# Foot-and-mouth disease epidemiology in relation to the physical, social and demographic farming landscape.

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# Declaration

This thesis is being submitted in accordance with the requirements for the degree of Doctor of Philosophy to the University of Edinburgh. The work in this thesis is my own unless clearly stated otherwise. Mathematical modelling simulations were conducted by Thibaud Porphyre, but analysis of these simulation results were conducted by myself, as were all other analyses in this thesis. All written work is my own, except for the mathematical modelling methods presented in the Appendix which were written by Thibaud Porphyre - this is stated in the text.

Jessica Flood, 2015

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# Abstract

The foot-and-mouth disease (FMD) virus poses a considerable threat both to farmers and to the wider economy should there be a future incursion into the UK. The most recent large-scale FMD epidemic in the UK was in 2001. Mathematical models were developed and used during this epidemic to aid decision-making about how to most effectively control and eliminate it. While the epidemic was eventually brought to a halt, it resulted in a huge loss of livestock and is estimated to have cost the UK economy around £6 billion. The mathematical models predicted the overall spatial spread of FMD well, but had low predictive ability for identifying precisely which farm premises became infected over the course of the epidemic. This will in part have been due to the stochastic nature of the models. However, the transmission probability between two farm premises was represented as the Euclidean distance between their point locations, which is a crude representation of FMD transmission. Additionally, the premises' point location data contain inaccuracies, sometimes identifying the farmer's residential address rather than the farm itself which may be a long way away.

Local FMD transmission occurs via contaminated fomites carried by people or vehicles between premises, or by infected particles being blown by wind between proximal fields. Given that these transmission mechanisms are thought to be related to having close field boundaries, it is possible that some of the inaccuracy in model predictions is also due to imprecisely representing such transmission. In this thesis I use fine-scale geographical data of farm premises' field locations to study the contiguity of premises (where contiguous premises (CPs) are defined as having field boundaries <15m apart). I demonstrate that the distance between two premises' point locations does not accurately represent when they are CPs. Using an area of southern Scotland containing 4767 livestock premises, I compare the predictions of model simulations using two different model formulations. The first is one of the original models based on the 2001 outbreak, and the second is a new model in which transmission probability is related to whether or not premises were contiguous. The comparison suggests that the premises that became infected during the course of the simulations were more predictable using the new model. While it cannot be concluded that this will translate into more accurate predictions until this can be validated during a future outbreak, it does suggest that the new model is more predictable in its route through the landscape, and therefore that it may better reflect local transmission routes than the original model. Networks based on contiguity of premises were constructed for the same area of southern Scotland, and showed that 90.6% (n=4318) of the premises in the area were indirectly connected to one another as part of the Giant Component (GC). The network metric of 'betweenness' was used to identify premises acting as bridges between otherwise disconnected sub-populations of premises. It was found that removing 100 premises with highest betweenness served to fragment the GC. Model simulations indicated that, even with some longer-range transmission possible, removing these premises from the network resulted in a large decrease in mean number of infected premises and outbreak duration. In real terms, premises removal from the network would mean ensuring these premises did not become infected by enhanced biosecurity and/or vaccination depending on policy.

In this thesis I also considered the role of biosecurity practices in shaping FMD spread. A sample of 200 Scottish farmers were interviewed on their biosecurity practices, and their biosecurity risk quantified using a biosecurity 'risk score' developed during the 2007 FMD outbreak in Surrey. Using Moran's I and network assortativity measures it was found that there did not appear to be any clustering of biosecurity risk scores on premises. Statistical analysis found no association between biosecurity risk and the mathematical model's premises' susceptibility term (which describes the increase in a premises' susceptibility with increasing numbers of livestock). This suggests that the model's susceptibility term is not indirectly capturing a general pattern in biosecurity on different sized farm premises.

Thus, this body of work shows that incorporating a more realistic representation of premises location into mathematical models, in terms of area (i.e. as fields) rather than a point, alters predictions of spatial spread. It also demonstrates that targeted control at a relatively small number of farms could effectively fragment the farming landscape, and has the potential to considerably reduce the size of an FMD outbreak. It also demonstrates that variations in premises' FMD biosecurity risks are unlikely to be indirectly affecting the spatial or demographic components of the model. This increase in understanding of how geographic, social and demographic factors relate to FMD spread through the landscape may enable more effective control of an outbreak, should there be an incursion in the UK in future.

# Lay summary

Foot-and-mouth disease (FMD) is a viral disease that infects cloven-hoofed animals. The UK is currently FMD-free, but it remains present in other countries so it is possible that it may be imported. If and when this happens, we need to know how best to prevent it from spreading through the farming landscape, as infected livestock have to be culled for productivity and trade reasons. This can result in considerable cost if the disease spreads widely: the last big outbreak in the UK in 2001 cost the economy around £6 billion.

Once FMD had been detected in 2001, a national ban on the movement of animals was put in place to prevent farmers unknowingly trading infected livestock that did not yet show clinical signs. However, the disease continued to spread between farms - most likely by the virus being carried on people's clothing/ footwear, on vehicle wheels, and by contact of animals over shared field boundaries. Biosecurity practices, such as disinfecting boots and vehicle wheels, helped to reduce the chances of infection.

Mathematical models were used to aid decision making about which control measures would likely be most effective. These models described the probability of transmission of FMD between an infected and uninfected farm based on the distance between them. This distance was taken as the straight-line distance between farms represented as point locations on a map. These point locations could be based on the main farm building, the postcode centroid, or even the farmer's address away from the farm. The models could capture the general pattern of geographic spread of the disease well, but could not accurately identify specific farms that became infected. My thesis demonstrates that this may be improved in future by using a representation farm location that better represents how FMD is likely to transmit between farms, by looking at the location of all their fields and whether they adjoin those of other farms.

I show that the distance between farms' point locations is not accurate in identifying which farms share field boundaries. I then look at how disease was predicted to spread across an area of Scotland by comparing predictions from model simulations, using the original model and a new model which based transmission probability on when farms shared field boundaries. The new model predicts that some farms would become infected premises in the majority of the simulations, which the original model did not, suggesting a less variable pathway of infection between farms. Looking at how farms were connected by their fields, I identify specific farms that link otherwise separate sub-populations of connected farms. By ensuring these farms do not become infected (e.g. using strict biosecurity practices), the likely geographic spread of FMD and outbreak size is predicted to be greatly reduced in simulations of the new model. This suggests that future outbreaks may be controlled by targeting a few farms that occupy key positions in the landscape.

I also consider how biosecurity practices on farms may impact the geographic spread of FMD via interviews with 200 Scottish farmers. I find that neighbouring farmers do not seem to imitate each other in terms of the biosecurity practices they used. Had they done so, this could have resulted in clusters of farms with poor biosecurity, which in turn may have accounted for geographical clustering of FMD cases in outbreaks. I also found that the level of biosecurity did not appear to be related to the estimated susceptibility of farms based on the number of livestock they kept. Therefore, the increase in a farm's susceptibility to FMD with increasing numbers of livestock are likely genuinely due to there being more animals at risk of infection, rather than, for example, larger farms having poorer levels of biosecurity.

In summary, I find that using farm field rather than point locations in mathematical models may better reflect actual FMD transmission routes, and enable identification of key farms to target control measures at which could have a potentially large impact on reducing outbreak spread.

# Contents

# 1 General introduction

This thesis is concerned with understanding foot-and-mouth disease (FMD) epidemiology, with a focus on potential FMD spread in Scotland. During an outbreak, initial FMD spread is likely to be by movement of infected stock into susceptible herds/flocks, although it continues to spread when movement of livestock is halted (e.g. by implementation of a livestock movement ban). This thesis aims to understand the latter, in terms of local disease transmission between farms, and will draw on landscape epidemiology and ecology to examine this. The assumptions and parameters of predictive mathematical models used to describe FMD spread following implementation of a livestock movement ban are investigated to try to elucidate how predicted patterns of spread may be altered by incorporating additional information regarding the farming landscape (i.e. the geography and topography of farm land across space), and to test the assumptions of their parameterisation.

This General Introduction chapter provides background information on FMD epidemiology and transmission, as well as the mathematical models (and transmission kernels) used to describe patterns of FMD spread during the UK's 2001 outbreak. It also provides a background on spatial epidemiology, disease ecology, and the Scottish farming landscape. The final section of this chapter lays out the specific questions of the thesis, and outlines the contents of each analysis chapter.

## 1.1 Foot-and-mouth disease

Foot-and-mouth disease (FMD) is a highly infectious viral disease that affects cloven-hoofed animals such as cattle, sheep, pigs, goats and deer. It is an Aphthovirus virus of the Picornaviridae family. There are seven serotypes of FMD: O, A, C, SAT1, SAT2, SAT3 and Asia 1, with many subtypes within these (Mahy, 2005). The different serological types (i.e. serotypes) were first identified in different geographical regions: O, A and C in Europe; SAT1, SAT2 and SAT3 in Africa; and Asia 1 in Asia (Mahy, 2005). Symptoms often include blisters in the mouth and on the feet for cattle, and lameness for sheep and pigs; it needs laboratory confirmation to differentiate it from other vesicular fevers (DEFRA, 2014). While it is not necessarily a life-threatening disease, animals suffer reduced productivity following infection, resulting in economic losses. Some animals become carriers, with persistent infection (Sutmoller et al., 2003).

FMD can be transmitted by contact with infected animal secretions and excretions (Alexandersen and Mowat, 2005; Sutmoller et al., 2003). The virus is environmentally resistant, reportedly surviving many years in soil, and can remain viable in milk and frozen infected animal products (Mahy, 2005). For this reason, international trade laws do not allow animal products to be exported from countries with FMD (Mahy, 2005). The UK is currently FMD-free, but there is a continued risk of FMD incursion as the disease is still present around the world - including across Africa (Allepuz et al., 2015; Ayebazibwe et al., 2010; Ayelet et al., 2012; Bronsvoort et al., 2004; Hamoonga et al., 2014; Jori et al., 2009; Megersa et al., 2009; Vosloo et al., 2009) and Asia (Dukpa et al., 2011; Nampanya et al., 2013; Nawaz et al., 2014; Perez et al., 2006; Ur-Rehman et al., 2014). FMD is a notifiable disease in the UK, meaning there is a legal requirement to report suspected cases to the government authorities (DEFRA, 2014).

Culling livestock on infected premises (IPs) and premises surrounding IPs or that have been identified as being ‘at-risk’ (so-called dangerous contacts, DCs), as well as livestock movement restrictions, are the main control measures used to ‘stamp out’ disease from otherwise FMD-free countries to regain their FMD-free status. Livestock vaccination can also be used to help control FMD so long as the vaccination serotype matches the circulating strain, since there is poor cross immunity between serotypes (Alexandersen and Mowat, 2005). However, carrier animals can remain as such following vaccination, and until recently, because of this, FMD-free countries have not purchased animal product exports from countries that have FMD-vaccinated stock (Sutmoller et al., 2003). New Differentiation of Infected from Vaccinated Animals (DIVA) tests now enable distinction between infected and vaccinated livestock (Uttenthal et al., 2010). These can therefore be used to prove cessation of virus transmission following an outbreak (Uttenthal et al., 2010). The European Union does not allow vaccination to be used prophylactically, although it can be used as part of a disease control programme to ‘stamp out’ an FMD incursion (Porphyre et al., 2013). DEFRA’s contingency plan states it would consider the use of vaccination as an additional control measure to culling in the event of a future incursion to the UK (DEFRA, 2011). However, there are issues in carrying out such a strategy, particularly relating to the rapidity with which it can be implementated (Porphyre et al., 2013).

In conclusion, FMD is a livestock disease of potentially great economic burden - in terms of loss of productivity of infected animals, loss of international trade in animal products, and direct loss of animals due to culling and as a result of control measures. In the event of a future incursion of the disease to the UK, such costs could be minimised by ensuring that its spread is efficiently and effectively controlled.

