characteristics relevant to epidemic modelling of UK cattle movement data. The algorithm presented in this chapter, while less sophisticated than Dawson et al.'s model, offers the opportunity to vary the expected network before predicting sample size. Dawson et al. also describe targeted sampling of high-risk (high centrality) nodes as an approach to generate useful network data for disease modelling where it is not routinely or reliably collected. However, targeting high centrality nodes requires *a priori* knowledge of each node's network position – the very thing the analysis is usually trying to determine.

Where network data are too incomplete for analysis, or entirely unavailable, Amaku et al. (2015) propose an alternative approach to detect hub nodes that might be targeted for interventions, based on the friendship paradox. This approach suggests that, with knowledge of a sufficient number of farms' direct connections, targeting of surveillance or disease control activities can be achieved independent of the availability of livestock movement data. Further studies are needed to demonstrate consistency of the friendship paradox for livestock movements, before Amaku et al.'s approach is more broadly applied.

A Bayesian approach to scaling up incomplete networks has also been proposed (Lindström et al., 2013), which may prove useful where the sample size required for network analysis cannot be reasonably achieved with real data. However, while this approach is useful for understanding coarse network structure and geographic patterns, it has limited usefulness for activities like targeted surveillance that require network resolution at the individual node level. Furthermore, such imputation may replace missing nodes and edges with false positive nodes and edges in the network.

Wang et al. (2012) highlight this, noting that imputation should be avoided where the detection of false positive nodes and edges result in interventions that might be more detrimental (in terms of animal health outcomes) than those interventions applied when the nodes or edges remain missing.

Each of the approaches described here can provide meaningful information about overall network structure, but are less helpful when the aim of network analysis is at the individual node-level, such as identifying high-risk farms for targeted surveillance. Therefore, the simulation algorithm has its place among these methods. Smith et al. (2017) offer a computational approach to estimate the range of possible bias arising from incomplete network data including for node-level measures, which could be considered complementary to the simulation algorithm.

A direct application of this algorithm would be to investigate the missingness in Australian sheep movement data obtained from the National Livestock Identification Scheme (NLIS). The NLIS sheep movement data, further discussed in Chapter 7, is a targeted subset of the full network of sheep movement in Australia, with non-compulsory and therefore incomplete recording of movements that occur directly between pairs of farms. Therefore this algorithm could be used to estimate the volume of those farm-to-farm movements that could be tolerated before substantially affecting the precision of network measures calculated on the data available to the NLIS. As the missing farm-to-farm movement edges are expected to involve the less central nodes in the network, it could be hypothesised that a substantial volume of movements could be tolerated without affecting the major network measures. However, such an investigation is beyond the scope of this thesis. Nonetheless, this chapter has substantially contributed to the understanding and approach to missing data for network analysis, and has served as a further introduction to network terminology. Network data will now be investigated further in the next chapter, a descriptive analysis of the sheep movement network in Victoria, Australia, with a particular focus on network characteristics of interest for targeted surveillance activities.

Chapter 7.

NETWORK ANALYSIS OF SHEEP MOVEMENT
IN VICTORIA, AUSTRALIA:
THE POTENTIAL FOR TARGETED SURVEILLANCE
AND SPATIO-TEMPORAL DISEASE SPREAD

PREFACE TO CHAPTER 7

The movement of livestock has the potential to transmit infectious diseases, and so understanding patterns of livestock movement is informative for several areas of veterinary epidemiology including the design of targeted surveillance activities. Following the introduction to network analysis of livestock movement presented in Chapters 2 and 6 of this thesis, this chapter presents the first published investigation Australia's National Livestock Identification System sheep movement database.

7.1 ABSTRACT

Analyses of livestock movement data help veterinarians and policymakers understand the variability of potential infectious diseases transmission between farms in the real world. Livestock movement records also provide traceability in the event of a disease outbreak or food safety incident. Consequently, recording livestock movements is an increasingly common activity for governments and regulatory veterinary bodies. In Australia, movements are recorded for several species including sheep. This chapter reports the use of network analysis methods to describe sheep movement into, out of and within the state of Victoria, Australia, based on National Livestock Identification Scheme records. The sheep movement network in Victoria shows typical livestock movement network characteristics including scale-free and small-world topology, small diameter and short average path lengths. These characteristics suggest that, if infectious disease were not rapidly detected, the network could be vulnerable to the rapid and extensive disease spread. Victoria's position as a net importer of sheep and sheep flow is confirmed, driven substantially by the activity of saleyards (livestock markets) and abattoirs. Little variation within or between years in overall movement activity was detected. While most farms are connected to a very small number of other nodes in the network, small subsets of farms demonstrate high degree values or high frequency of sheep purchases or sales. These farms may be useful targets for emerging surveillance methods that can be implemented on-farm.

7.2 INTRODUCTION

Targeting surveillance to high-risk farms is an efficient method to detect both emergency as well as endemic diseases. In the state of Victoria, Australia, an estimated 11,000 sheep farms carry over 20% of Australia's 71 million sheep (Department of Economic Development, Jobs, Transport and Resources, 2014). The movement of sheep between farms, saleyards and to abattoirs form a network with potential to spread infectious disease. Since 2009, Australia has had a national system recording sheep movements, the 'mob-based movement' system of the National Livestock Identification Scheme (NLIS). Prior to the implementation of the NLIS, an investigation of sheep movement on a broad scale throughout the country was completed by East and Foreman (2011). That analysis took place during a period of industry restructure with a trend away from Merino production towards increasing sheep meat production, which has stabilised in more recent years (Agriculture Victoria, pers. comm.). With several years' data now available, an analysis of the NLIS records of sheep movement can now be undertaken, to better understand the flow of sheep between farms, saleyards and abattoirs.

Similar analyses have been conducted in other countries in sheep (Kao et al., 2006; Kiss et al., 2006; Volkova et al., 2010) and cattle (Robinson and Christley, 2007; Ribeiro-Lima et al., 2015; VanderWaal et al., 2016; Galvis et al., 2017). These studies provide some indication of what Australian sheep movement networks may look like, and are a starting point to select relevant measures for analysis. Describing a livestock movement network such as the NLIS sheep network has several potential applications (Dubé et al., 2011b), which include understanding the broad implications of the network structure for disease spread as well as identifying high-risk farms for targeted disease surveillance (Christley et al., 2005b). High-risk farms are often those that are highly connected in the network, such as farms that trade directly with many other farms (high degree), those whose trades form bridging links between otherwise separated parts of the network (high betweenness), or those that have indirect network connections to many other farms through livestock movements (ingoing and outgoing contact chains) with the potential for widespread dissemination of disease if the first farm were infected. The reader is referred to Appendix E for further discussion of these measures and the Glossary for definitions. Farms with particular patterns of trade, such as purchasing and then selling consignments of sheep within short periods of time, may also be useful targets for surveillance.

The main objective of this study was to describe the network of sheep movement in Victoria, Australia, as reported to the NLIS database. This description will demonstrate the trade patterns that affecting the flow sheep movement into, within and out of the Victoria, and identify the similarities and differences of the structure of this network, compared to sheep and cattle movement networks in other countries. The study also aimed to examine relevant node-level network measures to identify high-risk farms in the network that might be recruited for targeted farmer-based surveillance as proposed in Chapter 3. The intention here is to determine if use of different measures of approaches for detection of 'high risk farms' results in selection of the same (or similar) subset of farms.

7.3 METHODS

7.3.1 DATA SOURCE

The NLIS is "Australia's system for livestock identification and traceability" (Animal Health Australia, 2017), with two types of movement recording: 'mob-based movement' which captures data about the movements of groups (batches, or 'mobs') of animals and individual animal movements. The NLIS (cattle) system uses electronic identification (ear tags) to facilitate individual cattle movement recording and lifetime individual traceability. There is also potential for a future NLIS sheep system to move toward individual sheep movement recording, with compulsory individual electronic identification for sheep successfully introduced in Victoria in 2017 (Animal Health Australia, 2017). However, at present, the NLIS (sheep and goats) system operates by recording mob-based movements of sheep and farmed goats within Australia. It is compulsory to report all movements of groups of sheep and farmed goats to and from saleyards (livestock markets) and to abattoirs to the NLIS (sheep and goats) system, recording the source and destination properties. In Australia, every property which can hold livestock (including farms, saleyards, abattoirs, etc.) is required to have a unique property identification code (PIC), which is used as the unique property identifier for NLIS records. These PICs are associated with a centroid geographic location relevant to that property. However, under the system operational from 2010 to the time of writing in 2018, it is not compulsory to report movements directly between two farms, except for specific subsets of movement events such as a large stud's annual ram sales. Consequently, the sheep movement data collected by NLIS

(sheep and goats) in Australia is a targeted subset of certain movement types. Under this mob-based system, the movements of individual animals are not separately recorded, similar to the Animal Movement Licence scheme used in the UK for species other than cattle (Mitchell et al., 2005) and the Sanitary Management System (Sistema de Gestión Sanitaria, SGS) used for cattle in Argentina (Aznar et al., 2011). This is in contrast to the movement records which distinguish individual animals for the NLIS (cattle) system in Australia (Animal Health Australia, 2017) and many cattle movement recording systems in Europe and the United Kingdom (Anonymous, 2000).

For the analyses reported in this chapter, mob-based movement records were extracted from the NLIS (sheep and goats) database for dates between 1 January 2010 to 31 December 2015. Each movement represents the movement of one or more animals (a 'mob'), in this case restricted to movements of sheep. The data accessed was limited to movements where the centroid of the either source property, saleyard or destination property were located in Victoria. A single extracted record contained the following data relevant for the analyses presented in this chapter:

- Date of movement
- Source PIC
- Saleyard PIC (only if the movement occurred through a saleyard)
- Destination PIC
- Number of sheep in the mob moved, as despatched from the source property
- Number of sheep in the mob received by the destination property (at saleyards a mob may be split into two or more groups with different final destinations, so this number may differ from that despatched from the source)

In Australia, PICs are an 8-digit alphanumeric code which indicates limited information about the property type and broad geographic location of each property. The way these data are encoded varies between states, e.g. the PIC '3ABLE064' indicates an abattoir in Victoria because it contains the pattern '3ABxxxxx', compared to the PIC 'NI994711' which indicated an abattoir in NSW based on the pattern 'Nx99xx1x'. Full decoding information was not available for all states' PIC codes for this analysis. The data that could be derived from the PIC codes and therefore was available for the analyses presented in this chapter are summarised in Table 7-1. Additional spatial data (PIC centroid locations) were also sourced for these analyses, but were only available for PICs located in Victoria.

After extraction, any non-sheep records were removed from the dataset. The remaining records were then cleaned to remove invalid PICs and duplicate records, and then processed into four edgelist for network analysis. An edgelist is one way of presenting network data, with each row of data describing an individual edge in the network, and columns for the source node and destination node for each edge, as well as additional columns if needed for edge attributes such as date or the number of animals moved. The four edgelists constructed are briefly described here and summarised in Table 7-2, along with the relevant available edge and node characteristic data. In all cases, explicit date values for each edge were maintained, meaning there could be multiple edges in the edgelist with the same source and destination node, each with a unique date of movement. When multiple edges connecting the same nodes were aggregated over time, two additional edge weights were defined: the frequency of edge occurrence and the total number of sheep moved on that edge in the aggregation timeframe.

TABLE 7-1. PROPERTY TYPE AND SPATIAL INFORMATION AVAILABLE FOR ANALYSIS SHEEP MOVEMENT RECORDS FROM THE NLIS (SHEEP AND GOATS) DATABASE IN AUSTRALIA, BASED ON DECODING OF PIC CODES.

State	Property types distinguishable	Spatial location information
Victoria (VIC)	Abattoir, Agent, Farm, Saleyard	Shire within Victoria
New South Wales (NSW)	Abattoir, Saleyard, Other (primarily farm)	State only
South Australia (SA)	Abattoir, Saleyard, Other (primarily farm)	State only
Tasmania (TAS)	Saleyard, Other (primarily farm)	State only
Queensland (QLD)	No distinction	State only
Western Australia (WA)	No distinction	State only

Where appropriate, temporal aggregation by year was undertaken to create static networks. Annual aggregation has been shown to demonstrate topology that mimics that of the temporal network. For example, Lentz et al. (2016) demonstrated that paths between nodes in a static network aggregated over a year or more represent true time-respecting paths in the corresponding temporal network in ~70% of cases. While this result was based on a pig trade network, where the average lifetime of pigs

is 180 days (Konschake et al., 2013), little sheep-specific evidence is available to determine suitable temporal aggregation windows. Therefore, network-based measures on temporally aggregated static networks should be interpreted with caution. Wherever possible, the temporality of the network was maintained, however not all desirable measures could be calculated for temporal networks because methods and software capable of calculating some measures are still emerging.

Multiple edgelists were used in the analyses presented because the activity of saleyards network can be represented in a network in multiple ways: Saleyards can be treated as nodes (because they are epidemiologically important to the broad dissemination of disease, as in the outbreak of FMD in the UK described by Gibbens et al., 2001), as edge characteristics as a transient part of another movement (which gives a better understanding of the overall movement of sheep across the state), or even represented in a 2-mode network (farms and saleyards). Furthermore, the network can be viewed either including or excluding abattoirs. Excluding abattoirs can be justified by their network behaviour as ‘sinks’ (or dead-ends) for disease transmission. However, including abattoirs in the network is useful to understand the influence of abattoir activity on the overall flow of sheep through the network, as well as for the influence of spatial and network characteristics on the generalisability of abattoir surveillance activities.

A further complexity arises when movements occur via saleyards. Each record extracted from the database can describe either a single movement (e.g. from farm i to farm j , or from farm i to abattoir a), or describe multiple movements where animals moved from the source farm through a saleyard to multiple destinations (e.g. from farm i to saleyard s , where animals were split into two groups of size n and m and sent on to farm j and abattoir a respectively). Splitting these records into their single movements with saleyards as nodes in the network was useful for some analyses including investigation of degree values, whereas maintaining the origin and final destination of each movement with saleyard used as an edge characteristic was more meaningful for other investigations such as spatial patterns of movement.

The networks represented by the four edgelists that were constructed are described throughout this chapter as the ‘interstate-Victorian movement network’, the ‘within-Victoria movement network’, the ‘interstate-Victorian source-destination network’ and the ‘within-Victoria shire network’.

TABLE 7-2. SUMMARY OF FOUR NETWORKS CONSTRUCTED FROM NLIS (SHEEP) MOVEMENT RECORDS.

Characteristic	Interstate-Victorian movement network	Within-Victoria movement network	Interstate-Victorian source-destination network	Within-Victoria shire network
Nodes	Properties within and outside VIC, including saleyards	Properties inside VIC only, including saleyards	Properties within and outside VIC, excluding saleyards	Shires in VIC
Node characteristics	PIC ID	PIC ID	PIC ID	
	Centroid longitude & latitude	Centroid longitude & latitude	Centroid longitude & latitude	Shire ID
	State location	State location	State location	Polygon location
	Property type	Property type	Property type	
Edges	Mobs of sheep moved between nodes of any type	Mobs of sheep moved between nodes of any type	Mobs of sheep moved from farms, to farms or to abattoirs	One or more mobs of sheep moved between shires
Edge characteristics (non-aggregated)	Date	Date	Date	Date
	Number of sheep moved	Number of sheep moved	Number of sheep moved	Frequency
	Import/export type ^a		Import/export type ^a	
Edge characteristics (temporally aggregated)	Number of mobs moved on edge in timeframe	Number of mobs moved on edge in timeframe	Number of mobs moved on edge in timeframe	Number of mobs moved on edge in timeframe
	Total sheep moved on edge in timeframe	Total sheep moved on edge in timeframe	Total sheep moved on edge in timeframe	
	Import/export type ^a		Import/export type ^a	
Handling of movements via saleyards	Movements via saleyard result in two or more edges: one source-to-saleyard edge and	Movements via saleyard result in two or more edges: one source-to-saleyard edge and	Saleyard involvement used as an edge property. Movements via saleyard resulted in a	Saleyard involvement in movements ignored

Characteristic	Interstate-Victorian movement network	Within-Victoria movement network	Interstate-Victorian source-destination network	Within-Victoria shire network
	then one or more saleyard-to-destination edges	then one or more saleyard-to-destination edges	number of edges equal to the number of different destinations resulting from a single movement	
Edges included	Edges where at least one node was located in VIC	Only edges where both nodes were located in VIC	Edges where at least one node was located in VIC	Edges between two farms located in different VIC shires
Edges excluded	Edges where both nodes were outside VIC (for example, an interstate farm moving animals to an interstate saleyard)	Edges where one or both nodes were outside VIC	Edges where both nodes were outside VIC (for example, an interstate farm moving animals to an interstate saleyard)	Movements within a single VIC shire, movements where the destination was an abattoir
Years of data used	2015 only	2015 only	2015 only	2010 to 2015
Temporal aggregations	None (daily resolution) Annual (2015)	None (daily resolution) Annual (2015)	None (daily resolution) Annual (2015)	Monthly (in 2015) Annual (2010 to 2015)

^aImport/export movement types included 'movement within Vic', 'import into Vic', 'export from Vic'.

The **interstate-Victorian movement network** split the NLIS (sheep) records into individual movements, with each edge representing a group of animals that were moved from a single source to their next destination. For example, an NLIS record describing the movement of sheep from a farm through a saleyard to one or more destinations was split into multiple edges: one for the first movement from farm to saleyard, and additional edges to indicate the movement of those same animals from the saleyard onto the final destination(s) of that movement. Any resulting edges where both source and destination nodes were interstate PICs were then removed from the edgelist. The result was that at least one node in every pair linked by an edge in the edgelist was located in Victoria. This edgelist was temporally constrained to only include movements occurring between 1 January 2015 and 31 December 2015, inclusive.

The **within-Victoria movement network** was a subset of the interstate movement network, including only those edges where both nodes were located in Victoria (i.e. removing edges that were either ‘imports’ or ‘exports’ from Victoria). Again, the edgelist was temporally constrained to examine movements occurring between 1 January 2015 and 31 December 2015, inclusive.

The **interstate-Victorian source-destination network** took an alternative approach, where movements occurring via saleyards were not separated into multiple edges. Rather, for movements that occurred via saleyard, edges were designated to begin at the farm where the sheep were despatched, and to end at the final destination of those sheep. The saleyard through which the animals moved was included as an edge characteristic. Edges were classified as ‘import’, ‘export’ or ‘within-Victoria’ movements, depending on the location of the source and destination nodes. For movements where a mob of sheep were split at a saleyard and sent to multiple destinations, the number of edges generated was equal to the number of different destinations reported, with the source farm the same for each edge. The number of sheep received by each destination node in each movement, as recorded in the original movement records, were used as edge weights. Movements that were not via a saleyard resulted in a single edge from source to destination, with the ‘direct’ nature of the movement included as an edge characteristic. Once more, the edgelist was temporally constrained to examine movements occurring between 1 January 2015 and 31 December 2015, inclusive.