### 1.1.1 Recent UK outbreaks

***Contiguous (contiguous premises, CPs), contiguity:*** *where farm premises are neighbouring in such a way that may enable disease transmission via local routes. Various definitions of the sorts of neighbours that are classified as contiguous can be found in Table 2.1.*

The UK has had two FMD outbreaks within the past two decades: a widespread epidemic during 2001 of serotype O PanAsia strain and a small serotype O outbreak in Surrey in 2007. The 2001 outbreak in the UK lasted seven months and is estimated to have cost the economy in the region of £6-8 billion (Anderson, 2002; Thompson et al., 2002). Approximately 10,850 farm premises had their livestock culled either due to infection or pre-emptively as part of control measures (Tildesley et al., 2009). In 2007 the outbreak lasted two months, with only 8 farm premises becoming IPs (Anderson, 2008).

The 2001 outbreak is believed to have originated at a pig premises in Northumberland where pigs were likely infected via contaminated swill (Gibbens et al., 2001). Initial spread was largely via movement and trade of infected animals, but a national livestock movement ban was implemented 3 days after the first FMD case was confirmed and the disease continued to spread across the farming landscape (Gibbens et al., 2001). Such spread is thought to have occurred mainly by close contact of livestock across shared fence lines and by contaminated fomites (where fomites are objects capable of carrying infectious material) carried on people, vehicles, machinery, or on material passing between proximal pastures (Gibbens et al., 2001). Mathematical models were developed in order to capture the likely spread through space, to predict the potential impact of control strategies, and consequently to inform disease control policies implemented (Ferguson et al., 2001b; Keeling et al., 2001). Based in part on these, pre-emptive culling of livestock on premises contiguous to IPs (contiguous premises, CPs), livestock on premises identified as being DCs, and livestock on premises within

3km of/local to an IP was performed (Ferguson et al., 2001b). While it appeared that the culling control strategy helped to eventually bring the epidemic to a halt, it could have been better targeted to reduce the epidemic duration and impact since it appeared that, as implemented in practice, low risk premises were actually targeted over higher risk premises (Tildesley et al., 2009). Additionally, heterogeneities in the fragmentation of the livestock farming landscape across the country suggest that some regions did not require culls for disease containment (Kao, 2003).

Another outbreak occurred in Surrey in 2007 as the result of escaped FMD virus strain O1BFS 1860 from poor laboratory drainage systems (Anderson, 2008). Case detection spanned two months, with only 8 IPs identified; the outbreak was effectively controlled by implementation of livestock movement bans, prompt culling of livestock on IPs and increased local surveillance (Anderson, 2008).

### 1.1.2 Transmission and epidemiology

Transmission of FMD occurs via contact with infected animal secretions and excretions - this may be by direct animal contact, or indirect contact via contaminated fomites or aerosolised virus (Alexandersen and Mowat, 2005; Sutmoller et al., 2003). A number of experimental studies have been used to estimate transmission between infected animals and those in direct/indirect contact under different conditions which illustrate that virus transmission is dependent on several factors - in particular, host species (Alexandersen and Donaldson, 2002; Alexandersen et al., 2002) and husbandry (Alexandersen et al., 2002, 2003).

Host species are variably susceptible to FMD and also contribute differently to onward transmission potential. Although the 2001 FMD outbreak is thought to have started among pigs, they largely avoided infection through the rest of the outbreak, with sheep and cattle having been most affected (Gibbens et al., 2001).

Indeed, pigs excrete considerably more aerosolised virus than cattle and sheep (Alexandersen and Donaldson, 2002; Alexandersen and Mowat, 2005; Alexandersen et al., 2002), but cattle and sheep are more susceptible to it (Alexandersen and Donaldson, 2002; Alexandersen and Mowat, 2005; Alexandersen et al., 2002b).

In terms of husbandry, separation distance, air flow and number of infected animals are all factors that contribute to the transmission rate of FMD. A high transmission rate was observed between infected and susceptible sheep in direct contact by Alexandersen et al. (2002), although they had been kept in a room with restricted ventilation. Another study found cattle in a fully ventilated room had a longer incubation period than the sheep in Alexandersen et al. (2002), suggesting that air flow and husbandry are likely also to be factors affecting transmissibility (Alexandersen et al., 2003). Pigs are relatively resistant to aerosol infection as compared to cattle and sheep (Alexandersen and Donaldson, 2002). Pacheco and Mason (2010) observed no transmission between infected and susceptible pigs separated by 1.3m gaps between pens. While Eble et al. (2006) found a strain of FMD serotype O to transmit between pigs in separate but adjacent pens (separated by a 1.5m high wall), the transmission rate was much lower than that between pigs within the same pen. Similar findings were observed by van Roermund et al. (2010) (also using a serotype O strain), while no transmission was observed between pigs in pens separated by 40-70cm. The intensity of exposure, in terms of the number of infected animals in contact with uninfected animals, was also found to be associated with the incubation period among pigs (Alexandersen et al., 2003). Thus, a lower transmission rate is observed for greater separation distances between susceptible and infectious animals, greater airflow, and fewer infectious animals relative to susceptibles.

Another factor thought to affect FMD transmission is the stage of infection: among experimentally infected cattle, transmission appears to be closely related to onset of clinical symptoms (Charleston et al., 2011; Chase-Topping et al., 2013). Additionally, strain (Pacheco et al., 2012) and serotype (Alexandersen and Mowat, 2005) are thought to vary in their transmission potential.

While such experimental findings are useful to aid understanding of transmission possibilities, in non-experimental conditions it can be extremely difficult to conclude definitively how transmission has occurred between animals on different farm premises. Instead, epidemiological investigation and contact tracing are used to infer how infection has arrived. Analysis of the first five months of the UK's 2001 outbreak found that the majority of IPs had become infected as a result of local transmission in all counties except Essex and Kent, and was believed to have been responsible for 79% of IPs across the UK (Gibbens et al., 2001). Spread via people, vehicles and milk tankers combined were thought to account for a further 6% of IPs, while airborne transmission by viral plumes was thought to have contributed very little to national spread of the disease (Donaldson et al., 2001; Gibbens et al., 2001; Thrusfield et al., 2005). In Gibbens et al. (2001) 'local' transmission referred to IPs being within 3km of a previously confirmed IP, with more than one possible route of infection having been identified. Furthermore, the 2001 FMD transmission kernel (described below) within the mathematical models used indicated that approximately 50% of transmission occurred within 3km of an IP after the implementation of the livestock movement ban (Savill et al., 2006). Thus proximity to an IP was clearly a key risk factor, although the precise mechanism of spread could not be determined (Gibbens et al., 2001). Nonetheless, it was believed that much of the local transmission was a result of locally aerosolised virus between animals on CPs, or due to contaminated material passing between IPs and proximal premises (Gibbens et al., 2001).

During the 2001 outbreak, several classifications of premises' contact with IPs were used as a basis for the pre-emptive culling of their livestock. Two broad preemptive culling categories were the 3km cull (of any premises' sheep $<$3km of an IP), and the local cull. The main idea behind these culls was that many of these premises would have been infected and not yet showing signs of disease (Tildesley et al., 2009), although the exclusion of cattle from the 3km cull (Anderson, 2002) calls this reasoning into question. The 3km cull was theoretically applied to all affected areas (although in reality was variously applied), while the local cull was focussed on premises that had bought sheep from the Welshpool market during the 'at-risk' period (Tildesley et al., 2009). More premises-specific pre-emptive culling strategies of 'at risk' farms included those classified as Dangerous Contacts (DCs), and Contiguous Premises (CPs). DCs were defined as "Premises where animals have been in direct contact with infected animals or have, in any way, been exposed to infection", while CPs were defined as "A category of dangerous contacts where animals may have been exposed to infection on neighbouring infected premises" (Anderson, 2002)(p167). However, specific definitions of what it meant for a premises to be a CP during the 2001 outbreak are hard to come by in the literature. One paper, Thrusfield et al. (2005) state that in Dumfries and Galloway such premises were initially identified on the ground by veterinarian judgement of proximity of animals, and later by cartographical inspection, where they were identified as having a land border touching that of an IP, or as being separated from an IP by only a country road, river, railway or woodland belt <20m in width. Based on this definition, they identified contiguous spread as playing a considerable role in transmission: it was the probable source of infection for 14% IPs, and possible source for a further 25% IPs in the region (Thrusfield et al., 2005). However, fomite transmission routes (via people and vehicles) were thought to be responsible for the majority of transmissions (Thrusfield et al., 2005). In this thesis, I focus on studying 'map-based' contiguity, as the next best method to studying premises on the ground. I consider premises to be map-based contiguous if they have fence boundaries separated by <15m as shown on fine-scale maps. The distance of 15m was chosen as the maximum distance at which premises were considered to be contiguous based on an educated guess of the maximum distance between field edges should a small road lie between them, since Savill et al. (2006) found that small roads did not appear to act as barriers to FMD transmission in 2001.

It should be acknowledged that other animals may also contribute to the spread of FMD between farms. Indeed, in the 1960's and 70's Maureen Capel-Edwards demonstrated that several species including rats, squirrels and water voles are susceptible to FMD as well as having potential for contributing to ongoing transmission (particularly rats) (Alexandersen and Mowat, 2005). Furthermore, the role of deer was not investigated for the 2001 outbreak. Although these contributions to FMD spread between livestock farms during outbreaks have not be quantified and so cannot be modelled precisely, the method of using map-based contiguity in this thesis should in some way capture them since proximity of premises makes it more likely that any such animals may pass between them.

### 1.1.3 Biosecurity

Biosecurity practises are also likely to play a role in determining which premises become infected. Such practices may include those related to livestock purchasing, livestock movement, wildlife control and staff and visitor management. During an FMD outbreak where movement bans are already in place however, biosecurity practices relevant to FMD are largely comprised of those that help to reduce transmission by contaminated fomites. Indeed, Ellis-Iversen et al. (2011) found that a composite biosecurity risk score, composed of 12 biosecurity practices relating to fomite transmission routes (e.g. use of a boot dip at the farm entrance), was significantly associated with a premises' probability of becoming a secondary FMD case during the 2007 outbreak in Surrey. Additionally, during an FMD outbreak in Japan, Muroga et al. (2013) found case farms to have a significantly greater odds of sharing farm equipment than did control farms, and that having physical barriers on livestock barns was protective. The level of biosecurity maintained on a farm premises outside of an outbreak situation will also have an effect on the potential for FMD spread during its silent phase, prior to the disease having been detected. Consequently, the 'peace-time' level of biosecurity maintained on farm premises may affect the probability of an outbreak taking off in the event of an incursion.

In a study looking at contact between a mixture of dairy and beef herds in north-west England, over half of adjacent herds were found to have direct nose-to-nose contact possible (Brennan et al., 2008). Furthermore, contiguous premises (CPs) had statistically significantly more connections via sharing of equipment and socialising than non-CPs (Brennan et al., 2008). It is therefore unsurprising that CPs played a considerable role in FMD transmission in 2001, probably via such direct and indirect contacts as highlighted by Brennan et al. (2008). Correct identification of such CPs should therefore be a priority. Given that the cost to each individual farmer is potentially very high in the event of an outbreak, what it means to be contiguous is a central issue. The effects of physical landscape features in preventing or enhancing transmission events between premises also need to be better understood to ensure control measures are properly targeted and proportionate to the risk of transmission.

### 1.1.4 Mathematical models

The accuracy of predictive mathematical models that are used to inform national livestock disease control policies is a crucial factor in ensuring the most efficient use of economic resources, and effective outbreak control. In 2001, mathematical models were rapidly developed (Ferguson et al., 2001a,b; Keeling et al., 2001), and used to help make recommendations for control. The Ferguson et al. (2001b) and Keeling et al. (2001) models described spatial transmission by incorporation of a transmission kernel, which can be seen in Figures 1.1 and 1.2. These described the decreasing risk of FMD transmission from an IP to surrounding premises, with increasing distance; the distance being based on Euclidean (straight-line) distance between farm premises' point locations.