The **within-Victoria shire network** was constructed by aggregating Victorian farm nodes into recognised local government regions known as ‘shires’. There were 59 shires in Victoria with one or more registered PICs. This edgelist was created by extracting the subset of edges from the interstate-Victorian source-destination network where both the source and destination nodes were Victorian farms, resulting in a one-mode network (also referred to as a unipartite graph, where all nodes were of the same type as defined by Borgatti and Everett, 1997 and Guimerà et al., 2007). All interstate PIC and Victorian abattoir nodes were therefore excluded from the edgelist. This was intended to give a clearer picture of the potential disease spread risk across the state, by restricting the network to movements of sheep not destined for slaughter, as proposed by Martínez-López et al. (2009). After extracting only farm-to-farm edges, nodes were relabelled from their farm PICs to the ID of the shire in which it located (according to its PIC). The edges were then aggregated to give a single unique edge between any two shires on a given date (i.e. originating from any farm in shire i and moving to any farm in shire j), with edge weight equal to the number of movements on that edge on that date. The validity of spatial aggregations of network data prior to analysis has been previously described (León et al., 2006; Martínez-López et al., 2009). The resulting ‘shire edgelist’ was then temporally aggregated into both monthly static networks for all months in 2015, and into annual aggregations for all calendar years between 2010 and 2015. In each temporal aggregation, edge weights were the total number of movements between that pair of shires within the timeframe.

7.3.2 NETWORK ANALYSIS

Network summary measures were calculated for both the interstate-Victorian and within-Victoria movement networks as static networks aggregated over a year (2015). Although values are primarily reported for the interstate-Victorian movement network, measures were calculated for both networks throughout the analysis. In Australia, state governments are responsible for delivering surveillance and disease control programs, so detailed investigation of the network constrained to movements within Victoria provide relevant information to develop state-level policies for disease control. However, because infectious diseases do not generally respect jurisdictional boundaries, describing interstate network connections is also meaningful for disease risk.

Network summary measures calculated included diameter, average path length, density, and global clustering coefficient (calculated as the mean local clustering coefficient across all nodes). Centralisation indices were also calculated for both networks, expressed as a percentage of the theoretical maximum that could occur in a network with the same number of nodes. These indices included in-, out- and total degree and betweenness centrality. Reciprocity was examined for both networks, to describe how frequently node pairs were connected by edges in both directions in the static network. The size and composition of the giant strongly connected component and giant weakly connected component were also identified for both networks.

The topology of the network was investigated by considering the typical characteristics of small-world and scale-free networks. Namely, a small-world network typically has short average path length and a high clustering coefficient, although the exact values that define 'short' and 'high' appear to be relative. These highly clustered networks facilitate rapid spread of infectious disease, with high probability of spread within local clusters as well as the possibility of disease spread between clusters by high betweenness 'bridging' nodes in the network. A scale-free network is technically defined as having a power-law degree distribution, which in this case was assessed by plotting the frequency distribution of degree values on a log-log scale and visually assessing for linearity. The small number of high degree nodes occurring in a scale-free network are at increased risk of acquiring (high in-degree) or disseminating (high out-degree) disease throughout the network, facilitating disease spread more easily than a random network where degree distribution is homogeneous.

Farm nodes at potential increased risk for acquiring or disseminating disease were identified in a number of ways: using standard node centrality measures (degree, weighted degree and betweenness); using emerging centrality measures that incorporate time-respecting paths in the network (incoming and outgoing contact chains, and probability of disease ratio); by examining the characteristics of edges arising from farms (average distance per movement, average number of head per movement, and annual movement frequency); and by looking for a specific pattern of movements, termed 'trading pattern'.

Summary measures of in-, out- and total degree were calculated in both the interstate-Victorian movement network and within-Victoria movement networks, both for all

nodes and for the subset of Victorian farms and Victorian saleyards in both networks aggregated to static networks for the 2015 year. Correlation of in- and out-degree for Victorian farms was tested using Spearman's rank correlation, corrected for ties, with 95% confidence intervals bootstrapped with 1000 replicates. Degree values for each node were also examined after being weighted in two ways: the frequency of movements on each edge in the network in 2015, and the total number of sheep moved on each edge in 2015. Node betweenness was also examined. Both networks (without temporal aggregation) were then used to calculate the size of the ingoing contact chain, outgoing contact chain and probability of disease ratio (Frössling et al., 2014) in the time period 1 January 2015 to 31 December 2015. The PDR was calculated with a uniform prior prevalence value (probability of infection = 0.08) for all nodes.

To identify non-saleyard nodes that might be acting as traders (purchasing and selling animals frequently or in quick succession) a particular movement pattern was investigated in the interstate movement network. This 'trading pattern' of movement was defined as a pair of edges where a non-saleyard node received one mob of sheep, and then proceeded to despatch a mob of sheep in the subsequent 21 days. As the mob-based NLIS (sheep) data did not identify the individual animals in a consignment, it cannot be determined whether such a pair of movements would contain one or more of the same sheep. However, even if the two mobs were entirely different sheep, it remains possible for infectious disease to be spread between the two groups of sheep in those intervening days, either by direct contact or through contamination of land, equipment or personnel used for both mobs, such as sheep yards and loading races. Nodes with frequent occurrence of 'trading pattern' edge pairs were identified in the data, as a proxy to identify these potential trader nodes that might be important targets for surveillance. The movement types contributing to 'trading pattern' edge pairs were examined, as well as the number of days separating the two movements. Nodes where there were multiple cases of 'trading pattern' in the 2015 were examined, in particular to identify attributes of nodes undertaking this pattern frequently. Where there were multiple mobs received or despatched from a node within a 21-day period, each unique pair appears as an individual instance of 'trading pattern' – i.e. if purchased sheep from a saleyard two weeks in a row and then sold sheep in the third week, this would appear as two separate instances. These instances were retained in the analysis because each represents a pair of possible infection and

dissemination events, were the purchased mob infected with a disease and the mob subsequently sold already infected. Nodes with 'trading pattern' occurring on consecutive days were also investigated, as they may be acting as agents or buyers for abattoirs which again may have increased risk of acquiring and/or disseminating disease. This analysis of 'trading pattern', especially where the movements had a farm-saleyard-farm pattern, bears similarity to the approach used by Kao et al. (2006) when they examined movements bridging between livestock markets in the livestock movement network of the Great Britain.

To examine the distance moved by mobs of sheep in the within-Victoria movement network, centroid location data were required. These data were available for all Victorian saleyards and abattoirs and for 13,090/14,054 (93%) Victorian farms recorded in the 2015 network. As a result, movement distance could be calculated for 143,588/178,942 (80%) individual movements. Distances were calculated using the Haversine method as the shortest distance between two points (i.e. 'as the crow flies') based on longitude and latitude using the *geosphere* package (Hijmans, 2016) in R. For movements that occurred via saleyards, the total movement distance was calculated as the sum of distances between the source farm and the saleyard and the saleyard to the destination. The correlation between movement distance, number of sheep per movements and frequency of movement in 2015 was estimated using Spearman's rank correlation, corrected for ties, with 95% confidence intervals bootstrapped with 1000 replicates.

To determine whether the overall network of sheep movement varied substantially over time, the quadratic assignment procedure (QAP) was used to investigate the within-Victoria shire network. The QAP is a test of edge correlation between two networks with the same set of nodes that simultaneously controls for overall network structure. It uses a Markov-Chain Monte Carlo (MCMC) simulation of likelihood quantiles to determine the similarity in edges between the two networks. It uses pairwise comparison of all edges in the two networks to give a Pearson correlation coefficient (and p-value) to show whether the presence of each edge in the network at one point in time is correlated with its presence in the same network at another time. The null hypothesis is that there is no correlation of edges between the network at different times; the alternative hypothesis is that the presence of edges are correlated. The p-value therefore indicates the probability that there is no correlation between

the edges in the two networks, given the available data. The QAP has had limited previous applications to livestock movement data (Thakur et al., 2014; Marquetoux et al., 2016a), testing correlations between network connections and production type, region or disease status. The within-Victoria shire network was used for these analyses, aggregated monthly into static networks representing all movements within Victoria, using each month in 2015 to detect differences at a monthly scale, and annual static networks for years from 2010 to 2015 to detect longer-term changes over time. The within-Victoria shire network was used for these analyses because the MCMC procedure required by the QAP is highly computationally intensive and, as presently implemented in the *sna* package (Butts, 2016) in R, it is not optimised for networks with hundreds or thousands of nodes.

The within-Victoria shire network was also used to explore the geographic pattern of sheep movement within Victoria. Visualisation of spatial patterns of movement in livestock movement network analyses is challenging, because for networks with many edges, including all movements in a visualisation quickly renders it overcomplicated and impossible to interpret. By using shires as nodes in the network, and visualising only edges above a threshold frequency (≥ 52 movements on edge in the year, i.e. on average at least one movement per week), the coarse geographic pattern of movement could be appreciated. These patterns were verified by community detection analysis. Communities in the network are groups of nodes, where it is more likely that an edge exists between two nodes in the same community than an edge between two communities. For livestock movement networks, this means that an animal is more likely to be traded within a community than between communities (Grisi-Filho et al., 2013). There are many algorithms available for community detection, not all of which are easily implemented in existing software. In this study, community detection was performed using the walktrap algorithm (Pons and Latapy, 2006) from the *igraph* package (Csardi and Nepusz, 2006) in R, which was selected for its favourable performance on both small and large networks (Yang et al., 2016), despite the fact that for simplicity it treats directed networks as undirected when identifying the communities (Pons and Latapy, 2006).

All statistical and network analyses were completed using the *igraph* (Csardi and Nepusz, 2006), *sna* (Butts, 2016), and *EpiContactTrace* (Nöremark and Widgren, 2014) packages in R statistical software 3.4.1 (R Core Team, 2017). Network data were visualised using R and Gephi v.0.9.1.

7.4 RESULTS

7.4.1 DESCRIPTIVE OVERVIEW OF SHEEP MOVEMENT NETWORKS

The interstate-Victorian movement network documented 19.6 million individual sheep movements in 298,511 mob movements in 2015. These movements occurred on 34,894 unique edges between 18,484 nodes, including farms, saleyards, abattoirs and agents. The network had a diameter of 12 with an average path length of 4.45. The network had low density (0.00010) yet substantial global clustering coefficient (14.1%) characteristic of a small-world network, particularly notable considering that many nodes (69%, 10,216/18,484) had zero local clustering coefficient because they had a total degree of one (that is, they were connected to only one other node in the network). When these degree-one nodes were excluded, the global clustering coefficient increased to 31.5%, indicating that substantial clustering was present in the main central component of the network. Global total degree centralisation was 9.9%, with in- and out-degree centralisation of 15.9% and 3.8% respectively, and global betweenness centralisation of 9.0%. Values for the within-Victoria movement network were similar, indicating that excluding interstate edges in the network made little difference to overall network characteristics.

Most edges in the network connected node pairs in one direction only, with edges reciprocated in only 10.5% of cases. Reciprocated movements primarily existed between pairs of farms (5.3% of edges reciprocated), or between farms and saleyards (18.2% of edges reciprocated). Overall reciprocity was low, because abattoirs did not sell any sheep and many Victorian farms (66%, 9277/14,054) in the network did not have any recorded sheep purchases. Almost half of the farms that both purchased and sold sheep through saleyards did so through the same saleyard (reciprocity 43.3% for farm-saleyard edges, excluding nodes with zero in- or out-degree), and a tenth of farms both purchased and sold sheep to the same other farm (reciprocity 11.3% between pairs of farms).

The 298,511 mob movements in the interstate-Victorian movement network in 2015 included:

- 178,942 movements within Victoria, describing 11.3 million individual sheep movements between 24,347 unique Victorian node pairs;
- 94,944 import movements, describing 6.2 million individual sheep movements from interstate into Victoria between 6776 unique node pairs; and
- 24,625 export movements, describing 2.0 million individual sheep movements from Victorian nodes out of the state between 3771 unique node pairs.

Further details of the frequency of different movement types, including description of the flow of sheep into abattoirs, are available in Appendix G.

7.4.2 NODE MEASURES: IDENTIFYING INCREASED DISEASE RISK

The 18,484 nodes in the interstate-Victorian movement network are summarised by type and state location in Table 7-3. The majority of nodes (76%) were Victorian farms, while 22.8% of nodes were interstate. The geographic distribution of Victorian farms present in the network aggregated by shire is shown in Figure 7-1.

TABLE 7-3. NODE TYPES IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK FOR SHEEP MOVEMENT IN 2015.

Property type	Number of unique PICs						Total
	VIC	NSW	SA	TAS	QLD	WA	
Farm	14,054						14,054
Saleyard	27	22	16	1		4	70
Abattoir	34	9	8				51
Agent	100						100
Type unavailable (likely primarily farms)		2024	1690	412	46	37	4,209
Total	14,215	2055	1714	413	46	41	18,484

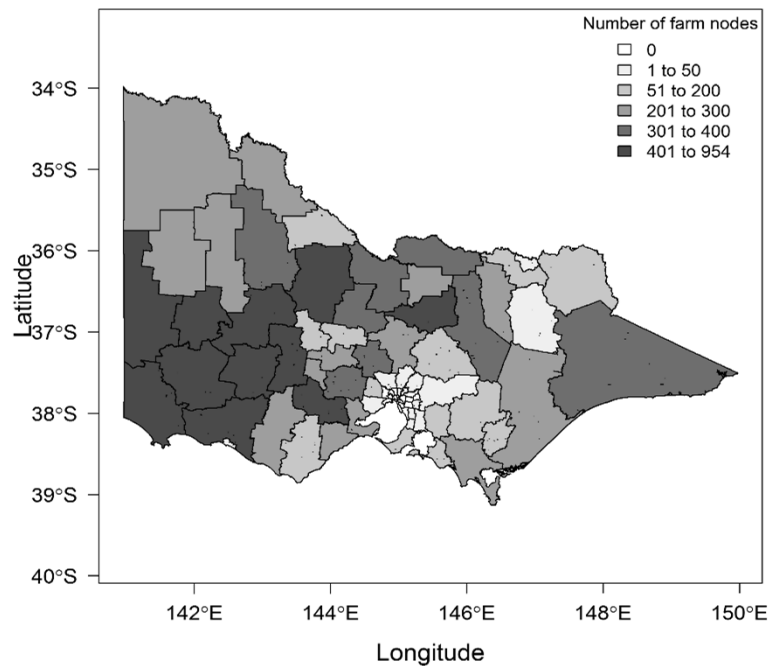


FIGURE 7-1. LOCATIONS OF VICTORIAN SHEEP FARMS IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK, AGGREGATED BY SHIRE.

7.4.2.1 NODE CENTRALITY MEASURES

Total degree values in the interstate-Victorian movement network had a mean of 3.78 and median of one, indicating most nodes were connected to few others (Table 7-4). Considering Victorian farm nodes only, the mean total degree was 2.2 (median 1). In- and out-degree values were also low in both networks. The degree distributions including all node types in both the interstate-Victorian movement network and the within-Victoria movement network are shown in Figure 7-2. The coefficient of variation (CV) for degree values in the interstate-Victorian movement network was in-degree 22.4, out-degree 5.2, total degree 13.3, with low correlation between in- and out-degree values (Spearman's ρ 0.058, 95% CI 0.040 to 0.076). Using equation (2) from Chapter 6, the basic reproductive number (R_0) of an outbreak of disease is estimated to increase by a factor of 7.8 due to heterogeneous contact in the network, based on these CV and correlation values.

Some Victorian farms in the within-Victoria movement network traded solely with interstate nodes for both incoming and outgoing sheep movements, indicated by 796 farms having zero total degree when nodes located interstate were excluded from the network. Degree distributions for Victorian farm nodes in both the interstate-Victorian movement network and within-Victoria movement network are shown in

Figure 7-3, with the strongly skewed distributions suggestive of scale-free network topology.

TABLE 7-4. MEAN AND MEDIAN VALUES FOR IN, OUT AND TOTAL DEGREE IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK.

Node type	Degree type	Count of nodes with zero degree	Mean	Median	Max
All nodes	In-degree	12,692	1.89	0	2943
	Out-degree	1214	1.89	1	705
	Total degree	0	3.78	1	3648
Victorian farms	In-degree	9277	0.53	0	98
	Out-degree	761	1.66	1	167
	Total degree	0	2.19	1	248
Victorian saleyards	In-degree	0	504.1	257	2943
	Out-degree	0	149.0	73	705
	Total degree	0	653.1	375	3648

In- and out-degree values for Victorian farms in the interstate-Victorian movement network were not strongly correlated (Spearman's rho 0.12, 95% CI 0.10 to 0.14), with similar results in the within-Victoria movement network. There were 657 Victorian farms in the interstate-Victorian movement network with total degree >5, although only 15 farms had both in- and out-degree >5. Six of those 15 farms were receiving and selling sheep in very small numbers, largely directly to other farms (average movement size range 1 to 33), suggestive that they were stud farms primarily buying and selling rams. The remaining nine farms in the interstate network, one of which was also the remaining farm in the Victoria-only network, had far larger average movement size (range 309 to 1397), purchasing and selling from agents, farms and saleyards and selling to farms, saleyards and abattoirs. These farms could be considered as potential 'superspreader' farms in the network (Lloyd-Smith et al., 2005), with a mean total movements per farm of 106 (range 18 to 336 movements).

Victorian saleyards in the interstate-Victorian movement network had a mean total degree of 653 (median 375) with mean in-degree 504 (median 257) and out-degree 149 (median 73). Victorians saleyard in- and out-degree were strongly correlated (Spearman rho 0.89, 95% CI 0.72 to 0.96). The two highest in-degree saleyards were also the two highest out-degree saleyards.

Considering degree values weighted by both number of sheep moved and frequency of movements in the interstate-Victorian movement network, the average Victorian farm purchased a mean of two consignments totalling 88 sheep, and sold a mean six consignments totalling 558 sheep. However, small numbers of farms were moving animals substantially more often or in increased volumes. Victorian farms in the top 20% of frequency-weighted degree values were responsible for 64% of all sheep movements to and from Victorian farms. Similarly, Victorian farms in the top 20% of number of sheep-weighted degree values were responsible for the movement of 71% of all sheep moved to and from Victorian farms. There were 48 Victorian farms with values in the top 1% for weighted degree values. These 48 farms purchased a mean total of 5959 sheep in 140 consignments and sold a mean total of 7298 sheep in 43 consignments. Together these 48 farms were responsible for 7% of all sheep moved to and from Victorian farms. Table 7-5 summarises weighted degree values for Victorian farms, saleyards and abattoirs.