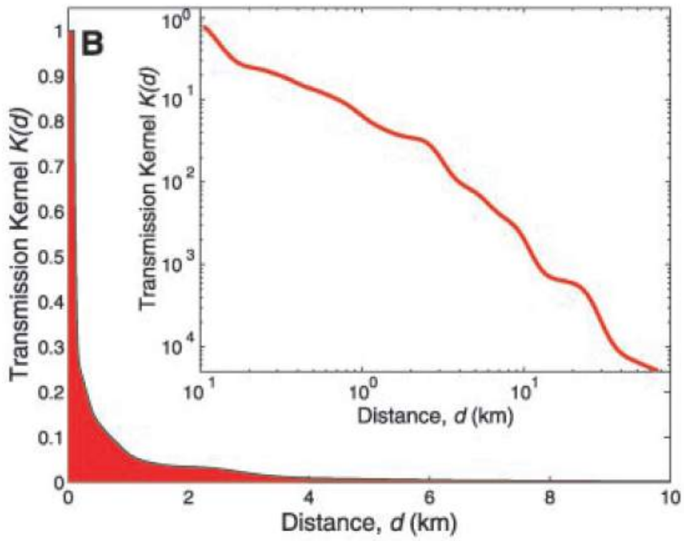



Figure 1.1: Transmission kernel from Keeling et al. (2001), describing the rate of transmission from an infected premises to surrounding premises at a distance (in km) away from it. These distances are the distances between point locations of premises.

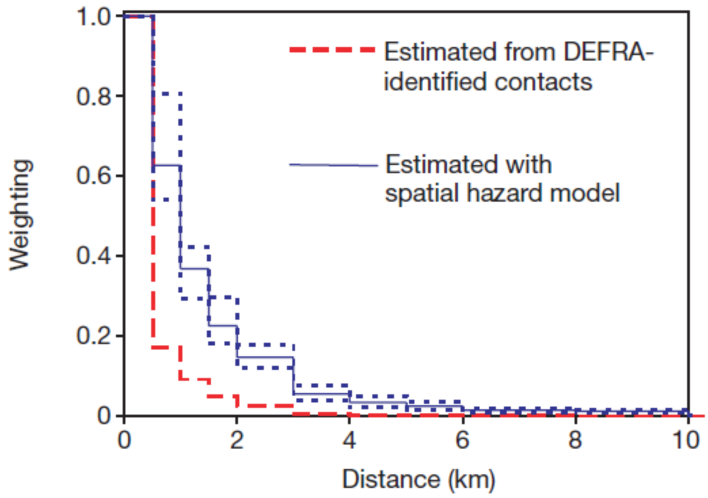



Figure 1.2: Transmission kernel from Ferguson et al. (2001b), describing the rate of transmission from an infected premises to surrounding premises at a distance (in km) away from it. These distances are the distances between point locations of premises.

This thesis will focus on the Keeling et al. (2001) model, which is described in detail in Appendix 1. This is because of the expertise in the research group for this model. Briefly, a premises' probability of infection is comprised of its susceptibility (based on the number of sheep and cattle present on the premises), together with any surrounding IPs' transmissibility (based on the number of sheep and cattle kept, and its proximity to the susceptible premises). While this model captured the overall pattern of spread, it was found that it only identified individual IPs over the course of the 2001 outbreak with an accuracy of around 12% (Tildesley et al., 2008). Although this is likely to be partially due to the model's stochastic nature meaning that there is a probability attached to parameters that results in some inevitable randomness in predictability, its over-simplification of the landscape may also play a role.

The transmission kernel effectively views the landscape as homogeneous, and the risk of disease transmission as isotropic (i.e. equal in every direction). Therefore, the assumption is that all farm premises within a certain Euclidean distance of an IP have the same risk-distance relationship to the IP, regardless of any geographical features that may separate them and act to aid or hinder transmission. Not only this, but since the distance upon which the transmission risk is based is measured from one point location to another, this does not take into account the reality of farms as areas, which vary in their shapes, size and degree of fragmentation. Furthermore, point locations do not necessarily relate to where the livestock are - while they can represent the main farm buildings, they may also represent the position of the postcode or parish centroid, or the home address of the farmer (which may be away from the farm premises).

Contiguity of premises (as discussed above) has been proxied by various methods based on point locations within mathematical modelling and statistical analyses of various diseases' spread, including FMD. These approximations will, to some degree, capture the essence of spatial proximity and its relationship with transmission, but are yet to be assessed for their truthfulness in describing landscape connections that could enable effective contacts. Such approximations are described below, following an introduction to landscape epidemiology.

## 1.2 Landscape epidemiology and disease ecology

***Landscape*** - the geography and topography of the land across space.

The increase in computation capabilities and available technologies (including Geographic Information Systems (GIS)) over the past twenty years has enabled a growing body of research into how the landscape and environment affect disease transmission. The idea behind such spatial, or landscape, epidemiology is to ascertain what aspects of the landscape and processes of space influence where disease is likely to spread to (Clements and Pfeiffer, 2009; Ostfeld et al., 2005). This can be analysed using metapopulation models, whereby a population of susceptible hosts is divided into subpopulations with within sub-population infection dynamics and interaction between sub-populations (Hess et al., 2002). It has also been examined extensively by using GIS and spatially explicit methods to map and analyse the risk of infection, vector distribution, or reservoir host distribution (Batchelor et al., 2009; Baylis et al., 2001; Bessell et al., 2013; Brooker et al., 2001; Clements et al., 2006; Glass et al., 2002; Lindsay et al., 1998; Ostfeld et al., 2005; Wardrop et al., 2010; Yiannakoulias et al., 2006).

In ecology, landscape plays an important role in the population dynamics of species (Fitzpatrick et al., 2012; Nelson and Robertson, 2012; Pickett and Cadenasso, 1995; Zhou et al., 2011). There is also a growing body of literature on disease ecology, investigating the relationship between landscape structure and fragmentation (defined in Section 1.2.2, page 18) and disease dynamics: for hantavirus in deer mice (Langlois et al., 2001), (human) risk of Lyme disease (Allan et al., 2003; Brownstein et al., 2005; Jackson et al., 2006), louping-ill virus in red-grouse (Jones et al., 2010); emergence of infectious diseases (Despommier et al., 2006), and disease spread in plants (Parnell et al., 2010; Plantegenest et al., 2007). Additionally, the identification of 'corridors' between habitat patches can enable control interventions of disease to be targeted at these zones to prevent transmission between sub-populations (Haydon et al., 2006). Such corridors act to connect otherwise separated habitat patches, resulting in greater spatial continuity of habitats across the landscape. Similarly, Highfield et al. (2008) found greater spatial continuity of deer population distributions increased the likelihood of simulated FMD outbreaks taking off, compared to lower spatial continuity of population distributions.

In relation to livestock diseases, fragmentation can be thought of in terms of (i) the spatial configuration of each farm premises' fields and the number of contiguous premises that arise as a result of this, or (ii) the number of contiguous connections between livestock farms. In this more broad way, fragmentation of the farming landscape was found to affect infection dynamics of the 2001 FMD epidemic in the UK by Kao (2003). A more fragmented landscape in Devon was predicted to eventually halt transmission of its own accord, while lower fragmentation in Cumbria led to the conclusion that pre-emptive culling measures were necessary to halt transmission (Kao, 2003).

Landscape features also play a role in preventing or enhancing disease transmission through space. Research has found rivers to reduce transmission of rabies in racoons by a factor of seven, since the racoons cannot easily cross rivers (Smith et al., 2002), and a similar relationship was found for a strain of rabies among striped-skunk (Barton et al., 2010). Similarly, there is some genetic evidence for badger dispersal being reduced by a wide river or motorway (Frantz et al., 2010), which may effect bovine tuberculosis (bTB) transmission. Fence permeability around Kruger National Park in South Africa is thought to increase cattle and buffalo contacts, which may result in an increased FMD transmission risk (Dion et al., 2011; Jori et al., 2009).

In relation to the 2001 FMD epidemic in the UK, at a coarse scale estuaries were found to prevent transmission between premises on either side of the Solway Firth and around the River Severn estuary, such that a kernel based on shortest road, rather than Euclidean, distance fitted the data better for these areas (Savill et al., 2006). Despite road-related transmissions (via personnel, milk tankers, shared machinery etc.) (Gibbens et al., 2001) Euclidean distance was found to be sufficient for explaining the kernel in regions without major estuaries by Savill et al. (2006). It was suggested however, that finer scale data on access tracks not shown at the scale of their map could have affected results (Savill et al., 2006). At a finer scale (of up to 3km), presence of geographical features between IPs and Euclidean distance-matched cases and controls was analysed, with rivers and railways being found to act as semi-permeable barriers to transmission (Bessell et al., 2008).

Among livestock populations then, the effects of landscape on the spread of disease can be thought of in the following terms. The connectivity of susceptible livestock hosts is shaped by farm premises location and more precisely by environmental factors that make particular fields suitable for livestock. This connectivity is in turn affected by the presence or absence of landscape features such as rivers, roads, tracks, railways, trees, and even, perhaps, ditches. Roads and tracks may act as corridors between potential host populations, where livestock are moved by these means (on the ground) between fields or to and from milking premises, since infected fomites may be dropped at close proximity to another herd. The probability of a disease reaching a certain premises is not only likely to be affected by the number of CPs it has, but also by the number of connections these CPs have to further premises. Thus there are many ways in which the landscape is likely to play a role in the dynamics of disease spread, although the exact relationships will be specific to each disease and depend upon the relative contribution of different modes of transmission. The following sections provide an overview of different representations of the local landscape and concepts of 'neighbourhood' commonly used in epidemiological studies to date, and an overview of the ways in which fragmentation may be considered to effect disease epidemiology.

### 1.2.1 Characterising neighbourhoods: distance and adjacency

Infectious disease dissemination is dependent on contact patterns. Among livestock populations direct nose-to-nose contact, proximity of suitable habitats for wildlife reservoirs or for vectors, or local contact between farmers (Brennan et al., 2008) may go a long way to explaining local disease transmission. Thus the closer in space that infected hosts and susceptible hosts are, the more likely transmission is to occur. When looking to describe spatial relationships, one can think in terms of (i) distance to an infected premises (IP) (e.g. the transmission kernel), (ii) adjacency to an IP, or (iii) a neighbourhood based on distance, where the number of IPs within a set distance from the susceptible premises are of interest. Once the neighbourhood has been defined, it enables investigation into the effect of having infected neighbouring or proximal premises on the likelihood of disease presence. There is a lack of consistency in defining neighbourhoods, and approximations are frequently used.

Mathematical models of infectious diseases among livestock and plants often incorporate space by using a transmission kernel term, describing the probability of transmission as a function of Euclidean distance from the point location of an infected source (Boender et al., 2007; Ferguson et al., 2001a,b; Firestone et al., 2012; Kao, 2003; Keeling et al., 2001; Parnell et al., 2010; Plantegenest et al., 2007; Savill et al., 2007; Ster and Ferguson, 2007; Szmaragd et al., 2009; Tildesley and Keeling, 2009; Tildesley et al., 2006, 2009, 2010). In this way, the effect of surrounding premises on a premises under consideration is weighted depending on their distance from it: the closer to an IP a premises is, the higher its risk. The two main problems with the transmission kernel are (i) that it is measured in Euclidean distance between point locations, and (ii) that it is isotropic. Anisotropic (different depending on direction) kernels have however been developed for the dispersal of fungal spores based on wind speed and direction (Savage et al., 2011). Thus, it is possible that a kernel could be parameterised to capture the wind effects of viral plumes thought to play a role in the UK's 1967-8 FMD outbreak (Sanson et al., 2011) (should they play an important role in transmission in future outbreaks), and for vector borne diseases where vectors are dispersed by wind - for example, bluetongue (Gloster et al., 2008) and Schmallenberg virus (Bessell et al., 2013; DEFRA, 2012). It is also possible to use distances based on other measures, such as shortest road distance, which may explain observed data better than Euclidean distance under some circumstances (Savill et al., 2006). The method by which the kernel is parameterised may affect the distance-risk relationship observed (Ferguson et al., 2001b).

The relative contribution of direct (e.g. nose to nose contact across shared field boundaries) and indirect (e.g. via contaminated fomites carried by vehicles) contact to transmission when looking at distance-weighting methods can be difficult to untangle. Consequently, definitions of neighbourhoods based on adjacency have been used in statistical analysis of livestock diseases to investigate the role of CPs in transmission (Ersboll et al., 2010; Johnston et al., 2011; Kao, 2003; Munroe et al., 1999). Adjacency still does not guarantee actual contiguity of farm boundaries however, or contiguity of herds of livestock. Kao (2003) used a regular hexagonal lattice (as illustrated in Figure 1.3) to investigate fragmentation; in this process neighbours were defined as livestock premises sharing a hexagon edge, resulting in a maximum of 6 neighbours per premise. This illustrates the frequency dependent nature of some methods of spatial CP classification - each farm makes contact with a set number of premises, which is determined by the regular polygon shape used to tessellate across the landscape. CPs may also be approximated by Voronoi polygons created around point locations whereby the perpendicular bisector of a line drawn between two points forms a polygon edge (as described in Figure 1.4). From this, points that share a polygon edge or vertex

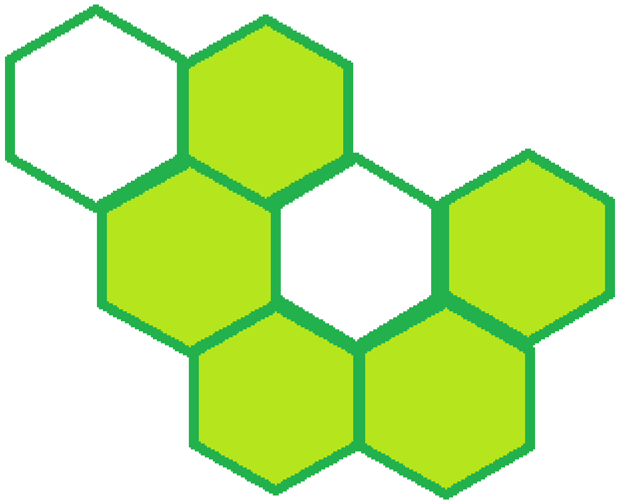


Figure 1.3: Illustration of a hexagonal lattice which can be used to investigate disease transmission between farms, where hexagons represent either a farm premises (filled hexagons), or land with no livestock (white hexagons). Sharing a hexagonal edge means that premises are neighbouring.

are considered to be adjacent (Figures 1.4 and 1.5). A maximum distance is often set beyond which the connections are not made; this prevents unrealistic connections over long distances. In this way, Ersboll et al. (2010) used this method limited by 5km to define neighbours when looking at local spread of bovine viral diarrhoea (BVDV). Voronoi polygons can also be weighted by known areas of premises (i.e. area weighted tessellation) to improve the approximations. Investigation of CP culling strategies for FMD outbreaks has been performed using the latter method (Keeling et al., 2001; Tildesley et al., 2006, 2008).

Farmer-defined direct and indirect contiguity has recently been used in place of adjacency-based approximations to investigate local spread of bTB (Johnston et al., 2011), with analyses indicating that case herds have 2.24 (95% CI 1.24-4.05) times the odds of having direct contact with cattle from contiguous herds compared to control herds. Another bTB study investigated the association of breakdown with reason for testing, finding that herds tested because they had

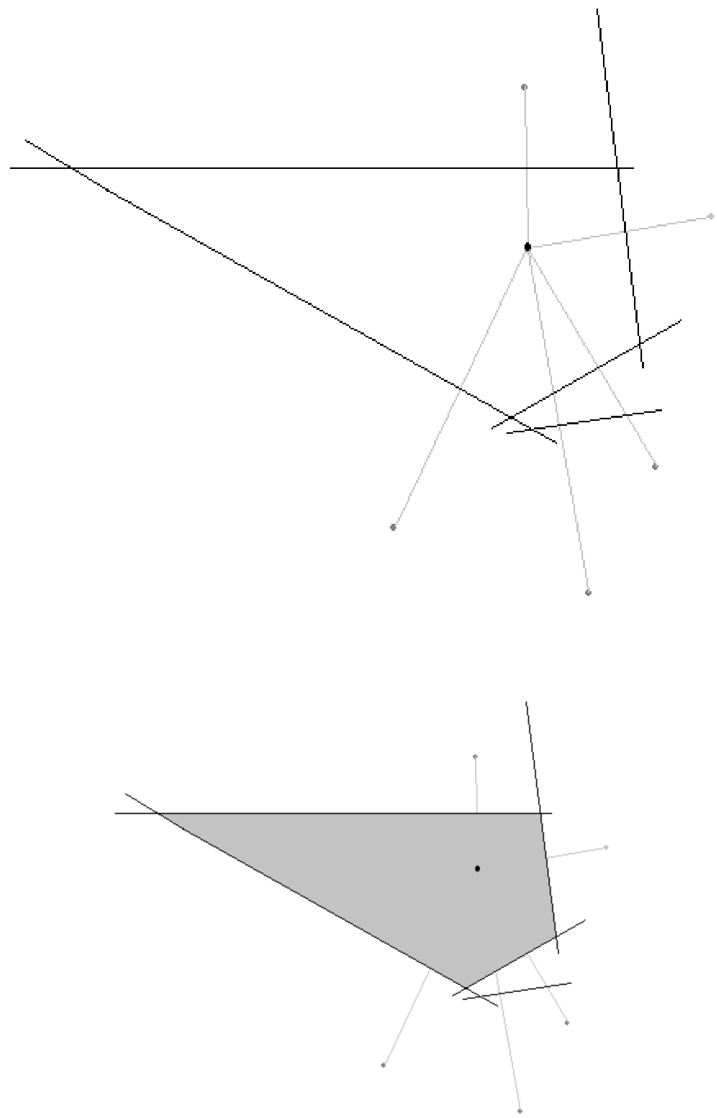


Figure 1.4: Illustration of method for creating Voronoi polygons for defining neighbours for farm premises. The black dot indicates the point location of the premises we want to find the Voronoi polygon neighbours for. The grey dots indicate the surrounding premises. Grey lines are drawn between the premises of interest's point location to each of the surrounding premises' point locations. The perpendicular bisectors of each of these lines (the black lines) are then drawn until each of these overlaps to form a Voronoi polygon (bottom, solid grey polygon) around the premises' point of interest. This illustration shows that all but the lowest (bottom-right) premises would be considered to be neighbouring the premises of interest, since the perpendicular bisector for this premises falls outside of those of others.

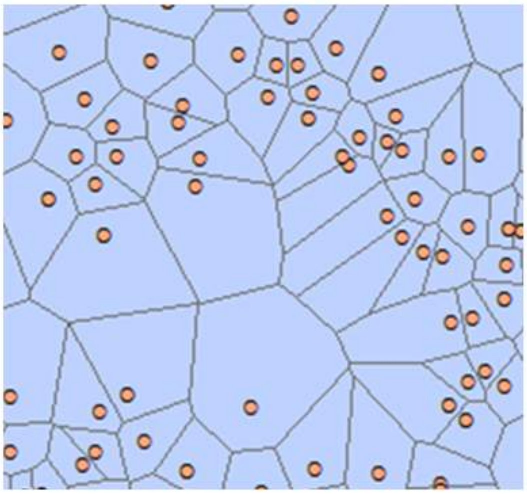


Figure 1.5: Illustration of many Voronoi polygons following the process described in Figure 1.4.

direct contact by shared pasture or fence-line contact with a bTB breakdown herd had 29.6 (95% CI 5.5-159.1) the odds of breakdown, compared to herds tested because they were within a certain radius of, but with no direct contact with, a breakdown herd (Munroe et al., 1999). While these measures of adjacency are clearly more accurate than the approximations above, there may still be some inaccuracies from farmer-reporting: Brennan et al. (2008) found only 66% of fences reported by farmers to allow fence-line contact truly enabled direct nose-to-nose contact.

Neighbourhoods have also been defined as the set of premises falling within a distance of a premise. This is usually implemented by creating a circular buffer around a point location of each premise (as shown in Figure 1.6), such as in mathematical modelling simulations of ring vaccination for FMD (Porphyre et al., 2013; Tildesley et al., 2006). Similarly, ring culling strategies for FMD epidemics take the form of a circular buffer, acting to deplete the susceptible population surrounding an IP (Ferguson et al., 2001a,b; Keeling et al., 2001; Tildesley et al., 2009, 2010). Analysis of transmission of a Classical Swine Fever outbreak in the Netherlands used radius distances of $<$500m and 500-1000m to define neigh-

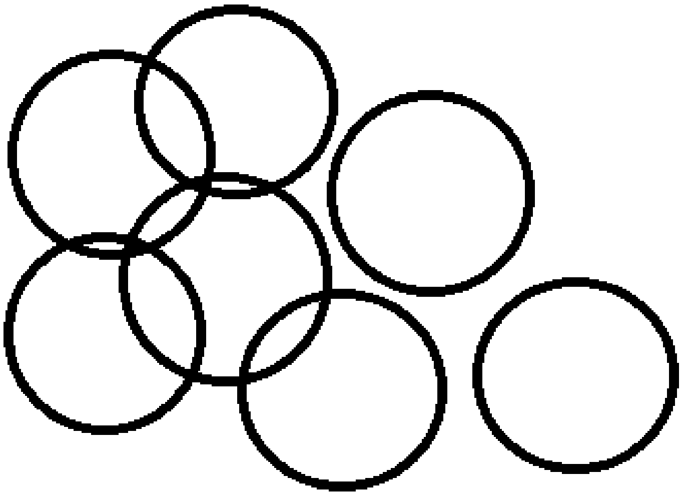


Figure 1.6: Illustration of the circular buffer method for defining neighbourhoods around e.g. farm premises. Circular buffers of standardised size are drawn around the point location of the premises. Any premises' whose buffers overlap with one another are considered to be neighbouring.

bourhoods around infected herds (Stegeman et al., 2002). The centroid distance method also uses a circular buffer drawn around each home-range/premises centroid point location where the radius size is based on known area (as shown in Figure 1.7). If the centroids' of other groups' home-ranges fall within this then they are considered to be neighbouring. Laffan et al. (2011) found that, compared to the degree of buffer overlap (as described in Figure 1.7) between cattle and swine premises in the USA, the centroid distance method resulted in a larger simulated FMD epidemic size, illustrating the impact of different neighbour definitions on predictions.

Recently, distance-based neighbourhoods have been made more realistic by looking at the distance between nearest field edges of premises rather than point locations. Studying bTB in Ireland, White et al. (2013) looked at the influence of premises within 25m, between 26-150m, and between 151-1000m field-edge distance of herds tested for bTB in 2006. They found that breakdown herds in 2006 were associated with increased animal incidence in all three neighbourhood zones

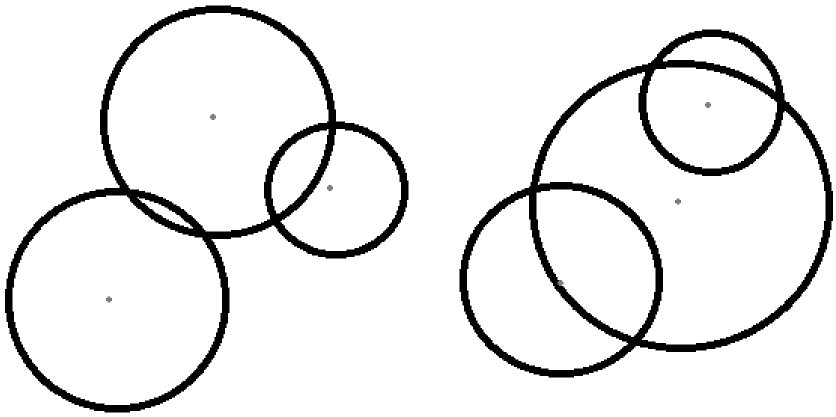


Figure 1.7: Illustration of the centroid distance method used to define neighbourhoods around e.g. farm premises. Grey dots indicate the premises' centroids, while the circular buffer size is based on the premises' known land area. If one premises' centroid falls within another's buffer then premises are neighbouring. Here, none of the left three premises would be considered to be neighbouring each other, but the two smaller premises on the right would each be considered to be neighbouring the larger premises. Degree of buffer overlap can also be calculated from this method, such that transmission is based on the degree of buffer overlap.

in 2005, and in the 'directly-contiguous' zone (within 25m field-edge distance) in 2004, thus suggesting that both transmission via fence-line contact and via a shared wildlife source (badger reservoir) likely contributed to infection persistence in an area (White et al., 2013).