TABLE 7-5. SUMMARY OF WEIGHTED DEGREE FOR NODES IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK.

	Node type	Degree type	Mean	Median	Max
Weighted by frequency (movements per node)	Victorian farms	In	1.69	0	1017
		Out	5.82	4	324
		Total	7.57	4	1144
	Victorian saleyards	In	2389	507	23,156
		Out	4427	819	31,731
		Total	5851	1341	52,816
	Victorian abattoirs	In	5015	2347	18,183
		Out	N/A	N/A	N/A
		Total	5015	2347	18,183
Weighted by sheep numbers (sheep moved per node)	Victorian farms	In	88	0	20,733
		Out	558	196	51,309
		Total	666	230	51,309
	Victorian saleyards	In	187,634	27,471	1.5 million
		Out	187,631	27,193	1.5 million
		Total	375,164	54,664	3.0 million
	Victorian abattoirs	In	306,478	154,322	1.3 million
		Out	N/A	N/A	N/A
		Total	306,478	154,322	1.3 million

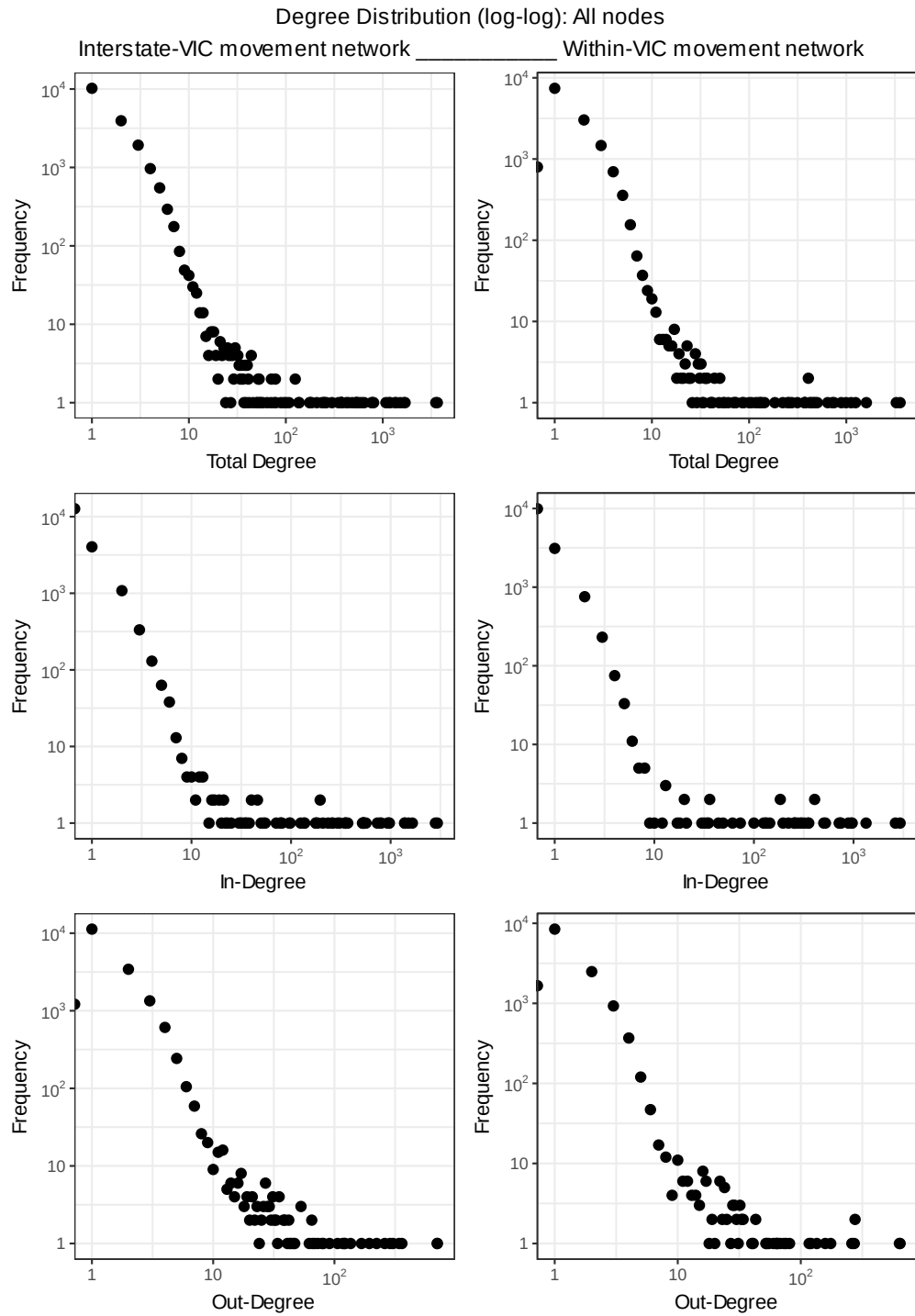


FIGURE 7-2. DISTRIBUTION OF TOTAL, IN- AND OUT-DEGREE VALUES INCLUDING ALL NODES IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK (LEFT) AND THE WITHIN-VICTORIA MOVEMENT NETWORK (RIGHT).

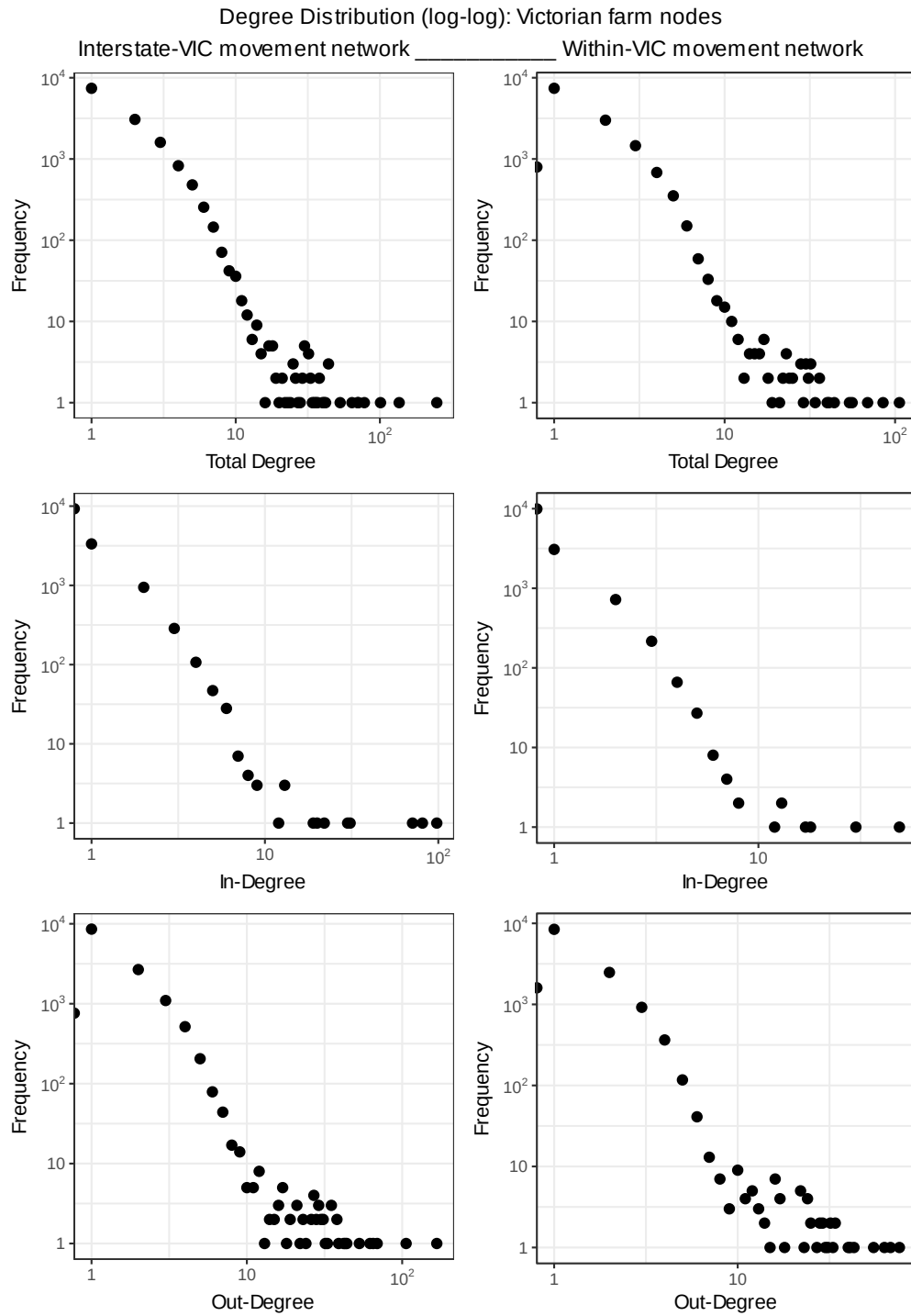


FIGURE 7-3. DISTRIBUTION OF TOTAL, IN- AND OUT-DEGREE VALUES OF VICTORIAN FARM NODES IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK (LEFT) AND THE WITHIN-VICTORIA MOVEMENT NETWORK (RIGHT).

Betweenness was low for most nodes in the interstate-Victorian movement network (81.7% had zero betweenness, 15,107/18,484), because nodes with require both in-degree and out-degree ≥ 1 , and must be on the shortest path between two other nodes, to have betweenness >0 . The remaining 3377 nodes in the network had median betweenness of 997 (i.e. were on the shortest path between a median of 997 other node pairs). Of the nodes with non-zero betweenness, 87% (2950/3377) were Victorian farms, with median betweenness of 1095.

Time-respecting centrality measures calculated for the interstate-Victorian network included the incoming contact chain (ICC), outgoing contact chain (OCC), and the probability of disease ratio (PDR). Victorian farms had zero median ICC (first quartile, Q1, 0; third quartile, Q3, 50) and median OCC size 2986 nodes (Q1 1987; Q3 3309). By definition, Victorian farms with zero in- or out-degree also had a zero contact chain for that direction of movement. Excluding these farms, the median contact chain sizes were ICC 7869 nodes (Q1 36; Q3 12312) and OCC 3008 nodes (Q1 2346; Q3 3331). Victorian farms with an in-degree greater than 1 had a median PDR of 6.3 (Q1 1.6; Q3 12.5); these farms had their probability of incoming infectious contact increased by 6.3 times due to their incoming sheep movements, compared to an equivalent farm with zero in-degree and assuming all nodes in the network had the same baseline probability of infectious disease. Of Victorian farms with values in the top 1% for these measures ($n = 141$ farms with ingoing infection chain $\geq 13,114$; $n = 217$ farms with outgoing infection chain ≥ 3823 ; $n = 223$ farms with PDR = 12.5), no farms were in the top 1% for both ICC and OCC, and only one farm was in the top 1% for both OCC and PDR. However, 44 farms had values in the top 1% for both ICC and PDR.

7.4.2.2 DETECTING TRADING EVENTS IN THE NETWORK

There were with 57,548 pairs of edges fitting the ‘trading pattern’ criteria in the interstate-Victorian movement network, with 2019 non-saleyard nodes having at least one instance of ‘trading pattern’, primarily Victorian farms (82%, 1652/2019). Of the 57,548 ‘trading pattern’ edge pairs, three patterns were common: sheep bought from a saleyard followed by a movement to another farm (36% of cases), sheep bought from a saleyard followed by a movement back to a saleyard (27% of cases), or sheep bought from a saleyard followed by a movement to an abattoir (26% of cases) as shown in Table 7-6. The most common time intervals between the first and second

movements of the 'trading pattern' edge pairs were seven, fourteen or twenty-one days (Figure 7-4), representing 35% of cases (19,948/57,548).

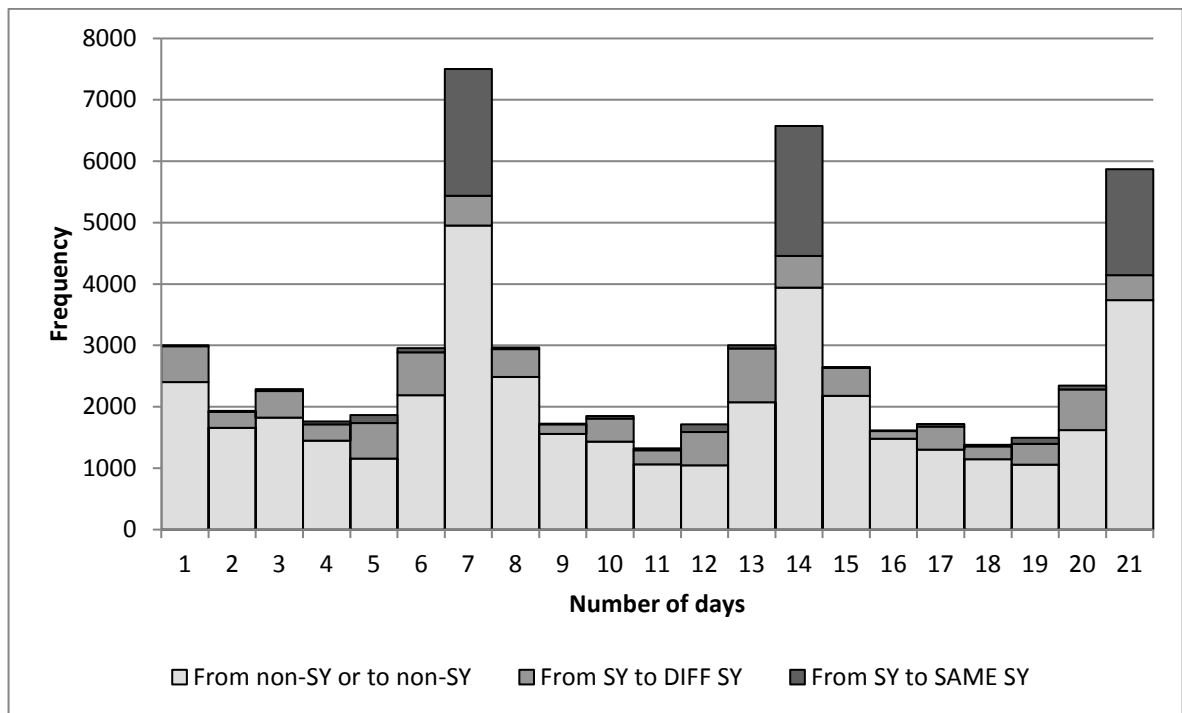


FIGURE 7-4. TIME DIFFERENCE BETWEEN ON-MOVEMENT AND OFF-MOVEMENT IN INSTANCES OF 'TRADING PATTERN' OF ≤ 21 -DAY INTERVAL IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK, CATEGORISED BY ORIGINAL SOURCE AND FINAL DESTINATION; SY = SALEYARD, DIFF = DIFFERENT.

TABLE 7-6. INITIAL SOURCE AND FINAL DESTINATION TYPES IN INSTANCES OF 'TRADING PATTERN' IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK.

First movement (to 'trading pattern' node)	Second movement (from 'trading pattern' node)			Total
	To saleyard	Direct to other farm	Direct to abattoir	
Direct from other farm or agent	3483 6%	1451 3%	1314 2%	6248 11%
From saleyard	15,529 27%	20,883 36%	14,888 26%	51,300 89%
Total	19,012 33%	22,334 39%	16,202 28%	57,548 100%

Considering interstate or within-state trade as well as node type, there were two equally common styles of 'trading pattern' on the 2019 Victorian farms: both styles included an initial purchase from a Victorian saleyard, and were distinguished by a subsequent movement to a Victorian abattoir (representing 37% of all 'trading pattern' instances for Victorian farms) or a subsequent movement to another Victorian saleyard (a further 37% of all instances for Victorian farms). The next most common (6% of instances) were initially a purchase from a Victorian farm followed by a movement to a Victorian saleyard. The remaining movements had an initial purchase from a Victorian farm, interstate saleyard and other interstate property, and a subsequent movement to destinations including both interstate and Victorian saleyards, abattoirs and farms; each possible combination of these remaining movements represented < 3% of instances. While instances of trading pattern were unlikely to involve the same individual sheep, they still represent sheep trading behaviour of interest for disease surveillance.

There were 666 Victorian farms in 2015 that purchased animals from a Victorian saleyard and then sold animals at a Victorian saleyard within 21 days, and again the most common interval between the two movements was 7, 14 or 21 days. Both movements were through the same saleyard in 68% (458/666) of cases. The highest frequency farms had ≥ 13 instances of 'trading pattern' through the same saleyard, representing the top 11% (49/458) of farms. Most farms only had a single occurrence of 'trading pattern' between two saleyards. However, 30 farms (29 Victorian and one NSW farm) had more than 26 instances of 'trading pattern' in 2015 (summarised in Table 7-7), averaging one or more instance per fortnight. Information to verify the nature of their trading activity was not available for this analysis. Seven of the nine 'superspreader' farms identified in the degree analysis (Section 7.4.2.1) were also identified by having multiple cases of 'trading pattern' in 2015, ranging from 16 to 1705 instances. Three of the seven farms had > 100 instances.

TABLE 7-7. NUMBER OF VICTORIAN SALEYARD TO VICTORIAN SALEYARD 'TRADING PATTERN' INSTANCES PER FARM IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK.

Number of saleyard to saleyard 'trading pattern' instances		Number of farms*
1		260
2		148
3-6		150
7-13		71
14-26		29
27-52		14
23-100		7
101-2895		9

* Farms located in Victoria (n = 666), NSW (n = 21) and SA (n = 1).

One or more occurrences of 'trading pattern' of a single day's duration (i.e. an incoming movement recorded one day followed by an outgoing movement the following day) were detected for 29 Victorian agent nodes, as well as for 122 Victorian farms. The instances of agents with single day duration 'trading pattern' were always from a saleyard via the agent and then onto a farm, with 85% from Victorian saleyards to Victorian farms, and the remainder to interstate farms. However, for instances of single day duration 'trading pattern' through Victorian farms, most of the outgoing movements were either to another saleyard (62% of instances) or to an abattoir (33%). Almost half (56/122) of these Victorian farms moved 100% of the relevant outgoing movements to abattoirs, although only four did so frequently (≥ 10 instances). The remaining 66 farms had at least one instance of an outgoing movement to a saleyard or farm, including four farms with frequent (≥ 10 instances) single day duration 'trading pattern'. Of the 29 Victorian farms identified as potential traders based on high frequency (≥ 26 in 2015) of 'trading pattern' through two saleyards, nine also had instances of single day duration 'trading pattern', with eight having multiple instances.

7.4.2.3 AVERAGE MOVEMENT CHARACTERISTICS FOR FARM NODES

In 2015, Victorian farms moved a median of 24 sheep per movement (first quartile, Q1, 6; third quartile, Q3, 63) and with a median distance from source to destination of 176km (Q1 107km; Q3 258km) with a median of 6 movements per year (Q1 3

movements per year; Q3 13 movements per year). There was poor correlation between the within-farm mean distance per movement and within-farm mean number of sheep per movement (Spearman's rho 0.15, 95% CI 0.12 to 0.16, Figure 7-5), and similarly poor correlation between mean distance per movement and the frequency of outgoing movements (Spearman's rho 0.17, 95% CI 0.16 to 0.19, Figure 7-6). Despite low correlation overall, 27 farms exceeded the 95th percentile for both within-farm mean distance and mean sheep per movement, and 20 farms exceeded the 95th percentile for both mean distance and movement frequency. No farms exceeded the 95th percentile for all three measures.

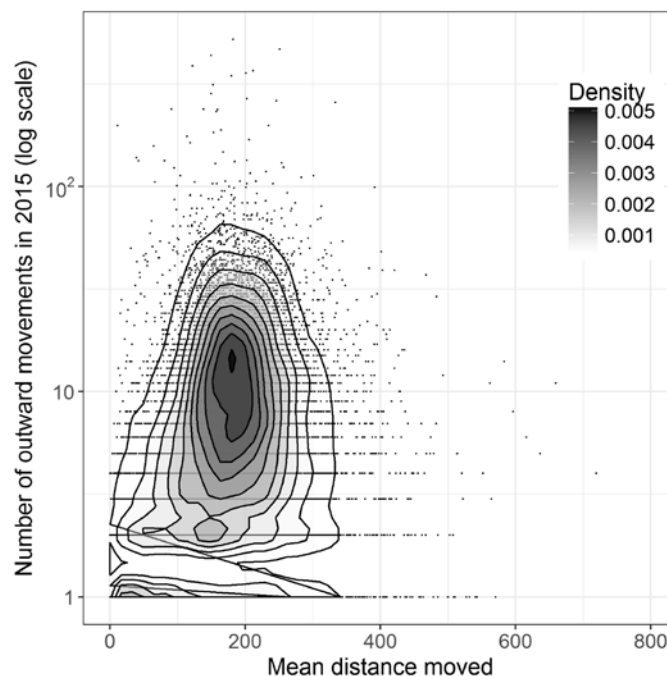


FIGURE 7-5. DENSITY PLOT OF WITHIN-FARM ASSOCIATION BETWEEN MEAN DISTANCE TRAVELLED BY OUTGOING MOVEMENTS AND MEAN NUMBER OF SHEEP PER OUTGOING MOVEMENT, FOR FARM NODES LOCATED IN VICTORIA IN THE INTERSTATE-VICTORIAN SOURCE-DESTINATION NETWORK.

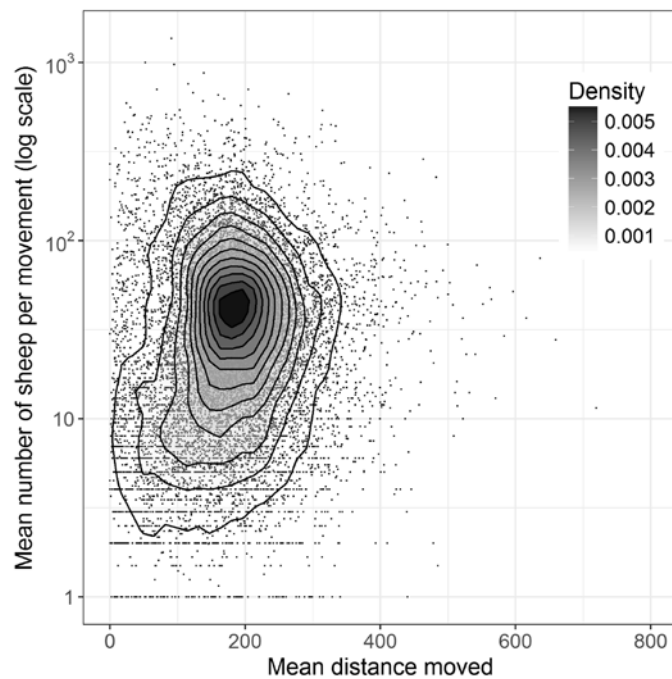


FIGURE 7-6. DENSITY PLOT OF WITHIN-FARM ASSOCIATION BETWEEN MEAN DISTANCE TRAVELLED BY OUTGOING MOVEMENTS AND NUMBER OF OUTGOING MOVEMENTS IN 2015, FOR FARM NODES LOCATED IN VICTORIA IN THE INTERSTATE-VICTORIAN SOURCE-DESTINATION NETWORK.

7.4.3 TEMPORAL DESCRIPTION OF SHEEP MOVEMENT

7.4.3.1 WEEKLY TEMPORAL PATTERNS

In 2015, Victorian saleyards were responsible for the majority of sheep movements recorded by the NLIS database. In the interstate-Victorian movement network, 184,041/298,511 (61.7%) of movements involved a Victorian saleyard as source or destination. The four biggest saleyards (Bendigo, Ballarat, Hamilton and Horsham) represented 79.5% (146,362/184,041) of those movements. Those four saleyards each sell sheep one day a week and each on different days, resulting in a weekly ‘churn’ of sheep moving throughout the network as illustrated in Figure 7-7.

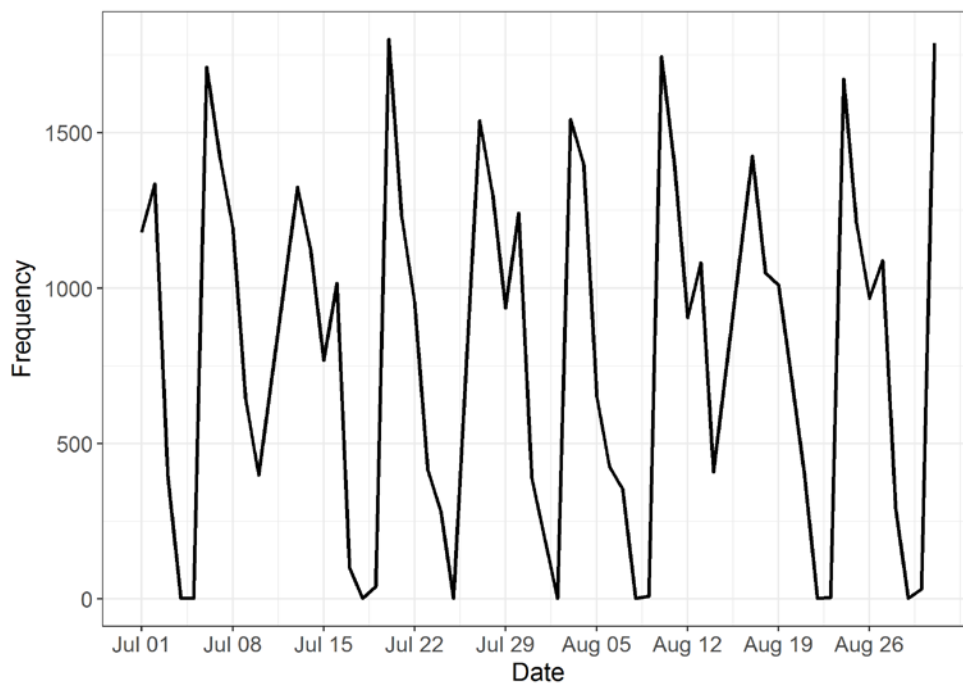


FIGURE 7-7. DAILY TEMPORAL PATTERN OF SHEEP MOVEMENT IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK, DEMONSTRATING WEEKLY 'CHURN' OF SHEEP THROUGH NETWORK.

TABLE 7-8. PROPORTION OF WEEKLY MOVEMENTS ATTRIBUTABLE TO DIFFERENT MOVEMENT TYPES, FOR THE INTERSTATE-VICTORIAN MOVEMENT NETWORK FOR THE FIRST 50 WEEKS OF 2015.

Movement type	Proportion of weekly movements			Proportion of all annual movements [#]
	Min	Mean	Max	
Farm to saleyard*	16.6%	22.6%	26.9%	23.0%
Saleyard to abattoir	42.7%	55.5%	64.4%	54.8%
Saleyard to farm	3.3%	7.3%	13.7%	7.6%
Saleyard to agent	2.2%	5.1%	7.0%	5.0%
Farm to abattoir	4.0%	7.3%	10.4%	7.4%
Farm to farm	0.1%	1.6%	10.8%	1.7%
Agent to farm	0.1%	0.5%	1.2%	0.5%
Agent to abattoir	<0.01%	<0.01%	<0.01%	<0.01%
Farm to agent	<0.01%	<0.01%	0.30%	<0.01%
Saleyard to saleyard	<0.01%	<0.01%	<0.01%	<0.01%

[#] The final column is the proportion of each type of movement overall in the network in 2015 (including all weeks). *Because a single movement from farm to saleyard could be split at the saleyard into multiple mobs for further movements, the proportion of movements out of saleyards exceeds the proportion of movements into saleyards.

There are thousands of movements each week throughout the year, except for the last two weeks of the year due to holiday periods. In the other 50 weeks of the year, the number of movements per week ranged between 2960 to 8884, with a mean of 5632 movements per week for the whole year. A summary of the relative contribution of different movement types to weekly movement volume is given in Table 7-8, with around half (42.7% to 64.4%) of weekly movements being consignments of sheep purchased from saleyards by abattoirs, and a further fifth (16.6% to 26.9%) being movements from farms to saleyards.

7.4.3.2 MONTHLY AND ANNUAL TEMPORAL PATTERNS

Edges present in the within-Victoria shire network showed little variation in between months and years based on analysis with the quadratic assignment procedure. The edges present in the network comparing years from 2010 to 2015 were moderately strongly correlated (Table 7-9), as were the edges present in different months of 2015 (Table 7-10).

TABLE 7-9. CORRELATION OF EDGES BETWEEN YEARS IN THE WITHIN-VICTORIA SHIRE NETWORK, CALCULATED BY THE QUADRATIC ASSIGNMENT PROCEDURE.

Year	Number of edges in year (shire to shire movements)	Pearson's correlation*
2015	18410	Reference
2014	18416	0.69
2013	18874	0.69
2012	17405	0.68
2011	19080	0.65
2010	16317	0.60

*P-value < 0.001 for all correlations, indicating the probability that there is more difference in the edges present in the network than due to chance i.e. a significant p-value indicates no difference between the networks.

TABLE 7-10. CORRELATION OF EDGES BETWEEN MONTHS IN 2015 IN THE WITHIN-VICTORIA SHIRE NETWORK, CALCULATED BY THE QUADRATIC ASSIGNMENT PROCEDURE.

Month	Number of edges in month (shire to shire movements)	Pearson's correlation*
Jan	1661	0.41
Feb	1317	0.43
Mar	1491	0.43
Apr	1041	0.44
May	942	0.46
Jun	966	0.46
Jul	817	Reference
Aug	951	0.41
Sept	1518	0.41
Oct	2906	0.41
Nov	2741	0.38
Dec	2059	0.40

*P-value < 0.001 for all correlations, indicating the probability that there is more difference in the edges present in the network than due to chance i.e. a significant p-value indicates no difference between the networks.

7.4.4 SPATIAL DESCRIPTION OF SHEEP MOVEMENT

The interstate-Victorian source-destination network demonstrated that Victoria is a net importer of sheep (Figure 7-8). Alongside 6.6 million individual sheep movements with both source and final destination in Victoria, a total of 5.9 million sheep were imported into Victoria in 2015. Of these imported sheep, 5.1 million sheep were destined for slaughter at Victorian abattoirs. 2.8 million sheep were imported for slaughter via interstate saleyards located in NSW (2.4 million sheep) or SA (410,000 sheep), with a further 2.1 million moved direct from interstate farm to Victorian abattoirs and 250,000 moved through Victorian saleyards. In the same network, there were only 1.7 million export movements with 1.25 million of these sheep exported to interstate abattoirs (with SA abattoirs receiving 970,000 sheep and the remaining 280,000 destined for NSW) and the remaining 450,000 to interstate farms, primarily in SA, NSW and TAS.

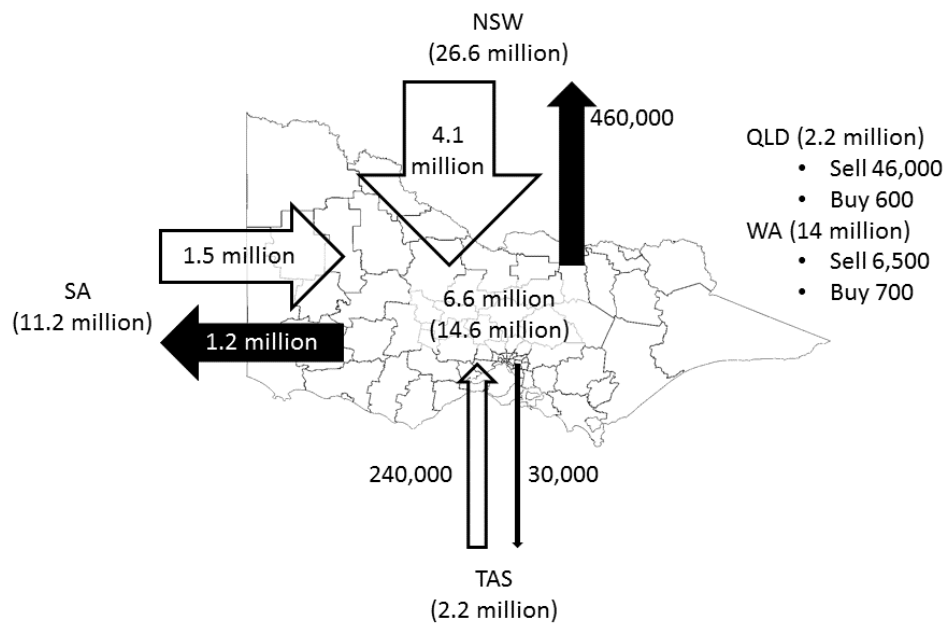


FIGURE 7-8. SCHEMATIC OF FLOW OF SHEEP BETWEEN VICTORIA AND OTHER AUSTRALIAN STATES IN THE INTERSTATE-VICTORIAN SOURCE-DESTINATION NETWORK. NUMBERS IN BRACKETS ARE ESTIMATED SHEEP POPULATION FOR EACH STATE AT JUNE 2015 (MEAT AND LIVESTOCK AUSTRALIA, 2016A).

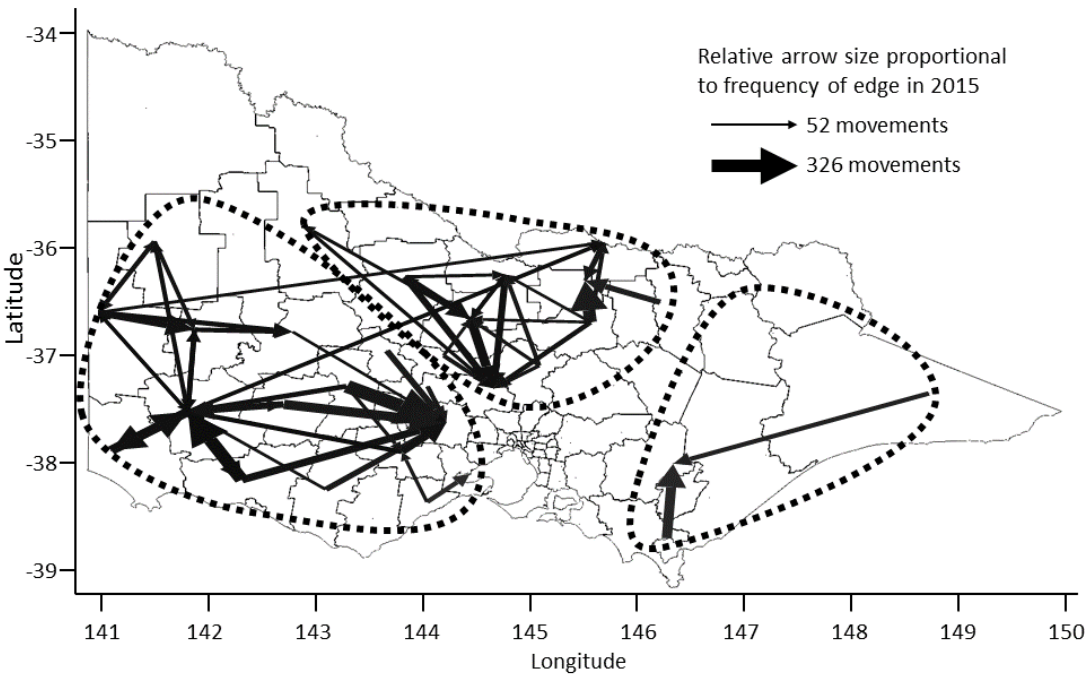


FIGURE 7-9. NETWORK OF EDGES WITH FREQUENCY ≥ 52 (ON AVERAGE ONE OR MORE SHEEP MOVEMENTS PER WEEK) IN THE WITHIN-VICTORIA SHIRE NETWORK IN 2015. COMMUNITIES APPARENT ON VISUAL INSPECTION ARE ENCLOSED BY DOTTED LINES.

Visual assessment of high frequency movements in the within-Victoria shire network suggested three highly connected communities of shires were present (Figure 7-9). These three communities (the western district, north-central Victoria, and Gippsland) were confirmed using the *walktrap* algorithm for community detection. The algorithm further divided each community into two sub-communities (east and west), as shown in Figure 7-10.