### 1.2.2 Fragmentation

***Fragmentation**: 1) in ecology; used to describe the degree of separation between habitat patches within the landscape, 2) in this thesis, in terms of farm premises; where farm premises have fields separated ≥15 metres such that the fields are separated across the landscape 3) in this thesis, in terms of farming landscape; where premises are separated ≥15 metres such that they are not contiguous, resulting in premises being separated across the landscape.*
***Land parcel**: a premises' individual fields are considered to be a land parcel where they are separated by <15 metres.*

In the ecological literature, fragmentation has been described as the relative number of habitat patch types and pattern of adjacency between them (Jackson et al., 2006; Jones et al., 2010; Langlois et al., 2001; Li and Reynolds, 1993; Zhou et al., 2011), and the relative size of habitat patches (Allan et al., 2003; Brownstein et al., 2005). Fragmentation of livestock farm premises can be thought of as having two dimensions, at two spatial scales: fragmentation of individual premises and fragmentation of the livestock farming landscape as a whole. Fragmentation of individual premises, where premises have multiple, separated land parcels, may increase the number of CPs and consequently the risk of disease. This was found to be the case for FMD in 2001 using Voronoi polygons to estimate contiguity of disconnected land parcel centroids (Ferguson et al., 2001b). Conversely, the more fragmented the farming landscape as a whole, the less likely disease will be able to transmit between the livestock occupied fragments, since they will be separated by livestock-free fragments. This was also found to be the case for FMD in 2001 by modelling the landscape as a hexagonal lattice, and altering the probability of livestock occupation in neighbouring hexagons according to level of landscape fragmentation (Kao, 2003). This thesis will attempt to consider fragmentation at both of these spatial scales.

For both neighbour/contiguity classification and landscape-level fragmentation, the presence of geographical and topographical features such as rivers, roads and woodlands will likely be another important factor to take into consideration. Such features may affect transmission potential between two CPs. The role of such features will need to be considered in relation to disease transmission routes. Studies by Savill et al. (2006) and Bessell et al. (2008) on the 2001 FMD outbreak found that where premises were separated by estuaries and rivers/railways, respectively, transmission events were reduced. However, these two studies both considered premises as point locations, and in Bessell et al. (2008) rivers and railways were defined as separating premises when they intersected the straight line drawn between two premises' point locations. In this thesis I will consider premises as areas and examine where landscape features lie the full length of a shared boundary.

Where landscape features act to reduce transmission, selection of CPs should be confined to directions where the features are not present. This has been done by Nelson and Robertson (2012), who constrained distance-based neighbourhoods by watershed boundaries to examine different predictions of pine beetle dispersal. They found that there were generally more pine beetle hotspots when the neighbourhood was unconstrained, and the suitable landscape more continuous, which is a similar effect to what might be expected for FMD spread between livestock premises. In reality, given that some landscape features are likely to prevent transmission events (Bessell et al., 2008; Savill et al., 2006), it would be expected that models of FMD taking these effects into account would predict fewer transmission events than models assuming the landscape is homogeneous and transmission isotropic. Fragmentation of the farming landscape and the contribution of landscape features to fragmentation is another key consideration when examining spatial patterns of FMD spread among livestock. This thesis will consider contiguity of premises both as unconstrained and constrained by landscape features. When constrained, selection of CPs will be limited to where landscape features do not lie between a shared boundary. It is possible too that landscape features may act to enhance transmission - for example, roads can act to transmit FMD by contaminated vehicles driving between premises (Gibbens et al., 2001) - however this will not be studied within this thesis.

Fragmentation of the farming landscape corresponds to the measures of fragmentation and habitat adjacency used in ecology, while fragmentation of farm premises unique to the farm situation. Both will clearly contribute to the potential for FMD transmission through the Scottish farm landscape. By considering farm premises as areas, I will be able to consider the fragmentation of the farming landscape (and therefore the spatial continuity of FMD-susceptible livestock in the landscape) in terms of the bigger picture of how many CPs are connected to one another, and also to capture the fragmentation of individual premises, since CPs will be identified on the basis of all land parcels belonging to an individual premises.

## 1.3 Livestock farming in Scotland

The farming landscape varies through Scotland, with different livestock production types concentrated in different regions (Holland et al., 2011; NFUS, 2012). This reflects environmental and geographical differences in the landscape which makes certain areas suited to particular uses (NFUS, 2012), and which in turn is likely to affect the relative neighbourhood size and level of fragmentation. Livestock farming in Scotland is largely extensive and animals usually graze outside, coming in to give birth or during the worst weather conditions (NFUS, 2012).

Most dairy production takes place in the lowland areas in south-west Scotland (southern Strathclyde, Dumfries and Galloway), while beef production is largely concentrated in the western parts of the Grampian and Tayside regions with some also in Dumfries and Galloway (Holland et al., 2011). A large area in north-west Scotland (covering the western Highlands and northern Strathclyde) are used for hill sheep farming, with some production also in the western parts of Grampian and Tayside (Holland et al., 2011). In addition to animal husbandry practices, individual premises' fragmentation, number of CPs, presence of landscape features, and landscape-level fragmentation will vary according to premises production type and location.

Farm premises are allocated county-parish-holding (CPH) numbers according to their location (RPA, 2015). For sheep and goat farms, a CPH number will cover all the farm's land parcels so long as they fall within a five mile (8.05 km) radius of the main farm building location, or are adjacent to a land parcel which is (DEFRA, 2009). If the farm has further parcels of land that do not fall within this category, another CPH number will be allocated to it. For all other types of livestock farms, this distance is extended to a ten mile (16.1 km) radius (DEFRA, 2009). Farm businesses may have a Sole Occupancy Authority (SOA) which connects multiple CPHs at any distance from each other. These enable movement standstills on arrival of new animals to apply at the level of the SOA rather than the level of the CPHs within the SOA (i.e. animals may be freely moved between CPHs within the SOA during the standstill) (DEFRA, 2006). Cattle premises may also apply to be linked premises (have a Cattle Tracing System (CTS) Link) under one of two circumstances: a permanent shared facilities link, where there is shared ownership of premises <25 miles (40.2 km) apart and there are frequent movements to the shared facilities; or a short-term (renewed every 364 days) additional land link, where animals are moved to summer grazing/winter housing (Orton et al., 2012). Thus, ultimately, in an FMD outbreak, classification of CPs would likely need to take into account all SOAs and CTS Links, since animals may move freely between different premises within these.

## 1.4 Thesis structure

This thesis seeks to draw on landscape epidemiology and ecology to examine how the farming landscape, farm demography, and farm biosecurity are likely to affect local spread of FMD in the event of any future outbreak. How these factors may relate to the parameters within the current FMD models is considered, to examine if the models may be improved by changing the way in which FMD epidemiology is represented within them. The thesis is particularly concerned with how transmission probability is defined between farms within the landscape, and how fine-scale maps may provide an alternative, more realistic representation of this. The specific questions this thesis seeks to answer are:

- How accurate is the transmission kernel at capturing contiguity of premises?
- What happens to model predictions if transmission is based on contiguity? How do these predictions compare to that of the kernel-based model?
- How connected is the Scottish livestock farming landscape by contiguity of farm premises? Can it be fragmented to reduce the number of contiguous connections between farm premises, and consequently also predicted FMD spread?
- Is FMD-biosecurity risk spatially autocorrelated between contiguous farm premises, with neighbouring farmers undertaking similar levels of biosecurity? Might this account for some of the clustering of IPs observed during outbreaks?
- Is FMD-biosecurity risk related to the number of livestock a farm premises keeps, and consequently to susceptibility as defined in the mathematical models? If so, could biosecurity be being indirectly captured by the models?

The data used are described within each chapter, but are largely based on: Integrated Administration and Control System (IACS) data which show the position and area of farm premises' fields; premises' point location data from the Animal and Plant Health Agency (APHA); OS MasterMap and OS Meridian2 data which show the location of landscape features (e.g. rivers/railways); June Agricultural Census data which provides information on number of livestock on premises; and survey data on premises' FMD-biosecurity risk collected through field work. The analysis chapters contained within this thesis are described, in order, below:

1. **Creating a realistic landscape on which to study local FMD spread.** The transmission kernel, used in current FMD models, describes decreasing risk in transmission with increasing Euclidean distance from an infected farm premises' point location. Chapter 2 aims to assess the accuracy of Euclidean distance between farm premises' point locations for identifying whether two premises are contiguous according to several map-based definitions based on field locations and presence/absence of landscape features. The accuracy of premises' point locations in terms of the distance of the point from the nearest field belonging to the premises is also studied.
2. **Incorporating a realistic physical landscape into models of FMD spread in Scotland.**
   Chapter 3 compares outputs from simulations of two mathematical models that describe FMD transmission differently. One model bases transmission on the transmission kernel, the other on a combination of map-based contiguity (defined as premises having fields <15m apart) and a low level of background transmission. Simulations use the same 5 seed premises to ensure the comparability of the spread of disease through the landscape. The frequency with which individual premises become infected is compared for the two models, as well as the overall pattern of geographical spread.
3. **How connected is the farming landscape in Scotland? Implications for FMD.**
   Networks based on map-based contiguity of farm premises are created, and network analysis is used to examine the connectivity of farms in a large area of Scotland to examine the potential for FMD spread through the farming landscape. Network properties are then used to identify farm premises

that occupy key positions in the landscape - acting to connect otherwise disconnected sub-populations of contiguous farms. The contiguity-based model developed in Chapter 3 is used to run simulations and examine the effect of removing these key premises on FMD outbreak size and duration. The premises are also characterised in terms of their demography using statistical analysis.

4. **Investigating the social patterns in the farming landscape in relation to FMD-biosecurity risk.**
   After conducting biosecurity practice surveys with 200 farmers in Ayrshire and Aberdeenshire, the collected data are used to examine whether farmers on contiguous premises have similar biosecurity practices, to assess whether this could create clusters of lower/higher biosecurity and hence clusters of FMD cases during outbreaks. Network and spatial analytic methods are used to assess this, with the outcome based on an FMD-biosecurity risk score developed by the APHA during the 2007 Surrey outbreak.
5. **Farm demography in relation to FMD-biosecurity risk.**
   Chapter 6 questions whether a premises' FMD-biosecurity risk is already indirectly taken into account by the mathematical model's susceptibility term. The susceptibility term is a decreasing power law function of the number of cattle and sheep present on the premises. Statistical analyses are performed to study the relationship between premises' production type, holding size (in terms of number of cattle/sheep) and susceptibility and two outcomes: the FMD-biosecurity risk score (used in Chapter 5), and whether or not premises make 'risky movements' of livestock.

This body of work builds on previous knowledge of FMD transmission, and increases our understanding of FMD spread in relation to the farming landscape - both physical and social - and in relation to the demography of farm premises. On the basis of these findings, new recommendations for control measures in the event of another incursion of FMD to the UK in future can be made. While these findings suggest exciting developments in the potential effective control of FMD outbreaks, they do however require validation against real-time outbreak data, since only simulated FMD data are used within this thesis.

# 2 Creating a realistic landscape on which to study local FMD spread

Much of this chapter's content has been published in Flood et al. (2013), which can be found at the back of the thesis. The chapter goes into more detail than the paper regarding the proximity of premises' point locations to field locations, found in section 2.3.1.