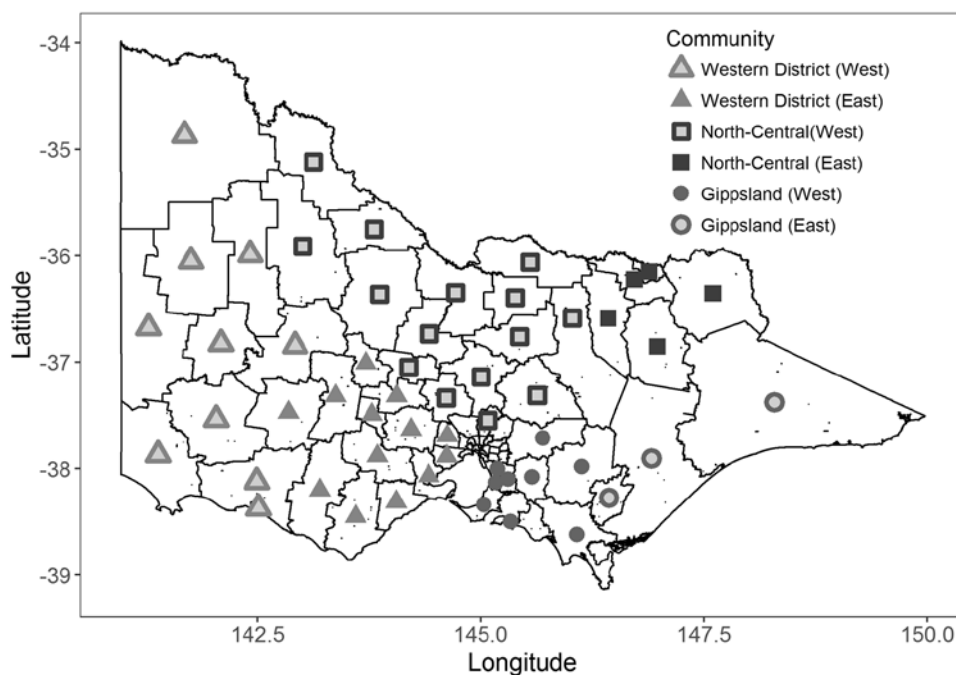


FIGURE 7-10. COMMUNITIES (AND SUB-COMMUNITIES) OF SHIRES IN THE WITHIN-VICTORIA SHIRE NETWORK, DETECTED USING THE WALKTRAP ALGORITHM (PATH LENGTH = 6 FOR MAIN COMMUNITIES AND PATH LENGTH 4 FOR SUB-COMMUNITIES).

7.5 DISCUSSION

This study has demonstrated how network analysis of NLIS data can identify farms of interest for targeted surveillance, as well as illustrating the risk of disease spread in the state overall. The substantial volume of sheep movement into and throughout Victoria is clear, highlighting the potential risk of infectious disease spread and the need for effective disease surveillance in the Victorian sheep industry to facilitate early detection, in order to avoid a widespread disease outbreak requiring substantial resources for control. Overall, there is a net inflow of sheep into the state, driven by the activity of saleyards and abattoirs. Over three-quarters of these imported sheep are destined for abattoirs and are moved through interstate saleyards or direct to

abattoir. However, the remaining quarter of imported sheep that move through Victorian saleyards could spread infectious disease to sheep destined for Victorian farms, through direct or indirect contact at the saleyard. Within the state, there are an average of over 5000 movements each week, of which over three quarters are either to or from saleyards. This, along with the high degree values of saleyards, reinforces the potential of saleyards to disseminate disease widely, as was seen in during the foot-and-mouth disease outbreak in the United Kingdom in 2001 (Gibbens et al., 2001). These values demonstrate the substantial risk of disease transmission through Victoria's sheep movement network, making effective disease surveillance critical to detect disease outbreaks within the state and also more widely (as, due to the large numbers of sheep imported from interstate, Victoria is somewhat of a sentinel for sheep disease in neighbouring states).

The network characteristics likely to be associated with increased individual farm risk of acquiring or disseminating infectious disease included high in- and out-degree (both > 5 , $n = 15$ Victorian farms), farms that moved animals over long distances either frequently or in large numbers ($n = 47$), and farms with pairs of inward and outward movements occurring within a short period (21 days, defined as 'trading pattern' above, $n = 666$ with $n = 29$ that had > 26 instances). Most farms identified in the latter analysis had only a single pair of movements meeting the 'trading pattern' criteria, which may be consistent with typical farm management activities, such as purchasing replacement ewes shortly before prime lambs are sold. While these movements are still notable for their potential to transmit disease between farms, these farms may not be at substantially increased epidemiological risk of widespread disease dissemination, and further research to categorise movement types would contribute to their meaningful interpretation. However, other farms with multiple occurrences of 'trading pattern' were identified, including some with high degree values or average movement distances, highlighting the potential disease risk associated with those farms. A useful further step would be to correlate these network features with other farm characteristics, such as major farm outputs (stud sheep, wool, prime lamb or dual purpose), source of replacement stock (self-replacing vs. purchased), and scale of production (such as ewe numbers, grazing area, stocking rate). Unfortunately, this information was not available for the individual farms in the present study. Nonetheless, targeting of surveillance activities can be achieved by identifying both individual high-risk farms, and minimum 'cut-off' values of measures of interest. If

temporal variation in the distribution of those measures is low, the cut-off values established in the analysis of one year's data could be applied in future years, to ensure farms with increasing disease risk are also identified for surveillance purposes.

Time-respecting measures that accounted for the temporal order of movements in the network, including incoming and outgoing contact chains, and the probability of disease ratio, were used in this study to overcome the limitations of static approximation of temporal networks. On average, Victorian farms were connected to over 2000 others through outgoing time-respecting paths in the network, driven by the central position and high degree values of saleyards. If anything, this figure is an underestimation of total contact chain size, because the network only included nodes within Victoria, or trading directly with Victorian nodes. This was because this study focussed on the potential spread of disease within Victoria, rather than into and beyond the state, because Australian states hold jurisdictional responsibility for disease surveillance and the practicalities of disease response programs.

Consequently, contact chains of additional interstate nodes not directly connected to Victoria could not be measured in this study. Nevertheless, on average, in just 12 months, sheep movements could spread disease from a single index farm to over 2000 others in the network through the connections between properties recorded by the NLIS (notwithstanding spread by other mean such as fomites or airborne spread), if no control measures were implemented. It would be useful to repeat this analysis over shorter time periods to understand the potential outbreak size if disease were detected more rapidly, although this was beyond the scope of the present study.

This study has also quantified the degree distribution of Victorian farms and saleyards, confirming the presence of scale-free topology and allowing estimation of how the heterogeneity of contact in the network could affect disease spread overall. Scale-free topology reflects the power-law distribution of degree values in the network, where most nodes are connected to a small number of other nodes, but a small number of nodes are connected to a large number of other nodes. This was seen in both the interstate-Victorian and within-Victoria movement networks, with high in- and out-degree values for both saleyards as well as small numbers of farms. The basic reproductive number of an outbreak of disease would be 7.8 times higher than would be expected with homogeneous contact between farms, due to the heterogeneity of farms and saleyard degree values in the network (Woolhouse et al., 1998). This

increase in the basic reproductive number, estimating the average number of additional nodes that would be infected by a single infected node, is substantial despite the low correlation between in- and out-degree values overall. The strong correlation between saleyard in- and out-degree further highlights their potential to act as 'superspreaders' of disease in the network (Lloyd-Smith et al., 2005). The role of saleyards was expected to be prominent in these data, because NLIS records are targeted to high-risk movements and not all direct farm-to-farm movements are captured by the database. Nonetheless, saleyards are known to play a substantial role in sheep movement within and between states. The strong correlation between saleyard degree values reinforces the substantial role saleyards could have for disease spread throughout the network, because of the large number of farms connected as both sources and destinations for sheep moved through saleyards. It is therefore vital for resources to continue to be dedicated to disease detection and control activities at saleyards.

The communities present in the within-Victoria shire network demonstrate the most likely areas of geographic infectious disease spread within Victoria, based on the probability of between-shire movements. Although it is likely that the connections between individual farms and saleyards may vary between years, there was minimal variation in the connections between shires over the months and years examined, in contrast to the distinct seasonality of the sheep movement network in Great Britain (Kiss et al., 2006). This suggests that, in the event of a disease outbreak, disease is likely to spread primarily within the communities of the network, regardless of the year or season. This information can inform the prioritisation of disease response resources outside the affected communities, so that between-community spread can be rapidly detected and managed to limit total outbreak size. Given there is minimal variation in the connections between shires over time, it is likely that temporal variability in the network is occurring within-shires at smaller geographic aggregations. It would be useful to further investigate variability of spatial patterns in the network in smaller geographic aggregations over time, to appreciate the effects this may have on disease spread.

Overall, the network of sheep movements in Victoria (including interstate movements) was structurally similar to other state- or country-based sheep and cattle movement networks. The betweenness centrality, reciprocity and the low correlation

between in- and out-degree found in this study were similar to values reported in other studies (Volkova et al., 2010; Ribeiro-Lima et al., 2015; VanderWaal et al., 2016). The average of 66 sheep per movement exceeded that reported for sheep in Scotland (21.5 per movement, Volkova et al., 2010), or for cattle in Great Britain (13.5, Robinson and Christley, 2007), Minnesota (14.3, Ribeiro-Lima et al., 2015) and Italy (4.5, Bajardi et al., 2011).

The topology of this network also reflected the common small-world structure seen in other livestock movement networks (Dubé et al., 2011b). Small-world topology, where small numbers of nodes act as 'bridges' between otherwise isolated clusters in the network, is common in livestock movement networks despite their typical low density. It is typified by moderate to high clustering coefficients and short average path length. The interstate-Victorian movement network had an average local clustering coefficient of 14.1%, compared to values between 10.8% and 27% in studies of other networks (Mweu et al., 2013; Ribeiro-Lima et al., 2015; VanderWaal et al., 2016), and an average path length of 4.45, with other networks ranging from 4.3 to 9.0 (Dubé et al., 2011a; Rautureau et al., 2011; Mweu et al., 2013; VanderWaal et al., 2016). The average local clustering coefficient in this study was reduced by the substantial number of farms that were only connected to a single saleyard and therefore had zero clustering. Given that it was not compulsory to report all direct farm-to-farm sheep movements to the NLIS in 2015, non-reported farm-to-farm movements may result in even greater levels of clustering. At present it is assumed that there is a low volume and frequency of these non-reported sheep movements (Agriculture Victoria, pers. comm.). Estimating the true number of missing edges would be useful for future analyses, as they are likely to increase the overall connectedness of the network and therefore the risk of disease spread independent of the activity of saleyards.

A challenge in this analysis was how to appropriately aggregate and interpret the raw network data extracted from the NLIS database. It can be difficult to determine exactly how to process the data to a form that is manageable for analysis but retains its important features. For example, the within-Victoria shire network aggregated the NLIS data both spatially into shires, as well as aggregating movements to reflect their source and destination rather than the saleyard through which they were moved, and taking only the subset of those movements that did not have an abattoir as its final

destination. This proved useful to understand the overall flow of sheep within the state to understand geographic patterns of potential disease spread, but removed the potential effect of saleyards as 'superspreaders' where sheep could become infected halfway through their journey, for example through contact with other sheep that were destined for an abattoir. The appropriate network structure will be dictated by the research question(s) posed, and in some cases different aggregations of the same data may be needed to answer different questions even in a single study.

Additional information about both the nodes and the individual movements would have been beneficial for these analyses, but unfortunately was not available. For example, some farms had high degree values but purchased and sold sheep in very small numbers, mostly trading directly to other farms. These were likely to be stud farms primarily buying and selling rams, and therefore may not be the highest priority farms for targeted surveillance due to expectations of above-average biosecurity and management related to monitoring the health of their animals and. However, these hypotheses could not be verified due to practical constraints preventing additional data collection. A similar area of ambiguity was found when examining instances of the 'trading pattern' of single day duration. In one third of these instances recorded for individual farms, the second (outgoing) destination of the movement-pairs was an abattoir. It was unclear whether these movements were the same animals (i.e. the farms acting as 'buyers' for abattoirs), or different animals that happened to be moved on consecutive days (either because the farmer happened to have purchased and slaughtered stock in the same week as part of farm management, or because the farm is acting as a 'holding' farm for abattoirs). The ambiguity about whether individual animals were being moved multiple times was a known limitation of the NLIS data, because it was based on identifying groups of sheep that are moving rather than individual animal movements. It is hoped that individual sheep movement recording, which was first introduced in 2017, will in future help to clarify these types of movement patterns. It would also be beneficial to categorise movements, for example by recording the type of animals moved (such as rams, cast-for-age ewes, young ewes and prime lambs), as the epidemiological risk of disease spread via sheep movement may vary between these different stock classes.

This study has confirmed the usefulness of descriptive network analysis to give both an overview of livestock movement, and to identify individual farms and farm

characteristics that may be associated with disease spread risk and are therefore of interest for targeted surveillance. Further work extending these analyses could include validation and triangulation of trading behaviour, tracing the movements of individual animals backward to farm of birth rather than just farm of sale, and estimation of the volume of farm-to-farm movements and their effect on the overall network. It would also be useful to examine the data temporally, for example using shorter, rolling periods of temporal aggregation (as per Kiss et al., 2006) and employing additional network measures that account for time-respecting paths.

7.6 CONCLUSION

This chapter has presented the first published investigation of an NLIS sheep dataset, focussed on the flow of sheep movement within, into and out of Victoria. Victoria's status as a net importer of sheep driven by demand from abattoirs has reinforced the importance of an effective disease surveillance strategy in the Victorian sheep industry. The strong influence of saleyard and abattoir activity on the flow of sheep throughout the state means that there is little variation in sheep movement between months or years, and so a disease outbreak at any point in the year can be disseminated effectively on this network. Farms with large in- and out-degree values, large in- and out- contact chains, high PDR and who demonstrate a 'trading pattern' are all potential targets for on-farm disease surveillance activities such as syndromic surveillance of farmer observations. The next chapter will discuss the implications of this study, considered together with the review presented in Chapter 2 and the other studies reported in Chapters 3 to 6, drawing together the final conclusions of this thesis.

Chapter 8.

GENERAL DISCUSSION

8.1 IMPLICATIONS OF THE STUDIES PRESENTED

This thesis has sought to address the challenge of improving the usefulness of disease surveillance in the Australian sheep industry, through a farm-based observational approach to collecting surveillance data. Three research questions were at the heart of this objective:

- Are Australian sheep and beef farmers willing and able to provide useful data for disease surveillance?
- How do farmers respond to signs of disease occurring in their livestock, and what implications does this behaviour have for surveillance?
- How can farmer-reported data be effectively and efficiently used to improve surveillance?

This chapter will bring together the key findings of the preceding chapters to address the three research questions above, highlighting the novel contributions this work makes to the existing literature and identifying where further investigation is required.

The LANDI syndromic surveillance system, described in Chapter 3, is an example system, demonstrating a practical way for farmers' observations to be collected for surveillance purposes. It has previously been uncommon for farmers' observations to be the main data source for syndromic surveillance in developed countries, although it has been reported in developing countries such as Kenya and Myanmar (Walker et al., 2011; Hanks et al., 2017). There are several reported examples of the evaluation of other syndromic surveillance systems, namely those with veterinary practitioners as the data source (Amezcuca et al., 2010; Zurbrigg and Van den Borre, 2013; Struchen et al., 2016). Unlike other reported systems which focussed only on specific syndromes, such as Equinella in Switzerland (Struchen et al., 2016) only collecting data about infectious diseases of horses, LANDI had a broader (syndrome non-specific) case definition of ten syndromes designed to allow cases of any aetiology to be detected and recorded by the system. This aligned with the system's broad objective, to collect

information about endemic diseases in sheep and beef cattle in order to better describe the prevalence of common disease presentations.

There are two areas reported by other systems that were not fully utilised by LANDI: the provision of summarised data as an incentive for participation, and more automation in data analysis, especially for detection of unusual disease occurrence. The ability of the surveillance system to provide information on disease trends had been previously recognised by Struchen et al. (2016) as an important incentive to motivate participants for ongoing data provision. Feedback of summary data from the system to the participating farmers was only provided in informal and sporadic ways. Structuring this feedback in a more timely and accessible way should be prioritised in the ongoing development of this and similar systems. Considering analysis of surveillance data, LANDI did not have automated algorithms for detecting unusual disease signals in the data being collected (reported to be common by Dórea and Vial (2016)). In part, this was because of the relatively small number of participating farms in this phase of the system's operation, but automated analyses could be incorporated into this or similar systems as their operational scale increases.

Nonetheless, LANDI provides important proof-of-concept in several areas. When the system was first being designed, it was unclear whether farmers would be willing and able to provide their observations of clinical syndromes in their livestock regularly and consistently. The busy pace of farming life and recognition that disease surveillance may not be farmers' highest priority were the basis for scepticism of the syndromic approach to collecting farmers' observations. Accordingly, ease of data submission was a priority in the development of LANDI, as it had been previously identified as a major contributor to system sustainability by Zurbrigg and Van den Borre (2013). Careful consideration was given to details of the system, such as selecting syndromes that aligned with farmers' language and anticipated interpretation of disease events, and the use of logic to control the number of fields presented in the online report entry interface. These details aimed to maximise acceptability and facilitate participation within the willing farmer cohort. Based on the high overall response rate, including several farmers who submitted every report requested, the system appears to have achieved sufficient acceptability for sustainable operation. Careful consideration of acceptability, as has been demonstrated in this system's design, is recommended for similar programs in other countries. The overall

timeliness of reporting (Chapter 3) was comparable to other surveillance approaches and was suitable for monitoring endemic and emerging diseases, as well as to provide evidence of the absence of unusual or emergency disease.

When considered together, Chapter 3 and Chapter 4 demonstrate that Australian sheep farmers are willing and able to report timely data that is useful for surveillance, based on their observations of disease signs in their livestock. However, some farmers were unable or unwilling to provide regular, ongoing reports, despite being recruited by convenience and having anticipated compliance higher than the broader population. This suggests that recruiting a random sample of farmers for observational syndromic reporting is unlikely to be successful, and that selective recruitment is probably needed. This selective recruitment could occur in several ways, including targeted sampling using risk-based approaches such as analysis of livestock movement data (Chapter 7) keeping in mind the effect of sampling on the observed characteristics of a network (Chapter 6), or identifying characteristics that are associated with desirable response behaviour (Chapter 3). The relevance of each approach may vary between countries and between surveillance objectives, depending on livestock industry structure and the hazard(s) included in the surveillance system's scope.

A combination of recruitment strategies encompassing both disease risk and likely reporting behaviour may yield the best results for participation in many countries, by first identifying farms of interest and then recruiting within those farms based on predicted desirable participation. In all cases, a balance must be struck between the system's surveillance objectives (World Health Organization, 1997) and the resources available to the system (particularly considering the cost and feasibility of effectively delivering incentives to the desired number of participants). Of course, the results of a surveillance system that uses these non-random sampling approaches must be interpreted with care and consideration of selection bias. Therefore, as similar systems are implemented both in Australia and elsewhere, continuing research into farmer characteristics associated with participation rates and the effects of selection bias will be useful. It would be particularly beneficial to apply the emerging methods of quantitative bias analysis to biased surveillance data (Dohoo, 2014), to encourage the appropriate interpretation of information generated by the system.

A challenge faced in the interpretation of syndromic data collected by LANDI was generating appropriate denominator values, to allow measures of within-farm disease (or syndrome) frequency to be calculated. In other countries, smaller average flock size and the presence of existing monitoring systems or regulatory requirements for those farms may make it easier to determine appropriate denominators (Volkova et al., 2010; Dutta et al., 2014). Nonetheless, the approach taken in this thesis would be relevant for other extensively managed systems such as those encountered in South America (Aznar et al., 2011).

It was very difficult to accurately determine how many animals were in the population at risk for a given syndrome or diagnosis on a farm at the specific relevant point in time. These difficulties occurred for several reasons, included deciding whether the population at risk ought to be limited to a single paddock, age group or other, as well as the practicality of determining how many animals are present on the farm when stock are only counted periodically and some deaths occur without immediate detection. Australia's sheep industries are not alone in these challenges, and similar situations may arise in other countries with comparable production systems. As such, it would be valuable to investigate methods to more accurately estimate the size of the population at risk. Possible approaches to achieve this could include ecological approaches such as capture-recapture methods (El Allaki et al., 2015), or alternatively increased frequency of counting through individual RFID identification of animals and remote counting using proximity readers. The recent introduction of compulsory individual electronic identification of sheep in Victoria, Australia (Animal Health Australia, 2017), may provide an opportunity to investigate whether remote counting is feasible. These methods need to be tested on livestock farms for accuracy and practicality before they can be widely implemented, but have potential to increase the usefulness of surveillance data such as syndromic reports.

The behaviour of farmers, both in terms of their participation in LANDI and their approaches to managing disease problems in their livestock more generally, received strong focus in this thesis. It became clear through the operation of LANDI that despite minor animal health problems being frequently identified on-farm, the participating farmers rarely sought veterinary advice, especially for disease in their sheep. Previous Australian studies had suggested that this was because farmers were unwilling to pay for a veterinary visit (Lanyon et al., 2015; Wright et al., 2016) and that they sought to

avoid being identified as farms with animal health problems, for fear of the consequences if an emergency disease was present (Frawley, 2003). However, the comments made on the monthly reports received by LANDI suggested instead that farmers were well aware of the problems in their animals, but seemed not to see the relevance of having a veterinarian involved in most cases. As the participants in LANDI were a convenience sample and likely represented the types of farmers that were more likely to seek veterinary advice, the perceived relevance of veterinarians on Australian sheep farms more generally was likely to be even lower. Therefore, the reasons for the low proportion of disease events where farmers sought the assistance of a veterinarian were explored further using qualitative methods in Chapter 5.

It would have been ideal to conduct the qualitative study with the same farmers participating in the syndromic surveillance system. However, the surveillance system had already been operational for over 12 months before the study in Chapter 5 took place, meaning that participating farmers' behaviour had already been influenced by their participation in LANDI. Therefore, other farmers were recruited from the same population with similar selection bias (pro-active farmers who had some previous connection to the Mackinnon Project). The attitudes expressed in the qualitative study are therefore likely to be similar to those that were held by the farmers at recruitment into the syndromic surveillance system, which again may represent the 'best-case' farmers for disease surveillance rather than the average Australian sheep farmer in the broader population.

The farmers who participated in the focus groups suggested that, rather than not wanting to contact a veterinarian, farmers tend to work from their experience to solve problems. In many cases, their own experience was felt to be sufficient to determine either what the cause of a disease problem was and what to do about it, that the problem had either ceased and no longer posed a threat, or that a diagnosis was unlikely to be reached because of the quality of potential diagnostic material. Therefore, there were only a small proportion of disease problems where, after rational consideration of the problem in front of them, a veterinarian's assistance was perceived as required. While this has been reported previously in other studies in developed countries such as the Netherlands (Elbers et al., 2010a) and France (Bronner et al., 2014), it has not received sufficient attention as a major driver of how farmers respond to disease. The study reported in this thesis did not fully investigate

how farmers determine the limits of their experience. This area is worthy of further investigation, as the accuracy of this self-assessment is critical to ensure the farmer can effectively respond to disease when they choose to take an independent approach.

Where the farmers did consider that veterinary assistance was needed, they reported very little hesitation to seek help. This agrees with the common finding in both Australia (Hernández-Jover et al., 2016) and in the UK (Heffernan et al., 2008; Garforth et al., 2013; Toma et al., 2013) that veterinarians are trusted sources of animal health advice. A deeper understanding of farmers' intentions to contact a veterinarian can be used to direct new approaches to both veterinary services and disease surveillance. The potential role for veterinarians to play as farm advisors on sheep farms seems to be underappreciated by farmers, both in Australia and overseas. Contributing factors appear to include a lack of evidence of the economic benefit of preventive veterinary services for sheep farms, uncertainty from farmers and perhaps even from veterinarians about what kinds of services could be provided, and a lack of marketing and promotion of these services (Ruston et al., 2016). To make progress in this area, it would be useful to evaluate novel or emerging financially viable models of veterinary practice that help reposition veterinarians as farm advisors and provide services that will be valued and sought after by farmers. To facilitate this repositioning, it would also be advantageous to identify additional skills or training that veterinarians working in this area would require. This could lead to recommendations to be embedded in veterinary training programs, allowing progress on the role of veterinarians on sheep farms to be made more broadly across the profession.

Furthermore, the new perspective on sheep farmers' disease response behaviour presented in Chapter 5 reinforces the potential importance of syndromic surveillance to fill gaps in surveillance systems, both in Australia and in other countries facing similar challenges. Given that Australian sheep farmers have rational approaches to manage familiar disease situations without veterinary advice, the short-term prospect of increasing the number of disease events detected by surveillance is most likely achievable through an alternative method of data collection that does not rely on veterinary contact. Collecting farmers' observations of clinical syndromes is a feasible way to achieve this, made possible through syndromic reporting. There are also other substantial benefits of syndromic surveillance of farmers' observations beyond

increasing the fraction of events detected. This includes increasing farmers' understanding of the importance of surveillance and encouraging them to take ownership of their role as stakeholders in livestock health. Increasing the engagement of farmers as stakeholders in this way could also prove beneficial in other countries, especially where there are existing tensions between farming communities and animal health authorities (Elbers et al., 2010a; Delgado et al., 2012). If delivered thoughtfully and in a way that is acceptable to farmers, it could also help to improve community perceptions of government animal health activities.

The information generated by syndromic surveillance could also be used longer-term to redefine the role of veterinarians on sheep farms, through the evidence it will generate about disease occurrence. Using farmers' observations to establish relatively accurate baseline estimates of disease frequency can allow the costs of endemic disease to be calculated more accurately (as recently called for by Lane et al., 2015), both on individual farms and across the industry. Understanding the costs of endemic disease on-farm could, in turn, be used to quantify the potential benefits of improved animal health management, including through the uptake of veterinary preventive health and animal management advice. Generating and communicating this kind of information could drive changes in industry behaviour to improve animal health and welfare in Australia. This approach may also be generalisable to other countries where the frequency of veterinary visits is limited. Of course, a solely economic argument to increase the utilisation of veterinary services will not be enough to change farmers' behaviour (Vanclay, 2004; Shortall et al., 2016). However, providing an evidence-based economic rationale could be a valuable contribution to redefining the role of veterinarians on sheep farms. If this resulted in increased uptake of veterinary services, even on a subset of all sheep farms, this could further improve the effectiveness of passive surveillance.

To extend the findings of Chapter 5, it would be useful to conduct a quantitative study of farmers' disease response behaviour. A survey of disease response behaviour could also be used as a baseline to measure behaviour change over time in response to an intervention, such as participation in a syndromic surveillance system. This could help quantify the effect of the participatory surveillance approach on broader attitudes and behaviours in farming industries. Based on informal feedback from LANDI, it is hypothesised that participating in surveillance activities 'sensitises' the farmers to

disease problems and can reduce their tolerance for disease events as expected or 'normal' for their farm, potentially increasing the rate of veterinary contact. If this hypothesis is proven true, it could present an opportunity for veterinarians to provide increased levels of service to sensitised farmers, allowing them to demonstrate the relevance of their skills and advice for enhancing farm profitability. However, further investigation and engagement of both farmers and veterinarians as stakeholders in surveillance and animal health management on-farm is needed to generate the evidence to test this hypothesis.

Alongside the potential benefits of a syndromic surveillance approach outlined above, the limitations of such a system must be carefully considered. Not all surveillance objectives can be achieved using syndromic data, and the data must be interpreted and communicated appropriately (Dórea et al., 2011). Syndromic surveillance data (such as presented in Chapter 4) is useful for establishing baseline disease prevalence, monitoring endemic disease and for early detection of changing and emerging diseases (Dórea et al., 2015). However, the objective to rapidly detect exotic disease incursions may not be suited to a syndromic surveillance system, at least not in isolation. The potential crossover in clinical signs between endemic and exotic diseases is the ongoing challenge of using case definitions based on syndromic presentation, rather than the results of diagnostic testing. Therefore, it is appropriate to interpret the information generated by a syndromic system alongside other surveillance activities that have better capacity to discriminate between the endemic disease and the index cases of an exotic disease outbreak (Welby et al. 2017). Nonetheless, there is some benefit of a syndromic surveillance system for exotic disease detection through the increased vigilance of participants to detect signs of disease in their livestock. If participating in syndromic surveillance sensitises farmers for disease detection, this could help improve the probability of an exotic disease being noticed as 'abnormal' by the farmer and therefore increase the likelihood of early detection of the first cases in an outbreak.

Despite limitations for exotic disease detection, syndromic data can support claims of proof of freedom of exotic diseases, again when used alongside other approaches to surveillance. Establishing an accurate baseline for the occurrence of syndromes allows the detection of fluctuations in syndrome frequency. Veterinary investigations of an appropriate proportion of baseline disease events, with increased rates of

investigation where syndrome frequencies increase above baseline, could then validate these data to demonstrate that both the baseline and any fluctuations are due to endemic diseases rather than exotic diseases of interest. In this way, syndromic surveillance that increases the total fraction of disease events under surveillance is a useful adjunct to existing surveillance activities with objectives focussed on proof of freedom. This approach could be supplemented by training farmers to collect appropriate samples to support confirmatory diagnostic activities, to help overcome the practical challenges of delivering timely and diagnostic veterinary investigations to on-farm disease events.

The use of multiple surveillance activities that have complementary attributes, combining to provide high quality evidence of the presence and absence of different diseases in the population, is the future of animal health surveillance (Hadorn and Stärk, 2008; Bertolini et al., 2011). Surveillance conducted in this way can overcome the resource limitations that can constrain the usefulness of individual surveillance activities, and increase the likelihood that systems will achieve their surveillance objectives. The studies in this thesis have demonstrated how farmers' observations can be used to contribute to surveillance, but has only provided a starting point for this style of farmer-focussed surveillance. Continuing reporting of example systems is needed to generate a body of evidence for how best to deliver these systems, and to begin to convince trading partners of the validity of newer approaches to surveillance. This evidence should include initial considerations for design as well as evaluation of operational systems, so that the lessons learned from each system can improve the design and delivery of future surveillance activities. Further investigation and reporting of example systems, as well as examples of the integration of multiple activities that combine to achieve their objectives, would contribute substantially to the evidence-base for effective surveillance design.

8.2 POTENTIAL FOR A SYNDROMIC SURVEILLANCE APP ON-FARM

Participatory approaches involving individual farmers can potentially facilitate connection and collaboration between those responsible for animal health, and farmers and farming communities, to improve livestock health surveillance. Large-scale collaboration with individual farmers could help to generate the social capital needed to drive a cultural shift in the livestock industries to improve surveillance. As digital technology continues to become integrated with farming practices, an opportunity seems to be emerging: the chance to combine the collection of data that is relevant for on-farm decision-making with data that is useful for surveillance. Some types of information, such as disease occurrence records and accurate livestock counts, are valuable both on-farm and for livestock health surveillance. Positive outcomes could be achieved if this information could be captured in a way that provides immediate value on-farm, as well as being collated (with appropriate aggregation and anonymization) for use by government/industry, with appropriate two-way communication between farmers and the people operating the surveillance system to establish a true 'data partner' relationship.

Therefore, an opportunity exists for an 'app' to be developed for on-farm use that could capture and analyse information for both on-farm use as well as for surveillance purposes. Features of such an app could include the provision for syndromic recording of animal health observations, paddock allocations and stock counts to more accurately record 'denominator' information, as well as recording routine management activities, chemical treatments to stock and pastures, withholding periods, and environmental data including rainfall and pasture availability. There is scope for features to be selected and integrated in response to the needs of both the farmers and an effective surveillance system. If such a system could be developed in consultation with farmers as end-users, and deployed successfully, it would give farmers a direct path to contribute to the sustainability of their industries through effective surveillance as well as providing individual benefits for farm data management. In addition to the on-farm benefits of using their data effectively, the intrinsic value of contributing to surveillance may also serve as an incentive for participation. This could potentially replace other, more costly incentives, to allow the system to be scaled-up to cover a greater proportion of the population of interest.

8.3 FINAL CONCLUSIONS

This thesis has described the first fully operational syndromic surveillance system of this scale to collect Australian sheep and beef farmers' observations of disease signs in their livestock, as well as presenting novel applications of multivariable analyses to investigate reliable participation in syndromic surveillance. In addition, it has provided an updated snapshot of ewe mortality on sheep farms in southern Australia, as well as a preliminary model of the disease response behaviour of Australian sheep farmers which had not been previously described. This behavioural model is the first to describe Australian sheep farmers' overall approach to disease, rather than focussing solely on disease reporting behaviour or the uptake of biosecurity behaviours. Finally, this thesis has also reported a practical approach to estimating the effect of missingness or sampling in livestock movement networks, and the first analysis of sheep movement in Australia based on the NLIS sheep movement database. While these studies have focussed on the Australian sheep industry, the principles that have been demonstrated are also generalisable to other extensive production systems with practical challenges limiting the effectiveness of passive surveillance, in Australia and overseas.

These studies have demonstrated the feasibility and potential value of syndromic surveillance to improve the effectiveness of livestock health surveillance in Australia's sheep industries. This approach has potential to overcome the limited veterinary contact occurring presently in these industries, and to generate valuable information that can be used as evidence to support longer-term changes in the perceived role of veterinarians on sheep farms.

While this thesis has investigated several key challenges for practical surveillance approaches that can overcome common challenges, there are several areas where additional research would support further improvement to surveillance, most crucially:

- Describing other syndromic surveillance systems collecting observations from farmers or other non-veterinary animal managers, including analysis of characteristics associated with desirable response behaviour.
- Demonstrations of quantitative bias analysis to account for systematic error in surveillance data, including the diagnostic accuracy of farmers' observations to determine aetiological causes of disease or death.
- Application of novel approaches, such as ecological methods or remote electronic stock counting, to accurately determine the size of the population at risk for livestock surveillance data.
- Validation of the model of farmer disease reporting behaviour, including quantitative methods to determine whether it is appropriate to generalise the model to sheep farmers in Australia beyond the sample presented in this thesis.
- Describing the integrated use of multiple surveillance activities to achieve surveillance objectives, and comparison of the usefulness and cost-effectiveness of individual surveillance activities to combinations of activities including syndromic surveillance.

Chapter 9.

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Chapter 10.
APPENDICES

Appendix A. EXAMPLE MONTHLY SYDNROMIC SURVEILLANCE REPORT



Resize font:


Monthly Syndrome Reporting

Please complete the questionnaire below, about animal health events on your farm in the previous CALENDAR MONTH. If you have any questions, please contact Caitlin Pfeiffer at the Mackinnon Project.

Thank you.

What calendar month is this report for?
This should be the month that has just finished.

e.g. If completing survey in February, please select January.

* must provide value

Please fill out the questionnaire, to indicate whether you have observed any of these syndromes on-farm in the calendar month you have chosen above. Please only include events that happened in that month. If yes, you will be prompted to enter some information about what you have observed. In the animals on your land, HAVE YOU OBSERVED ANY:

DEATHS * must provide value	☐ Yes ☐ No	reset
REDUCED PRODUCTION OR REDUCED GROWTH * must provide value	☐ Yes ☐ No	reset
GUT OR MOUTH SIGNS (including scours) * must provide value	☐ Yes ☐ No	reset
LAMENESS OR LIMB SIGNS (e.g. foot abscess, footrot) * must provide value	☐ Yes ☐ No	reset
REPRODUCTIVE FAILURE (e.g. abortions, stillbirths, poor conception rates) * must provide value	☐ Yes ☐ No	reset
NERVOUS SYSTEM SIGNS (e.g. staggers, circling) * must provide value	☐ Yes ☐ No	reset
RESPIRATORY SIGNS (e.g. coughing) * must provide value	☐ Yes ☐ No	reset
SKIN OR EYE SIGNS (e.g. lice, pinkeye) * must provide value	☐ Yes ☐ No	reset
URINARY TRACT SIGNS (e.g. red urine) * must provide value	☐ Yes ☐ No	reset
OTHER SIGNS (any other animal health issue that doesn't fit into the above categories) * must provide value	☐ Yes ☐ No	reset

Finally, please enter the following information about any routine counts of stock you have done in the CALENDAR month chosen at the start. This helps keep the statistics for your farm accurate.

Have you counted any groups of stock this month?
* must provide value

☐ Yes
☐ No

reset

Submit

Save & Return Later

FIGURE A1. APPEARANCE OF ONLINE SYNDROME REPORTING INTERFACE FOR LANDI SYNDROMIC SURVEILLANCE SYSTEM, WHICH RECORDED MONTHLY OBSERVATIONS OF DISEASE SIGNS FROM SHEEP AND BEEF FARMERS IN VICTORIA, AUSTRALIA, OPERATIONAL FROM 2014-2016.

Appendix B. HIERARCHY OF SUB-SYNDROMES IN SYNDROMIC REPORTS

TABLE B1. CATEGORICAL SUB-SYNDROMES FOR EACH MAIN SYNDROME USED IN A FARMER SYNDROMIC SUREVILLANCE SYSTEM IN VICTORIA, AUSTRALIA BETWEEN DECEMBER 2015 AND NOVEMBER 2016.