***Contiguous (contiguous premises, CPs), contiguity:*** *where farm premises are neighbouring in such a way that may enable disease transmission via local routes. Various definitions of the sorts of neighbours that are classified as contiguous can be found in Table 2.1.*
***Fragmentation****: 1) in ecology; used to describe the degree of separation between habitat patches within the landscape, 2) in this thesis, in terms of farm premises; where farm premises have fields separated ≥15 metres such that the fields are separated across the landscape 3) in this thesis, in terms of farming landscape; where premises are separated ≥15 metres such that they are not contiguous, resulting in premises being separated across the landscape.*
***Land parcel****: a premises' individual fields are considered to be a land parcel where they are separated by <15 metres.*

## 2.1 Introduction

A spatial transmission kernel, described in the General Introduction, was incorporated into the mathematical models (Ferguson et al., 2001a; Keeling et al., 2001) used to aid policy-making during the UK's 2001 FMD outbreak. This kernel described the decay in rate of transmission to susceptible livestock premises with increasing Euclidean distance from an infected premises (IP) source (calculated between farm premises point locations), when there was no transmission by movements of infected animals (since the National Movement Ban (NMB) was in place). The Keeling et al. (2001) model, while capturing the regional pattern of spread well, had a low level of accuracy for identifying individual IPs, with about 12% of reported case premises over the duration of the epidemic being captured by simulations (Tildesley et al., 2008). Although this low accuracy is in part due to stochastic variation, assumed homogeneity of the landscape by the kernel is also likely to have contributed.

In addition to incorporating space by using the spatial transmission kernel, contiguous premises (CPs) (farm premises neighbouring infected premises which were at highly elevated risk of infection (Anderson, 2002)) were modelled by area-weighted tessellation in order to examine the likely effect of culling CPs (Ferguson et al., 2001b; Keeling et al., 2001). Area-weighted tessellation uses the known land areas and the known point locations of premises to construct weighted Voronoi polygons around the points. Voronoi polygons are constructed by connecting the perpendicular bisectors of lines between pairs of points, where only the closest bisectors are considered. This results in tessellated polygons, where any point within a polygon will be closer to the point around which the polygon was constructed than any other. Area-weighting this process means that the square-root of the known land area of each point pulls or pushes the perpendicular bisector towards or away from a point, depending on the comparative size of the square-root of the paired farm's area. Contiguity is then based on having a shared polygon edge. This technique was applied to Great Britain's farm premises, as recorded by the June 2000 agricultural census, to determine which farms were contiguous to other farms, and culling of CPs within model simulations were determined on this basis (Keeling et al., 2001).

The approximations of farm connectivity in relation to FMD transmission are yet to be assessed for their accuracy. While the transmission kernel indicated the importance of local spread - approximately 50% of transmissions occurred within 3 km of an IP after the implementation of the NMB (Savill et al., 2006) - there is a lack of understanding as to how this is related to true contiguity. A kernel based on Euclidean distance between point locations not only fails to recognise that farms in reality are areas, but also that the landscape is non-homogenous and that transmission potential is therefore not equal in all directions. Although area-weighted Voronoi polygons consider farms as areas, these are nonetheless derived from point locations and therefore may not reflect how farms share boundaries in reality. Furthermore, summarising premises as a single point location does not reflect the true nature of the farming landscape, where some premises have their land parcels fragmented across it. Additionally, geographical features such as rivers, ditches and railways may act as barriers to transmission, and therefore prevent contiguity in terms of disease transmission (Bessell et al., 2008). It is possible that greater predictive accuracy of mathematical models may be achieved by incorporating increased detail regarding the landscape. This is important given that the outputs of such models help to inform control policies implemented, such as the pre-emptive culling of livestock contiguous to infected premises during the 2001 outbreak (Ferguson et al., 2001b).

The level of risk a premises is perceived to be at, based on its point distance from an IP, may be altered by knowing actual premises contiguity. This is particularly the case for contact spread diseases such as FMD since the distance between two farm point locations may be considerable despite their fields actually being in contact. Thus, at the extreme end of the spectrum, the decay in risk with increasing distance may simply explain the distribution of point distances between actual CPs.

Different methods of incorporating the spatial arrangement of farm premises into mathematical models of infectious diseases among livestock may have considerable impact on predicted epidemic size, spatial distribution, and optimal control strategies. Therefore, this chapter aims to compare the properties of the contact networks that arise from the classification of farm premises as being in contact by point distance measures, by Voronoi and area-weighted Voronoi tessellation, and by maps showing the field boundaries of premises and geographical features that surround them. Additionally, how well approximation methods capture farm premises considered to be contiguous according to the distance between field edges and presence of geographical features will be assessed (this will be termed map-based contiguity). Another measure based solely on distance between the closest field edges of premises will also be added to the comparison as such measures have recently been used in statistical analysis of bovine tuberculosis persistence (White et al., 2012). Areas in Ayrshire and Aberdeenshire were chosen to evaluate these measures since they are both important livestock farming areas in Scotland, but with different farm types dominating: Ayrshire consisting mainly of dairy cattle farming, and Aberdeenshire consisting of a mixture of cattle (mainly beef), sheep, pig and crop production (Holland et al., 2011; Thomson, 2008).

## 2.2 Methods

### 2.2.1 Data

Spatial data were visualised and manipulated in ArcGIS version 9.3 (ESRI, Redlands, CA, USA). Farm premises point locations were obtained from the Animal Health and Veterinary Laboratories Agency (AHVLA). Fields of farm premises were obtained from the Integrated Administration and Control System (IACS) dataset from 2006. The June 2006 Agricultural Census data was matched to the point location data based on the county-parish-holding (CPH) number to select only premises with any cattle, sheep or pigs. A sample study area was then selected within each of Aberdeenshire and Ayrshire based on the point locations of premises being within an area of approximately 15x15km. The point locations of these premises were then matched up with the IACS field data based on the parish-holding (PH) component of the CPH number. The distance between PH-matched point and field locations were calculated using the ArcGIS 'Generate Near Table' tool.

Ordnance Survey (OS) MasterMap® Topography Layer data, at a varying scale of 1:1250 to 1:10000, was used to map geographical features. The OS MasterMap® data used for Ayrshire was provided direct from the OS (updated on 23/08/2012), whereas for Aberdeenshire the data was downloaded from EDINA Digimap (EDINA Digimap Ordnance Survey Service <http://edina.ac.uk/digimap>, downloaded March 2012, updated on 08/06/2011). For Ayrshire roads were indicated by topographic lines where DescGroup = 'Road Or Track', and tracks by topographic areas where Theme = 'Roads Tracks And Paths'; for Aberdeenshire roads and tracks were indicated by topographic lines where Theme = 'Land; Roads Tracks And Paths'. In both sample areas rivers $>$2m wide were indicated by sets of double topographic lines where DescGroup = 'Inland Water', and inland water courses $\leq$2 m wide (henceforth referred to as ditches) were indicated by single topographic lines where DescGroup = 'Inland Water'. Railways were indicated by topographic lines where Theme = 'Rail'. Where a landscape feature was included in a definition of map-based contiguity, they were treated equally in terms of their effect on classification of premises contiguity.

### 2.2.2 Defining Contiguous Premises (CPs)

For each of the Aberdeenshire and Ayrshire sample areas a dataset was then created whereby every premises was paired to every other premises within 7km of it, in terms of Euclidean distance between point locations. From this dataset each premises pair was then classified as being contiguous or not contiguous according to eight CP approximation definitions:

a) $<$1km distance between point locations of premises;
b) $<$3km distance between point locations of premises;
c) $<$5km distance between point locations of premises;
d) $<$26m distance between premises field edges at their closest point;
e) $<$151m distance between premises field edges at their closest point;
f) $<$1km distance between premises field edges at their closest point;
g) sharing a Voronoi polygon edge;
h) sharing an area-weighted Voronoi polygon edge.

The Voronoi polygons were generated from the point locations in ArcGIS. A wider sample of points was used to create the Voronoi polygons to act as a buffer so that within-sample the polygons were not influenced by edge effects. This dataset was checked for occurrences where point locations were shared by different premises. These could arise where two premises shared the same postcode, and where each premises' point location was derived from that postcode. Where this happened, the pairs were taken to be CPs with each other, and to have identical other CPs. The area-weighted Voronoi polygons were weighted by known premises area. This was scripted and run in MATLAB (The MathWorks, Inc., Nat- ick, MA, USA) (conducted by M.J. Tildesley). Distances between point locations, field boundaries, and shared Voronoi polygon edges were calculated using the ArcGIS 'Generate Near Table' tool.

Maps of IACS and OS MasterMap® data were checked visually to assess whether each premises pair actually shared a fence boundary, had fence boundaries separated by <15m, were separated by a road/track or railway, were divided by a river or by a small river/ditch. The distance of 15m was chosen as the maximum distance at which premises were considered to be contiguous based on an educated guess of the maximum distance between field edges should a small road lie between them. This is because a small road may not act as a barrier to local FMD transmission (Savill et al., 2006). The entire length of each premises boundary was considered. The relative length of each type of separation between premises was not considered such that if the premises shared a boundary at any point, they were classified as having a shared boundary, regardless of the boundary length. For classification in terms of separation by landscape features, the premises pairs would only be classified as such if the entire length of the shared boundary appeared to be separated by this feature. In cases where premises were separated along the entire boundary by more than one types of geographic feature, but where each feature type did not run the entire length of the boundary, the feature with the lowest perceived 'barrier effect' was taken to be the feature of separation (small river/ditch <road/track <river). Only one premises pair had a railway line running the entire length of their shared boundary in Ayrshire, and no premises were separated by railway in Aberdeenshire. Thus separation by railways was not included for the purposes of this analysis.

Based on visual map inspection of each farm premises in the sample, nine further definitions of being contiguous were then considered: i-xi in Table 2.1. Figure 2.1 illustrates the point distance and map-based methods used for defining contiguity. For an illustration of the Voronoi polygon method, see Figures 1.4 and 1.5.

| | Definition of contiguous premises | Reference name |
|---|---|---|
| i | Having any fields separated up to a maximum distance of 15m | All <15m |
| ii | Having any fields separated up to a maximum distance of 15m not including premises separated by a river | All <15m - river |
| iii | Having any fields separated up to a maximum distance of 15m not including premises separated by a road | All <15m - road |
| iv | Having any fields separated up to a maximum distance of 15m not including premises separated by a railway | All <15m - railway |
| v | Having any fields separated up to a maximum distance of 15m not including premises separated by a river or a road | All <15m – river/road |
| vi | Having any fields separated up to a maximum distance of 15m not including premises separated by a river or a railway | All <15m – river/railway |
| vii | Having any fields separated up to a maximum distance of 15m not including premises separated by a road or a railway | All <15m – road/railway |
| viii | Having fields with a shared boundary (i.e. 0m separation) | Shared boundary |
| ix | Having fields with a shared boundary not including premises separated by a river or a railway (no premises with a 'Shared boundary' were separated by a railway) | Shared boundary – river/railway |
| x | Having fields with a shared boundary not including premises separated by a road | Shared boundary – road |
| xi | Having fields with a shared boundary not including premises separated by a river or a road | Shared boundary – river/road |

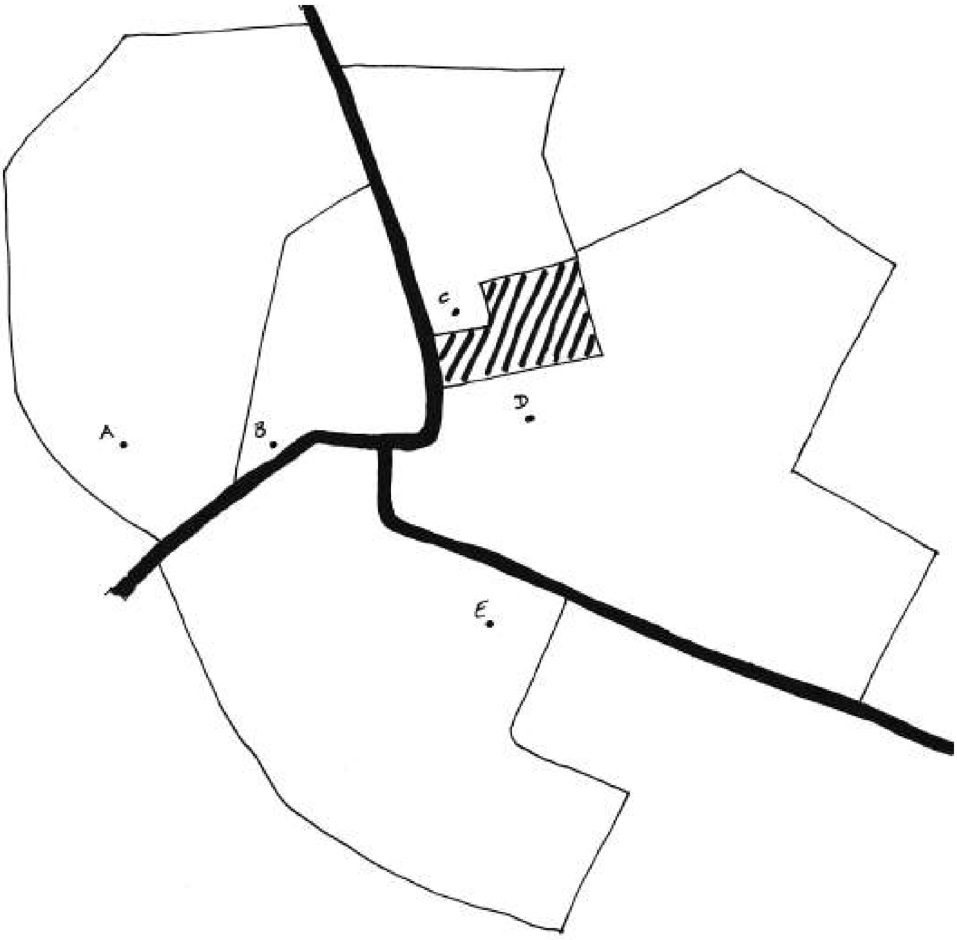
Table 2.1: Definitions of map-based contiguity and their reference names.

The distribution of distances between premises' point and field locations were inspected, by the information source of the point location. The distribution of premises pairs within 1km point distance bands where both premises had point locations <100m from their nearest field location was also studied - for premises considered to be contiguous and non-contiguous under the map-based CP definition 'All <15m'. The cumulative number of map-based CPs with 0.25km increases in point distance was calculated for the full CP-pair samples, as well as the cumulative proportion of map-based CPs where any premises pairings with a premises' point-to-nearest-field location distance ≥100m were excluded. The number and proportion of premises pairs considered to be contiguous under the map-based definition 'All <15m' within 0.25km distance bands was also examined, where the samples of premises pairs were also restricted.

### 2.2.3 Measuring agreement between the different CP definitions

Symmetric matrices of the sample premises were produced for each of the seventeen definitions of contiguity (approximation methods a-h, and map-based methods i-ix) using R (R Core Team, 2013). Each element took the value 0 or 1 depending on whether the premises pairs were non-contiguous or contiguous under the definition, respectively. Agreement between matrices of different CP definitions was estimated using four measures: concordance, sensitivity (Se), positive predictive value (PPV), and True Skill Statistic (TSS), where:

- Concordance = (TP + TN) / (TP + FP + FN + TN),
- Se= TP / (TP + FN),
- PPV = TP / (TP + FP),
- TSS = (sensitivity + specificity - 1); where Specificity = TN / (FP + TN), and where TP = true positive, FP = false positive, TN = true negative,




**Point distance**

| | A | B | C | D | E |
|---|---|---|---|---|---|
| **A** | - | 1.5 | 3.4 | 3.8 | 3.9 |
| **B** | | - | 2.1 | 2.5 | 2.7 |
| **C** | | | - | 1.3 | 3.0 |
| **D** | | | | - | 2.0 |
| **E** | | | | | - |

**All <15m**

| | A | B | C | D | E |
|---|---|---|---|---|---|
| **A** | - | Yes | *Yes* | No | *Yes* |
| **B** | | - | *Yes* | *Yes* | *Yes* |
| **C** | | | - | Yes | No |
| **D** | | | | - | *Yes* |
| **E** | | | | | - |

**Shared boundary**

| | A | B | C | D | E |
|---|---|---|---|---|---|
| **A** | - | Yes | No | No | No |
| **B** | | - | No | No | No |
| **C** | | | - | Yes | No |
| **D** | | | | - | No |
| **E** | | | | | - |

Figure 2.1: Illustration of point distance and map-based methods used for defining contiguity of farm premises. Farm premises point locations A-E shown by black circles, with their field areas around them. Solid filled lines show roads. Hatched area is non-farm land. Tables show point distance (i.e. the straight-line/Euclidean distance between points, in theoretical km) of premises from each other, and whether they are contiguous (yes/no) according to map-based definitions 'All <15m' and 'Shared boundary'. Italicised text within table for 'All <15m' indicates where premises would not be considered contiguous if roads were considered as boundaries (i.e. using definition 'All <15m - roads').

and FN = false negative.

Concordance, Se and PPV were multiplied by 100 to give a percentage.

Calculating Se of point distance, field edge distance, and tessellation measures against a 'gold standard' of map-based contiguity as defined by field edge separation and landscape features, enabled us to study how many farm premises were missed by the approximation methods that were contiguous under the map-based definitions (by identifying the proportion of map-based CPs that were correctly identified by each method). PPV enabled us to examine how many farm premises the approximation methods picked up that were not actually contiguous, by giving the proportion of approximation method CPs that were contiguous under the map-based definitions. TSS gave an overall assessment of how well the approximation methods discriminated between contiguous and non-contiguous premises pairs as defined by map-based methods.

TSS was used in preference to Kappa as it provides a similar measure of accuracy of the discrimination of two methods for a binary outcome, without being affected by prevalence (Allouche et al., 2006). This measure, also known as the Hanssen and Kuipers statistic and Youden's Index, has values ranging from -1 to +1 and has previously been used to assess the accuracy of weather prediction models (Accadia et al., 2005; Elmore et al., 2003; McBride and Ebert, 2000; Saseendran et al., 2002).

The methodology used means that there was some room for human error in the classification of contiguity based on presence of landscape features along or between farm premises boundaries. To minimise this, the boundaries of CP pairs were checked twice, and the symmetry of the resulting matrices was verified using the command 'isSymmetric' in R (R Core Team, 2013), with maps being rechecked in the event of apparent asymmetry.

### 2.2.4 Network properties of different CP definitions

**Network terminology**

***Node****: Individuals within the network. Within this chapter: premises.*

***Edge****: Connections between two nodes. In this chapter, two premises are said to share an edge where they are contiguous according to either approximation measures (point distance, field-edge distance, sharing a Voronoi/area-weighted Voronoi polygon edge), or to one of the map-based contiguity definitions described in Table 2.1.*

***Degree****: Network term for the number of edges each node has to other nodes. In the context of this work, is the number of map-based CPs a premises has.*

***Density****: Network term for the proportion of possible edges between all the nodes in the network that actually exist.*

Network density and mean degree were calculated for a subset of the contiguous definitions. Density was calculated using the 'igraph' package (Csardi and Nepusz, 2006) in R (R Core Team, 2013), and was calculated on the sample premises only. In order to correct for edge effects in the calculation of mean degree, new data sets were created to count all CPs associated with sample premises, rather than being limited to sample premises only. For map-based contiguity, all premises with fields listed in IACS with any cattle, sheep or pigs were included (this meant there were some premises within the sample area not previously included as they did not belong to a point location within the selected area). For point distance based contiguity, all premises with any cattle, sheep or pigs and point locations that matched up to IACS field data were included. Mean degree was calculated by species kept on premises for the categories that had $\geq 5$ premises in, for all map-based CP definitions and area-weighted tessellation.

## 2.3 Results

In the Aberdeenshire sample 113 premises points were first selected, but only 107 (94.7%) could be linked to fields within the IACS database. Of these point locations, 98 (91.6%) were sourced from an address match, 6 (5.6%) from a postcode match and 3 (2.8%) from the parish centroid. Four pairs of premises shared identical point locations; three of these were sourced from address matches, and one from a postcode match. For the Ayrshire sample 197 premises points were first selected, of which only 184 (93.4%) could be linked to fields within the IACS database. Of these point locations, 156 (84.8%) were sourced from an address match, 20 (10.9%) from a postcode match and 8 (4.3%) from the parish centroid. Seven pairs and one triplet of premises shared identical point locations. Five of the pairs with identical point locations were sourced from an address match, and one from a postcode match.

The majority of premises in the Ayrshire sample kept cattle only (70.1%), and no premises kept any pigs (Table 2.2). The median area of the farm premises was 73.5 hectares (IQR: 51.9-104.8), with a median of 16 fields (IQR: 11-22) (mean = 17.7). In the Aberdeenshire sample 47.7% of all premises kept cattle and sheep, while just over a third kept cattle only (34.6%), and only six premises kept pigs (Table 2.2). The median area of the farm premises was 76.4 hectares (IQR: 40.0-174.0), with a median of 19 fields (IQR: 11.0-32.0) (mean = 22.0).

Table 2.2: Distribution of types of livestock kept on premises in the two samples

| | Aberdeenshire | | Ayrshire | |
|---|---|---|---|---|
| Animals kept on premises | Number | % | Number | % |
| Cattle only | 37 | 34.6 | 129 | 70.1 |
| Sheep only | 13 | 12.1 | 16 | 8.7 |
| Pigs only | 1 | 0.9 | 0 | 0.0 |
| Cattle/sheep | 51 | 47.7 | 39 | 21.2 |
| Cattle/pigs | 1 | 0.9 | 0 | 0.0 |
| Sheep/pigs | 1 | 0.9 | 0 | 0.0 |
| Cattle/sheep/pigs | 3 | 2.8 | 0 | 0.0 |
| Total | 107 | 99.9 | 184 | 100 |

### 2.3.1 Proximity of point locations to field locations

Histograms showing the distribution of distances between premises point and field locations can be seen in Figure 2.2. In the Aberdeenshire sample, 89.7% (n = 96) of premises point locations were <100m from their CPH-matched nearest field; 1.9% (n = 2) were separated by 100-1000m, and the remaining 8.4% (n = 9) by ≥1000m. In the Ayrshire sample, 84.2% (n = 155) had point locations <100m from their parish-holding number (PH) matched nearest field, while 7.6% (n = 14) were separated by 100-1000m, and 8.2% (n = 15) by ≥1000m. The least accurate of the point location sources was the parish centroid, followed by the postcode. The distribution of the PH-matched point-field distances by the point location information source can be seen in Figure 2.3.

The majority of premises pairs that are not contiguous according to map-based definition ‘All <15m’ and with point locations <1km apart, have inaccurate point locations (≥100m between point and field location) for one or both of the premises (58.3% in Aberdeenshire; 78.2% in Ayrshire) (Tables 2.3 and 2.4). The proportion with inaccurate point locations are considerably lower in all other point distance categories. Conversely, an extremely high proportion of premises contiguous under definition ‘All <15m’ and with point locations <1km apart, both had accurate point locations (97.8% in Aberdeenshire; 93.0% in Ayrshire) (Tables 2.3 and 2.4). Inaccuracies in the point locations relative to the location of premises’ fields are likely to contribute to the inaccuracy of the spatial pattern of spread predicted by models that use these point locations to describe transmission between premises.

Looking up to a distance of 7km between premises point locations captured 98.1% (153/156) and 97.8% (348/356) of premises pairs contiguous according to map-based definition ‘All <15m’ in Aberdeenshire and Ayrshire, respectively. The pattern of map-based CP identification over increasing distance between the premises point locations differed slightly between Aberdeenshire and Ayrshire (Figure 2.4). In Aberdeenshire, the number of map-based CPs identified began to plateau at 2.5km point distance, such that 88.9% ($n = 136$) of premises contiguous under map-based definition ‘All <15m’ were captured within 2.5km. In Ayrshire however, the plateau was less distinct, and began at around 3.25km; 88.8% ($n = 309$) of premises contiguous under map-based definition ‘All <15m’ were captured by this distance. Kolmogorov-Smirnov (K-S) tests indicated there were no significant differences between the distributions of the cumulative proportions of premises classified as being map-based CPs in the two sample areas, where the datasets excluded premises pairs where one or both premises’ point-to-nearest-field locations were ≥100m (Figure 2.5, Table 2.5). Additionally, the proportion of premises contiguous under map-based definition ‘All <15m’ grouped within point distance bands followed similar patterns between the two areas (Figure 2.6; K-S $D$=0.29, p-value=0.203).