Syndrome	Species	Sub-syndrome	Possible causes
Deaths (reported by class)	Sheep	Around lambing	Hypocalcaemia Twin lamb disease (pregnancy toxaemia/ketosis) Vaginal prolapse Black mastitis Ruptured belly muscle Dystocia/lamb stuck Other (specify in comments)
		Non-lambing, specific cause known or suspected	Intestinal scour worms Barber's Pole/Haemonchus Liver fluke Flystrike Bacteria scours Clostridial/Pulpy kidney Pneumonia Post-shearing losses Predation Toxicity/poisoning (specify in comments) Age/teeth Johne's disease Other (specify in comments)
		Accident/Misadventure/Cast	n/a
		Euthanased (explain why in comments)	Specify in comments
		Unsure but can provide a comment	Specify in comments
		Found dead/unsure of cause	n/a

Syndrome	Species	Sub-syndrome	Possible causes
Deaths (reported by class)	Cattle	Around calving	Hypocalcaemia Ketosis/Pregnancy toxaemia Vaginal prolapse Mastitis Grass tetany Dystocia/calf stuck Calving paralysis Other (specify in comments)
		Non-calving, specific cause known or suspected	Intestinal scour worms Barber's Pole/Haemonchus Liver fluke Pestivirus/BVD Bacteria scours Clostridial/Pulpy kidney Pneumonia Hardware disease/foreign material in gut Predation Toxicity/poisoning (specify in comments) Age/teeth Johne's disease Other (specify in comments)
		Accident/Misadventure/Downer (non-calving)	n/a
		Euthanased (explain why in comments)	Specify in comments
		Unsure but can provide a comment	Specify in comments
		Found dead/unsure of cause	n/a

Syndrome	Species	Sub-syndrome	Possible causes
Reduced production or ill-thrift (reported by cause)	Sheep	n/a	Trace element deficiency (specify which in comments) Poor feed availability Johne's disease Intestinal worms Other (specify in comments)
	Cattle	n/a	Trace element deficiency (specify which in comments) Poor feed availability Johne's disease Intestinal worms Other (specify in comments)
Lameness or limb signs (reported by cause)	Sheep	n/a	Arthritis Foot abscess Scald/benign footrot Scabby mouth Hoof abnormality Grass seed damage Laminitis Virulent footrot Multiple causes (specify in comments) Other (specify in comments)
	Cattle	n/a	Arthritis Foot abscess Wire injury Birth injury Hoof abnormality Other (specify in comments)

Gut or mouth signs (reported by class)	Sheep	Scours/Diarrhoea	Intestinal worms Bacteria Nutritional Coccidia Other (specify in comments)
		Mouth signs	Scabby mouth Muzzle hair or skin abnormality Other (specify in comments)
		Other	Specify in comments
Gut or mouth signs (reported by class)	Cattle	Scours/Diarrhoea	Intestinal worms Bacteria Nutritional Coccidia Pestivirus/BVD Other virus (if known, specify in comments) Other (specify in comments)
		Mouth signs	Specify in comments
		Other	Specify in comments
Reproductive failure (reported by class)	Sheep	Ewes (hogget or adult)	Abortion Dystocia/Difficult lambing Stillborn lambs Newborn lamb deaths Poor scanning percentage Scanned but failed to lamb Poor marking percentage Prolapsed vagina Other (specify in comments)
		Adult Rams	Knob rot Testicle problem Lameness (unable to serve) Other (specify in comments)

Reproductive failure (reported by class)	Cattle	Adult Cows	Abortion Dystocia/Difficult calving Stillborn calf Newborn calf deaths Poor pregnancy testing percentage PTIC but failed to calve Poor marking percentage Prolapsed uterus Retained membranes Other (specify in comments)
		Adult Bulls	Testicle problem Lameness (unable to serve) Other (specify in comments)
Skin or eye signs (reported by cause)	Sheep	Skin signs (including itching)	Flystrike Lice Photosensitisation Grass seed Trace element problem (specify which in comments) Other (specify in comments)
		Eye signs	Pinkeye Eye cancer Blind Grass seed in eye Other (specify in comments)
		Other	Specify in comments

Skin or eye signs (reported by cause)	Cattle	Skin signs (including itching)	Lice Ringworm Photosensitisation Trace element problem (specify which in comments) Other (specify in comments)
		Eye signs	Pinkeye Eye cancer Blind Other (specify in comments)
		Other	Specify in comments
Nervous system signs (reported by cause)	Sheep	Staggers or wobbly walking Stargazing Circling Other (specify in comments)	Perennial ryegrass staggers Phalaris staggers Gudair® (vaccine) reaction Spinal abscess Other (specify in comments)
	Cattle	Staggers or wobbly walking Stargazing Circling Other (specify in comments)	Perennial ryegrass staggers Phalaris staggers Grass tetany Spinal abscess Other (specify in comments)
Respiratory signs (reported by cause)	Sheep	Coughing Nasal discharge/Runny nose Breathing difficulty when moving Other (specify in comments)	Specify in comments
	Cattle	Coughing Nasal discharge/Runny nose Breathing difficulty when moving Other (specify in comments)	Specify in comments
Other (reported by class)	Sheep	Other (specify in comments)	Specify in comments
	Cattle	Other (specify in comments)	Specify in comments

Appendix C. VETERINARY INVESTIGATIONS COMPLETED DURING LANDI SURVEILLANCE SYSTEM OPERATION

TABLE C1. SUMMARY OF VETERINARY DISEASE INVESTIGATIONS PERFORMED AS PART OF
LANDI SURVEILLANCE SYSTEM OPERATION, SEPTEMBER 2014 TO NOVEMBER 2016.

Disease presentation	Number of cases			Diagnosis	No. with diagnosis
	Sheep	Cattle	Goats		
Deaths with no other signs	37	2	0	Clostridial disease	5
				Metabolic (hypocalcaemia, hypomagnesaemia)	11
				Ruminal acidosis	8
				Phalaris sudden death	3
				Other (redgut, algal, renal, predation)	7
				Inconclusive or no diagnosis	5
Deaths with other signs (reduced production, ill-thrift, or gut or mouth signs)	50	7	7	Campylobacteriosis	6
				Intestinal parasitism	21
				Yersiniosis	17
				Pleuropneumonia	5
				Pestivirus	2
				Salmonellosis	2
				Other (<i>M. ovis</i> anaemia, vitamin E, gut accident)	7
				Inconclusive or no diagnosis	4
Reduced production or ill-thrift	15	3	0	Ovine Johne's Disease	5
				Renal disease/ other	5
				Woody tongue (actinobacillosis)	1
				Nutrition (trace element, vitamin E)	3
				Inconclusive or no diagnosis	4
Lameness or limb signs	13	0	1	Septic polyarthritis	9
				Ruminal acidosis (laminitis)	2
				Other (Trauma, predation, spinal damage)	3
Nervous system signs	19	4	0	Phalaris staggers	5
				Pregnancy toxaemia	3
				Clostridial disease	3
				Polioencephalomalacia	3
				Other sporadic disease (e.g. Perennial ryegrass toxicosis)	4
				Inconclusive or no diagnosis	5

Reproductive failure	5	0	0	Vaginal prolapse	2
				Poor male fertility	3
Reproductive failure: Abortion/ neonatal death	14	2	7	Abortion – campylobacter	7
				Abortion – listeria	3
				Abortion – other (Q fever, toxoplasma)	2
				Neonatal death – starvation/mismothering	5
				Neonatal death – congenital problem	1
				Abortion or neonatal death – inconclusive	5
Respiratory signs	0	2	0	Bovine respiratory disease	2
Skin or eye signs	10	2	1	Squamous cell carcinoma	1
				Photosensitisation	4
				Other (Dermo, Fibropapilloma)	2
				Pinkeye	3
				Other sporadic disease	3
TOTAL	163	22	16		201

Appendix D. DOCUMENTS ASSOCIATED WITH CHAPTER 5: A QUALITATIVE INVESTIGATION OF FARMER DECISION-MAKING

D1. PRE-DISCUSSION QUESTIONNAIRE

Researcher use only:

Participant ID:



Pre-Discussion Questionnaire

Decision-making in Victorian farmers' response to livestock disease

This questionnaire is to collect background information about each participant in today's discussion session.

These first questions are about yourself

Responses in this section will only be used to give an overview of each group.

What is your gender? Male ☐ Female ☐ Other ☐ Do not wish to disclose ☐

What is your year of birth? What is your home postcode?

The next questions are about your farming enterprise or business

Approximations are acceptable if exact figures are not available.

What are the major outputs of your enterprise?

.....
.....

How many head of sheep are on your property?

.....

How many head of cattle are on your property?

.....

What is the total grazing area of your property?

.....

The final questions are about what you consider the major constraints or issues for your enterprise

What are the **three** biggest issues or constraints to production for your enterprise?

.....
.....
.....

Thinking about your enterprise over the past 5 years, what is the **one** animal health issue that causes the most concern?

.....

What is the major reason this animal health issue causes concern?

.....
.....

D2. INTERVIEW GUIDE

The main part of the discussion will focus primarily on the scenarios as a prompt to get discussion going. Specific prompt questions listed here can be incorporated into discussion of scenarios, or can be raised separately if they don't come up during scenario discussion.

1. (Opening question) Go around the group and introduce yourself and your farm. (5 minutes) All participants are to respond to this question.
2. (Introductory question) In this discussion we'll be talking about responses to disease. To kick off, think about a time when you had a disease problem in your livestock. Can one or two of you share how you responded or what you did? (10 minutes) Only a few participants need to respond to this question.
3. (Transition question – behaviour) Now I would like to hear about your experiences with veterinarians when you had a disease problem. When was the last time you called a vet, and what happened? (10 minutes) Only a few participants need to respond to this question.
4. (Key question – intention) I have a few scenarios that I'm going to share with you now. I'd like to hear what you would do if each scenario happened at your place. (20 minutes per scenario)

Three disease scenarios (see Section D3: Scenario cards) read out in turn and also given in written form with photographs to participants. The resulting discussion should be guided to cover the prompt questions below, though not necessarily in the order listed. Each scenario is likely to bring out different parts of the prompts, not every prompt need be covered in every scenario.

Prompt questions:

- a. Who would contact a vet? (yes/no) Contacting a vet can include just phoning for advice or arranging a farm callout
- b. Those who would, why? Those who would not, why?
- c. Those who would, a government vet or a private vet? Why?
- d. Those who would not, would you get advice from anyone else? (Animal health officer, stock agent, rural supply store staff, other?)

- e. Outcomes of contacting vet (attitude) - I'd like to hear about what might happen when or after you contact a vet.
 - i. What is the likelihood of each outcome?
 - ii. Would that be good, very good, bad, very bad?
 - f. Outcomes of NOT contacting vet (attitude) - I'd like to hear about what might happen if you don't contact a vet.
 - i. What is the likelihood of each outcome?
 - ii. Would that be good, very good, bad, very bad?
 - g. Expectations of others (perceived norms) - Do you think others expect you to contact a vet or not? Do these expectations matter to you – do they make you more or less likely to contact the vet? Examples are neighbours, family, industry, government, employees, others?
5. (Key question – perceived control) I'd like to talk about any factors we haven't discussed yet, that make it easier or more likely that you'll contact a vet. (10 minutes) Examples are having a vet you trust, knowing investigation will help you control disease, others?
 - a. Assistant will make notes of these [and any that come up in scenario discussion] on a large sheet, then farmers can be given tokens/stickers to attach to rank what they individually think has the biggest effect.
 6. (Key question – perceived control) I'd like to talk about any factors we haven't discussed yet, that make it more difficult or less likely that you'll contact a vet. (10 minutes) Examples are vets are expensive, not having time for vet visit, fear of being quarantined, others?
 - a. Assistant again makes notes of these [and any that come up in scenario discussion] on a large sheet, then farmers can be given tokens/stickers to attach to rank what they individually think has the biggest effect.
 7. (Ending question) Assistant reads brief 1-2 minute summary of areas discussed. Is this a fair representation of what we've talked about today? Is there anything else important that we haven't talked about? (10 minutes – in case needs discussion)
 8. (Ending question) This is the first in a series of discussions like this that we are doing. Do you have any advice for how we can improve? (5 minutes)

After this question, the recording devices should be switched off.

Scenario One



It is March, the year has been dry but you have recently had some light rainfall. You go out to one of your paddocks where there is some standing dry feed and a very small green pick, to muster your 400 maiden ewes for crutching. You have to leave 20% of the maidens behind because they are too weak and slow to drive to the yards. You have not noticed any deaths in the mob.

Scenario Two



It is October and you have just finished marking your spring-drop lambs. You are reviewing the results for lambing and note that, out of 1000 ewes lambing, you have had 40 ewe deaths since scanning (4%). You didn't think you saw that many ewes dead out in the paddocks during lambing.

Scenario Three



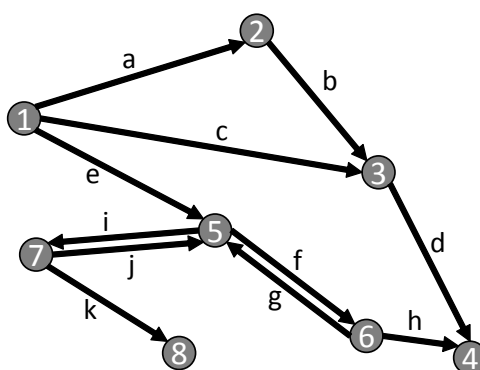
It is June, and you had a good break about 6 weeks ago. Your 600 merino weaners are grazing green pasture. You have noticed a mild scour in the mob for the past month. You drenched them with your normal drench two weeks ago, but they are still scouring. While you are out doing a routine check of the water sources in the paddock, you notice that the scour has increased and is now affecting about 20% of the weaners, and there are two dead weaners in the paddock that look like they have been there for a few days. You also note a few of the weaners are lagging behind the mob with a bad scour.

Appendix E. NETWORK TERMINOLOGY AND RELEVANT MEASURES FOR VETERINARY EPIDEMIOLOGY

This appendix gives a brief overview of network analysis terminology, provided as a supplement to Section 2.8 and Chapters 6 and 7. Definitions of frequently used terms are given in the Glossary (provided on page xxii), and fuller treatment of the complexity and mathematical derivation of network measures are available elsewhere (for example, Dubé et al., 2009; Martínez-López et al., 2009; Dubé et al., 2011b). The focus of this appendix is sufficient explanation of measures for comprehension of results and their implications, which is crucial for converting the results of network analysis into meaningful information.

Network data consists of information in two categories: the data that describes individual nodes, and the data that describes the edges between them (Wasserman and Faust, 1994). Nodes (or vertices) are the individual elements in the network, such as the locations where animals are held (farms, saleyards, abattoirs, etc.) in a livestock movement network. Nodes in livestock movement networks usually have attributes, including their name, geographic location, size and type (e.g. species kept). The nodes are linked in the network by edges, which represent the connections between the nodes, such as trade of a consignment of animals between two farms. A network can have either directed edges (where the connection between a pair of nodes has a direction e.g. a source farm and a destination farm) or undirected edges (where the connection between a pair of nodes has no direction and is by definition reciprocated e.g. a pair of neighbouring farms). Livestock movement networks where edges represent the movements of animals between farms are typically directed, and only some pairs of nodes will have edges linking them in both directions (reciprocated edges). For example, just because one farm sells animals to another farm, it does not necessarily have to purchase animals from that same farm, along the reciprocal edge in the network. While individual edges directly connect a specific pair of nodes, multiple edges can also form a path between two nodes that are not directly connected. Path length is the number of steps in the path between a given pair of nodes. Multiple livestock movements from farm-to-farm can create a path in the network through which infectious disease can spread, with path length equal to the number of movements required to move from the index farm to the final infected farm, assuming the movements occur in the appropriate temporal order (the

temporality of networks is discussed in Section 2.8.2). Useful related measures are the geodesic of a pair of nodes: the length of the shortest path between those two nodes in the network. These concepts are illustrated in Figure E1.



This directed network has eight **nodes** (1 to 8) and eleven **edges** (a to k). Most edges occur in one direction only, except the edges between nodes 5 and 6 (f and g) and between nodes 5 and 7 (i and j) which are **reciprocated**. There are three **paths** between nodes 1 and 4 (following edges $a \rightarrow b \rightarrow d$ with **path length** 3, $c \rightarrow d$ with path length 2, or $e \rightarrow f \rightarrow h$ with path length 3); the shortest of these paths (the **geodesic** value) of that node pair $1 \rightarrow 4$ is two. Note that there is no corresponding path $4 \rightarrow 1$ in this network, due to the directedness of edges; this is an example of **fragmentation**. There is also no path in either direction between nodes 1 and 8. The overall fragmentation of this network is 62.5%, because of all 56 possible node pairs in the network, there is no directed path joining 35 of them. Degree values for node 5 are **in-degree** three (nodes 1, 6 and 7), **out-degree** two (nodes 6 and 7) and **total degree** three (nodes 1, 6 and 7). Node 5 has an **incoming reach** of three (it can be reached by nodes 1, 6 and 7 along paths e, g and j) and an **outgoing reach** of four (it can reach nodes 4, 6, 7 and 8 along paths $f \rightarrow h$, f, i and $i \rightarrow k$, respectively).

FIGURE E1. AN EXAMPLE DIRECTED NETWORK, ILLUSTRATING COMMON NETWORK TERMINOLOGY.

Edges in a network can also describe other relationships between nodes, such as equipment sharing, contractors, purchase of supplementary feed, livestock transport vehicles, or neighbouring boundaries. Examples of these kinds of edges are described in studies by Brennan et al. (2008) and Thakur et al. (2014), and depending on the type of relationship described by the edges, they may result in either directed or

undirected networks. However, most studies of livestock movement data focus solely on the edges created between farms by livestock movement. Edges in livestock movement networks can also have attributes including such as the type of connection they represent (e.g. sale from farm to abattoir for slaughter), the date(s) on which the edge was present in the network, the number of animals moved, and the frequency with which that edge occurs in a given timeframe (for example, whether present at all times such as a shared fence-line, or a dynamic connection that occurs with a given frequency on one or more dates, for example a farm which directly supplies an abattoir).

Building from the fundamental concepts of nodes, edges and paths, there are many common measures used in network analysis to describe characteristics of the network overall, or the position or connectedness of nodes within the network. Measures in network analysis can be divided into three broad categories: topology (describing the overall structure of the network), cohesiveness (how well connected the network is overall), and centrality (how well connected individuals are, within the network). Centrality measures are typically expressed for individual nodes in the network, but can also be summarised into network measures, representing what percentage of the theoretical maximum value that could exist in the network is actually present. These groups of measures are used to compare different networks, and can indicate network features that influence disease transmission. By contrast, node-level centrality measures can identify individual nodes that are particularly well connected, in terms of their potential to receive infected animals or to send infected animals to other nodes.

Centrality measures that are useful for identifying highly connected nodes for targeted surveillance include degree, weighted degree, betweenness, closeness, reach and neighbourhood size. A node's degree value is the number of other nodes that are directly connected to it in the network (its first order neighbours i.e. nodes connected with a path length of 1, see Figure E1). In a directed network, degree can be divided into two parts, the in-degree (the number of other nodes with directed edges terminating on the node of interest) and the out-degree (the number of other nodes with directed edges beginning at the node of interest). Nodes with both high in-degree and out-degree are considered hubs, and increase the overall connectedness of the network (Dubé et al., 2011b). In the case of infectious disease spread, hubs are also

referred to as ‘superspreader’ nodes (Lloyd-Smith et al., 2005), due to their increased risk of both acquiring and disseminating disease. Weighted degree values (including weighted in-degree and weighted out-degree) can also be calculated by weighting edges in the network by edge characteristics, typically the number of batches or total number of animals moved along that edge in a given time-frame. Because these weighted degree values account for the volume or frequency of animals moved between node pairs, they can be more informative about the relative risk of acquiring or disseminating disease than simple degree values (Volkova et al., 2010). The betweenness of a node is the number of times a specific node lies on the geodesic path between two other nodes in the network. Nodes with high betweenness tend to act as bridging nodes in the network, connecting node pairs that would otherwise have either a far longer path connecting them, or would be fragmented from one another. The targeted removal of nodes with high betweenness therefore usually leads to fragmentation of the network (Dubé et al., 2011b), where clusters of nodes in the network become disconnected from one another. This has the effect of reducing the size of the giant strong connected component (GSCC, see below), and has therefore generated interest as a measure to detect nodes for targeted surveillance activities to detect disease spread in the early stages of an epidemic (Dorjee et al., 2013).

Closeness measures how closely connected a node is to all other nodes in the network, based not on its geographic location but its location in the network (Dubé et al., 2011b). It is mathematically defined as the inverse of the average length of all geodesics of that node. Closeness can be used comparatively to understand the spread of average path lengths in the network, with nodes with lowest closeness the topologically ‘furthest’ from others in the network and therefore the least threat of disease spread. A node’s reach is the number of other nodes in the network that can be reached along a directed path in the network, and can be expressed either as an absolute number or as a proportion of all nodes in the network. Similarly to degree, in a directed network reach can be considered as incoming reach (the proportion of other nodes in the network that can reach the node of interest) and outgoing reach (the proportion of other nodes in the network that can be reached from the node of interest), as shown in Figure E1. Respectively, these describe the maximum number of farms that could potentially spread disease to the farm of interest via the network, and the maximum number of farms that the farm of interest could spread disease to. A related measure is neighbourhood size, the number of nodes connected within a given

path length, or neighbourhood ‘order’, of the node of interest. For example, incoming reach considers all nodes that have an incoming path connected to the node of interest, whereas the node’s incoming second-order neighbourhood size is the number of other nodes that can reach the node of interest in two or fewer ‘steps’ on the network (path length ≤ 2). Neighbourhood sizes may provide a more relevant understanding of a node’s position in the network, compared to reach, as a path of just two or three movements may seem a more realistic model of disease spread compared to a path of eight or nine movements.

It is useful to also consider the correlation of centrality measures, to understand whether some easily calculated measures may be used as proxies for other more complex measures, or if considering multiple measures simultaneously identifies high-risk nodes more effectively. For example, in- and out-degree tend not to be strongly correlated in livestock movement networks, as shown for sheep movement in Scotland (Pearson’s $\rho = 0.109$, $p < 0.001$, Volkova et al., 2010) and cattle movement in Minnesota (Spearman’s $\rho = 0.05$, Ribeiro-Lima et al., 2015). However, Ribeiro-Lima et al. (2015) did show both in- and out-degree were moderately correlated with betweenness (Spearman’s $\rho = 0.67$ and 0.62 , respectively), with a similar finding reported for networks of cattle movement in Uruguay (Spearman’s $\rho = 0.73$ and 0.63 , respectively, $p < 0.01$, VanderWaal et al., 2016) and for total degree and betweenness for the network of livestock movements between a group of corporate farms in New Zealand (Spearman’s $\rho = 0.7$, $p < 0.0001$, Marquetoux et al., 2016b).

These node-level centrality measures are of great interest for the purpose of designing targeted surveillance. However, as node centrality occurs in the context of the broader network, it is also worth describing the entire network in terms of its topology and cohesiveness. Common topology measures for livestock movement networks include network size, diameter, and two specific topological patterns, ‘small-world’ and ‘scale-free’ networks. Network size is simply the number of nodes and number of edges in the network. A network’s diameter is the length of the largest geodesic in the network—the maximum number of steps required to follow a path from any node to any other node, for all node pairs linked by one or more paths in the network.

The two topological patterns seen commonly in livestock movement networks are termed small-world and scale-free. A small-world network occurs when most nodes are connected into separate small groups, but a small number of high-betweenness

nodes act as bridges between those groups, giving an overall network that is highly connected (Dubé et al., 2011b). This can be detected by checking the network for high global clustering coefficient (which occurs when direct neighbours of individual nodes tend also to be connected to one another), alongside a short average path length. In a small-world network, infection can spread both 'locally' within clusters in the network, but also between clusters by the bridging (high betweenness) nodes. Small-world topology has been repeatedly demonstrated in livestock movement networks (Dubé et al., 2011a; Rautureau et al., 2012; Mweu et al., 2013; Thakur et al., 2014). Scale-free networks are also commonly seen in livestock movement networks (Bajardi et al., 2011; Dubé et al., 2011a; Rautureau et al., 2012). In a scale-free network, most nodes have low degree values (are directly connected to very few others), while a very small number of nodes have very high degree values. The result is that the distribution of degree values in the network follows a power-law distribution, which is strongly positively skewed with no peak. This degree distribution means that a small number of nodes of high-degree nodes disproportionately increase the connectivity of the network, and are the nodes of interest for targeted surveillance or disease control strategies.

Following on from topology, cohesiveness measures describe how well-connected the network is overall (Dubé et al., 2011b), with a number of measures relevant for livestock movement networks. Common measures of cohesiveness include density, fragmentation, average path length, clustering coefficient and reciprocity. Density is the proportion of edges that exist in the network compared to the theoretical maximum number of edges that are possible (where N is the number of nodes in a directed network, the theoretical maximum number of edges is $2[N \times N - 1]$). Fragmentation is the proportion of node pairs in the network that have no path connecting them (see Figure E1). The more fragmented a network is, the more challenging it is for infectious disease to spread across the network, because some nodes are unreachable from a given starting node. The average path length is the average geodesic value for the network—the average number of 'steps' to get from any one node to any of the other nodes to which it is connected, either directly or indirectly via other nodes. The local (node-level) clustering coefficient is the proportion of direct neighbours of a node that are also connected to one another, with the global (or network) clustering coefficient being calculated as either the sum of clustering coefficients for all nodes, expressed as a percentage of the theoretical

maximum value that could occur in a network of that size, or alternatively as the mean local clustering coefficient value across all nodes in the network. Reciprocity is the proportion of connected node pairs in a directed network where edges exist in both directions between the pair (i.e. node pairs where the two farms each purchase animals from and sell animals to one another).

It is also of interest to understand the size of connected sub-networks within the full network, to estimate the potential size of a disease epidemic if control measures are not implemented. The giant strong connected component (GSCC) is a sub-network of the full directed network, where every node can be reached on a path from every other node (in both incoming and outgoing directions) by following the directed edges in the network. The giant weak connected component (GWCC) is similar, a sub-network where every node can be reached on a path from every other node, except that the sub-network is generated by ignoring the direction of edges. The size of the GSCC and GWCC have been proposed as estimators of the lower and upper bounds, respectively, of the maximum size of an epidemic in a livestock movement network (Dubé et al., 2008).

Finally, overall network connectivity can also be understood by the concept of communities, where the network is divided into complementary subnetworks based on relative cohesiveness; that is, each node in the network belongs to only one community, and there is greater connectedness within a community than between communities. Communities can be detected in a network by a variety of algorithms, as reviewed and evaluated by Yang et al. (2016). Note that communities in the network may not be associated with geographic proximity (Dubé et al., 2011b), so the geographic distance between nodes may not constrain disease spread through the network. This is why suspending livestock movements is essential in the early stages of an exotic disease outbreak, to reduce the potential for further wide geographic spread of the outbreak within network communities.

By describing a livestock movement network in terms of these measures of topology and cohesiveness, the potential for disease spread within the network can be better understood. These can include estimates of the potential size of undetected outbreaks and the overall connectedness (or disconnectedness) of the network. Pairing these measures with node-specific centrality measures can then begin to identify the nodes that are most influential on this overall connectedness. Resources for both

surveillance during 'peacetime', and disease response activities, can then be preferentially directed to these highly connected nodes to maximise their effectiveness. However, these strategies rely on the validity of network measures to truly understand the structure of the network.

Appendix F. SUPPLEMENTARY MATERIALS TO CHAPTER 7 MANUSCRIPT

TABLE S1. THE MINIMUM, MEAN AND MAXIMUM PROPORTION OF NETWORKS OF DIFFERENT SIZES AND TOPOLOGIES THAT MUST BE SAMPLED TO ESTIMATE MEDIAN AND MEAN TOTAL DEGREE MEASURES, WITH 80% POWER AND $\pm 5\%$ RELATIVE PRECISION, FOR SETS OF 10 SIMULATED NETWORKS AS DETERMINED BY A SIMULATION ALGORITHM. VALUES IN BOLD INDICATE WHERE THE RANGE OF SAMPLING PROPORTION OUTPUTS IS GREATER THAN 0.15 WITHIN EACH SET OF 10 NETWORKS.

Number of nodes	Topology	Sampling method	Median of total degree			Mean of total degree		
			Min	Mean	Max	Min	Mean	Max
100	Random	Random	0.15	0.25	0.85	0.7	0.8	0.85
1000	Random	Random	0.035	0.045	0.1	0.25	0.25	0.3
10,000	Random	Random	0.005	0.005	0.005	0.035	0.035	0.035
100	Random	Snowball	0.25	0.5	0.85	0.95	0.95	0.95
1000	Random	Snowball	0.15	0.275	0.5	0.95	0.95	0.95
10,000	Random	Snowball	0.1	0.15	0.2	0.95	0.95	0.95
100	Scale-free	Random	0.15	0.35	0.45	0.9	0.9	0.95
1000	Scale-free	Random	0.005	0.045	0.15	0.2	0.65	0.75
10,000	Scale-free	Random	0.005	0.01	0.01	0.2	0.2	0.25
100	Scale-free	Snowball	0.55	0.8	0.95	0.95	0.95	0.95
1000	Scale-free	Snowball	0.7	0.75	0.8	0.95	0.95	0.95
10,000	Scale-free	Snowball	0.7	0.7	0.75	0.95	0.95	0.95

TABLE S2. THE MINIMUM, MEAN AND MAXIMUM PROPORTION OF NETWORKS OF DIFFERENT SIZES AND TOPOLOGIES THAT MUST BE SAMPLED TO ESTIMATE STANDARD DEVIATION (*SD*) AND COEFFICIENT OF VARIATION (*CV*) OF TOTAL DEGREE MEASURES, WITH 80% POWER AND $\pm 5\%$ RELATIVE PRECISION, FOR SETS OF 10 SIMULATED NETWORKS AS DETERMINED BY A SIMULATION ALGORITHM. VALUES IN BOLD INDICATE WHERE THE RANGE OF SAMPLING PROPORTION OUTPUTS IS GREATER THAN 0.15 WITHIN EACH SET OF 10 NETWORKS.

Number of nodes	Topology	Sampling method	<i>SD</i> of total degree			<i>CV</i> of total degree		
			Min	Mean	Max	Min	Mean	Max
100	Random	Random	0.75	0.8	0.9	0.8	0.85	0.9
1000	Random	Random	0.3	0.325	0.35	0.3	0.3	0.35
10,000	Random	Random	0.04	0.045	0.045	0.04	0.04	0.045
100	Random	Snowball	0.65	0.725	0.8	0.95	0.95	0.95
1000	Random	Snowball	0.25	0.35	0.55	0.95	0.95	0.95
10,000	Random	Snowball	0.15	0.25	0.3	0.95	0.95	0.95
100	Scale-free	Random	0.9	0.925	0.95	0.8	0.9	0.95
1000	Scale-free	Random	0.9	0.9	0.95	0.8	0.9	0.95
10,000	Scale-free	Random	0.85	0.9	0.9	0.8	0.9	0.9
100	Scale-free	Snowball	0.9	0.9	0.9	0.6	0.675	0.85
1000	Scale-free	Snowball	0.9	0.9	0.9	0.35	0.475	0.5
10,000	Scale-free	Snowball	0.9	0.9	0.9	0.4	0.5	0.5

Appendix G. SUMMARY OF EDGE CHARACTERISTICS IN THE VICTORIAN SHEEP MOVEMENT NETWORK

The 298,511 mob movements in the interstate-Victorian movement network in 2015 are summarised in Table 10-2 (source and destination property types) and Table 10-3 (property type and import/export type). There was a discrepancy in the volume of movements to and from Victorian livestock agents, where agents were recorded to have purchased 807,121 sheep but only sold 180,426 sheep, leaving the final destination of 78% of purchases unaccounted for.

TABLE G1. NUMBER OF MOVEMENTS IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK, SUMMARISED BY SOURCE AND DESTINATION PROPERTY TYPE.

Source	Destination				
	Agent	Abattoir	Farm	Saleyard	Total
Livestock Agent	–	11 mvmts 627 sheep (10 pairs) ^a	1489 mvmts 179,624 sheep (767 pairs)	–	1500 mvmts 180,251 sheep (777 pairs)
Farm	46 mvmts 7380 sheep (26 pairs)	22,096 mvmts 4.9 million sheep (10,443 pairs)	4961 mvmts 363,148 sheep (3828 pairs)	68,582 mvmts 5.5 million sheep (14,932 pairs)	95,685 mvmts 10.8 million sheep (29,229 pairs)
Saleyard	15,029 mvmts 799,741 sheep (291 pairs)	163,544 mvmts 6.7 million sheep (509 pairs)	22,744 mvmts 1.1 million sheep (4085 pairs)	9 mvmts, 56 sheep (3 pairs)	201,326 mvmts 8.6 million sheep (4888 pairs)
Total	15,075 mvmts 807,121 sheep (317 pairs)	185,651 mvmts 11.6 million sheep (10,962 pairs)	29,194 mvmts 1.6 million sheep (8680 pairs)	68,591 mvmts 5.5 million sheep (14,935 pairs)	298,511 mvmts 19.6 million sheep (34,894 pairs)

^a Listed as: number of movements (mvmts), number of sheep moved, (number of unique node pairs connected by movements in network).

TABLE G2. NUMBER OF MOVEMENTS IN INTERSTATE-VICTORIAN MOVEMENT NETWORK, SUMMARISED BY MOVEMENT TYPE AND GEOGRAPHIC MOVEMENT TYPE.

Property type	Number of movements		
	Within Victoria	Import into Victoria	Export from Victoria
Agent-Abattoir	10 mvmts 615 sheep (9 pairs) ^a	–	1 mvmt 12 sheep (1 pair)
Agent-Farm	1245 mvmts 142,133 sheep (651 pairs)	–	244 mvmts 37,491 sheep (116 pairs)
Farm-Abattoir	11,418 mvmts 2.2 million sheep (5273 pairs)	8540 mvmts 2.1 million sheep (4012 pairs)	2138 mvmts 584,332 sheep (1158 pairs)
Farm-Agent	24 mvmts 6163 sheep (20 pairs)	22 mvmts 1217 sheep (6 pairs)	–
Farm-Farm	2777 mvmts 117,290 sheep (2036 pairs)	1221 mvmts 117,607 sheep (1079 pairs)	963 mvmts 128,251 sheep (713 pairs)
Farm-SY	61,116 mvmts 4.7 million sheep (12,796 pairs)	3380 mvmts 384,671 (812 pairs)	4086 mvmts 388,494 sheep (1324 pairs)
SY-Abattoir	80,732 mvmts 3.2 million sheep (223 pairs)	69,806 mvmts 3.0 million sheep (231 pairs)	13,006 mvmts 614,370 sheep (55 pairs)
SY-Agent	5698 mvmts 292,478 sheep (217 pairs)	9331 mvmts 507,263 sheep (74 pairs)	–
SY-Farm	15,913 mvmts 709,173 sheep (3120 pairs)	2644 mvmts 152,924 sheep (561 pairs)	4187 mvmts 268,250 sheep (404 pairs)
SY-SY	9 mvmts 56 sheep (3 pairs)	–	–

^a Listed as: number of movements (mvmts), number of sheep moved, (number of unique node pairs connected by movements in network).

Victorian abattoirs were the destination for 57% (170,506/298,511) of movements in the interstate-Victorian movement network, with 88% (150,538/170,506) of movements to abattoirs being sourced from saleyards (80,732 from Victorian saleyards and 69,806 from interstate saleyards). A total of 10.4 million sheep were received by Victorian abattoirs, summarised in Table 7-20. Despite representing only 12% of movements to abattoirs, 41% (4.3 million/10.4 million) of sheep slaughtered were sourced directly from farms with an average 215 sheep per consignment. The remaining sheep were sourced via saleyards in far smaller consignments with average 41 sheep per consignment.

The interstate-Victorian source-destination network contained 232084 movements, including 188,575 movements within the state, 90,825 import movements and 22,695 export movements. The majority of import movements (85%, 78,044/90,840) were between an interstate and a Victoria abattoir, with 10.9% (8540/78,044) direct farm to abattoir movements, 6.1% (4741/78,044) via Victorian saleyards, and 83.0% (64,763/78,044) via interstate saleyards, primarily saleyards in NSW (68.7%, 53,606/78,044) or SA (14.3%, 11,122/78,044). These movements resulted in a total of 5.1 million sheep being imported for slaughter at Victorian abattoirs, 86.6% of the total 5.9 million sheep imported into Victoria in 2015. This is contrasted by just 1.7 million sheep exported from Victoria, of which 73% were destined for interstate abattoirs in NSW (n = 282,011) and SA (n = 971,032).

TABLE G3. SHEEP RECEIVED BY VICTORIAN ABATTOIRS IN THE INTERSTATE-VICTORIAN MOVEMENT NETWORK , CATEGORISED BY SOURCE.

Source	Movements received		Sheep received		Average number of sheep per movement
Victorian agent	10	<0.1%	615	<0.1%	62
Victorian farm	11,418	7%	2.2 million	21%	193
Victorian saleyard	80,732	47%	3.2 million	31%	39
Interstate farm	8540	5%	2.1 million	20%	244
Interstate saleyard	69,806	41%	2.9 million	28%	42
Total	170,506		10.4 million		61