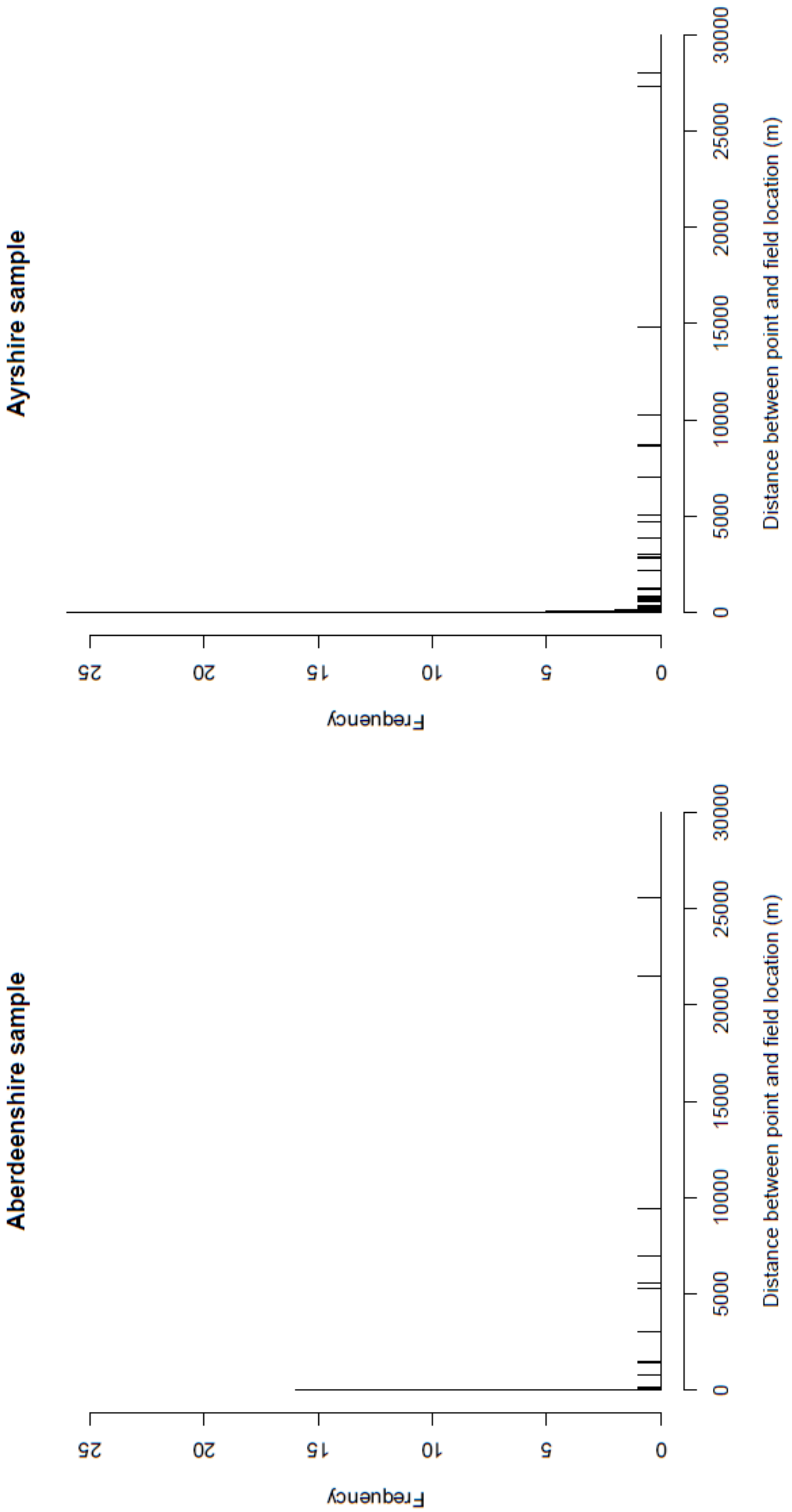



Figure 2.2: Histogram showing distances between premises' point and field locations.

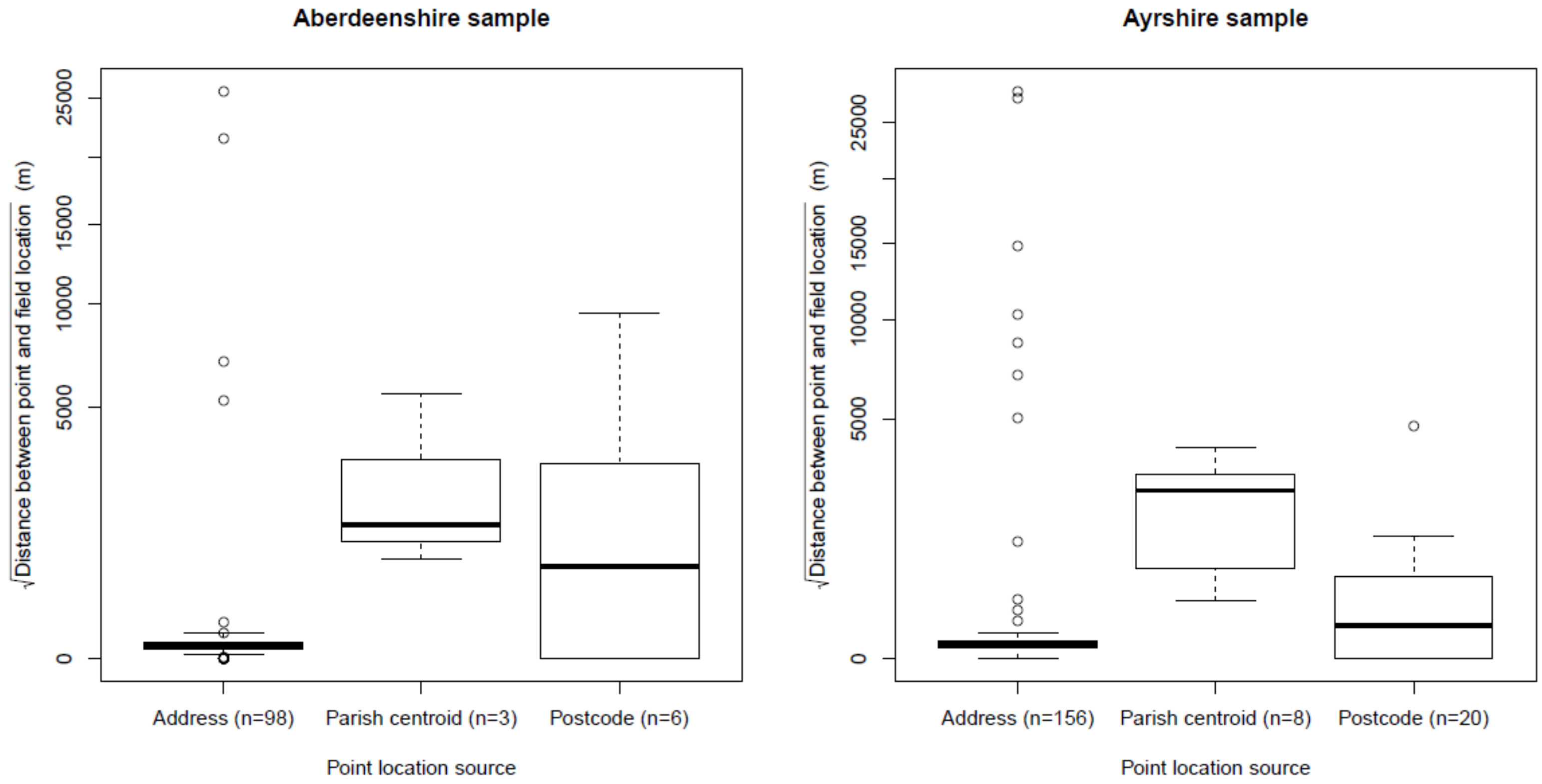



Figure 2.3: Box and whisker plots showing distribution of distances between point location and nearest field location by point location source. Boxes represent the lower (Q1) to upper (Q3) quartiles, and the heavy lines across them indicate the medians. The whiskers extend to Q1-1.5*IQR (the Interquartile Range), and Q3+1.5*IQR. Dots beyond these limits indicate data points lying outside of these ranges.

| Point distance | Field edges ≥15m apart | | | | | Field edges <15m apart | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Distance between premise point location and field location | | | | Total (%) | Distance between premise point location and field location | | | | Total (%) |
| | Both of pair <100m | | One or both of pair ≥100m | | | Both of pair <100m | | One or both of pair ≥100m | | |
| | Number | % | Number | % | | Number | % | Number | % | |
| **<1km** | 10 | 41.7 | 14 | 58.3 | 24 (100) | 44 | 97.8 | 1 | 2.2 | 45 (100) |
| **1-2km** | 128 | 79.0 | 34 | 21.0 | 162 (100) | 66 | 86.8 | 10 | 13.2 | 76 (100) |
| **2-3km** | 232 | 80.6 | 56 | 19.4 | 288 (100) | 13 | 72.2 | 5 | 27.8 | 18 (100) |
| **3-4km** | 286 | 80.6 | 69 | 19.4 | 355 (100) | 4 | 100.0 | 0 | 0.0 | 4 (100) |
| **4-5km** | 341 | 82.4 | 73 | 17.6 | 414 (100) | 2 | 100.0 | 0 | 0.0 | 2 (100) |
| **5-6km** | 402 | 83.9 | 77 | 16.1 | 479 (100) | 2 | 50.0 | 2 | 50.0 | 4 (100) |
| **6-7km** | 407 | 79.6 | 104 | 20.4 | 511 (100) | 0 | 0.0 | 4 | 100.0 | 4 (100) |
| **Total** | 1806 | 80.9 | 427 | 19.1 | 2233 (100) | 131 | 85.6 | 22 | 14.4 | 153 (100) |

Table 2.3: Number and proportion of premises pairs within given point distances of each other, that both have accurate point locations (distance between their point and field location <100m), for map-based contiguous and non-contiguous pairs (according to definition 'All <15m'), Aberdeenshire.

| Point distance | Field edges ≥15m apart | | | | | Field edges <15m apart | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Distance between premise point location and field location | | | | Total (%) | Distance between premise point location and field location | | | | Total (%) |
| | Both of pair <100m | | One or both of pair ≥100m | | | Both of pair <100m | | One or both of pair ≥100m | | |
| | Number | % | Number | % | | Number | % | Number | % | |
| **<1km** | 19 | 21.8 | 68 | 78.2 | 87 (100) | 106 | 93.0 | 8 | 7.0 | 114 (100) |
| **1-2km** | 314 | 67.1 | 154 | 32.9 | 468 (100) | 131 | 86.8 | 20 | 13.2 | 151 (100) |
| **2-3km** | 643 | 70.9 | 264 | 29.1 | 907 (100) | 24 | 63.2 | 14 | 36.8 | 38 (100) |
| **3-4km** | 876 | 71.1 | 356 | 28.9 | 1232 (100) | 13 | 56.5 | 10 | 43.5 | 23 (100) |
| **4-5km** | 1052 | 70.3 | 445 | 29.7 | 1497 (100) | 6 | 85.7 | 1 | 14.3 | 7 (100) |
| **5-6km** | 1093 | 73.6 | 392 | 26.4 | 1485 (100) | 7 | 87.5 | 1 | 12.5 | 8 (100) |
| **6-7km** | 1204 | 72.1 | 466 | 27.9 | 1670 (100) | 5 | 71.4 | 2 | 28.6 | 7 (100) |
| **Total** | 5201 | 70.8 | 2145 | 29.2 | 7346 (100) | 292 | 83.9 | 56 | 16.1 | 348 (100) |

Table 2.4: Number and proportion of premises pairs within given point distances of each other, that both have accurate point locations (distance between their point and field location <100m), for map-based contiguous and non-contiguous pairs (according to definition 'All <15m'), Ayrshire.

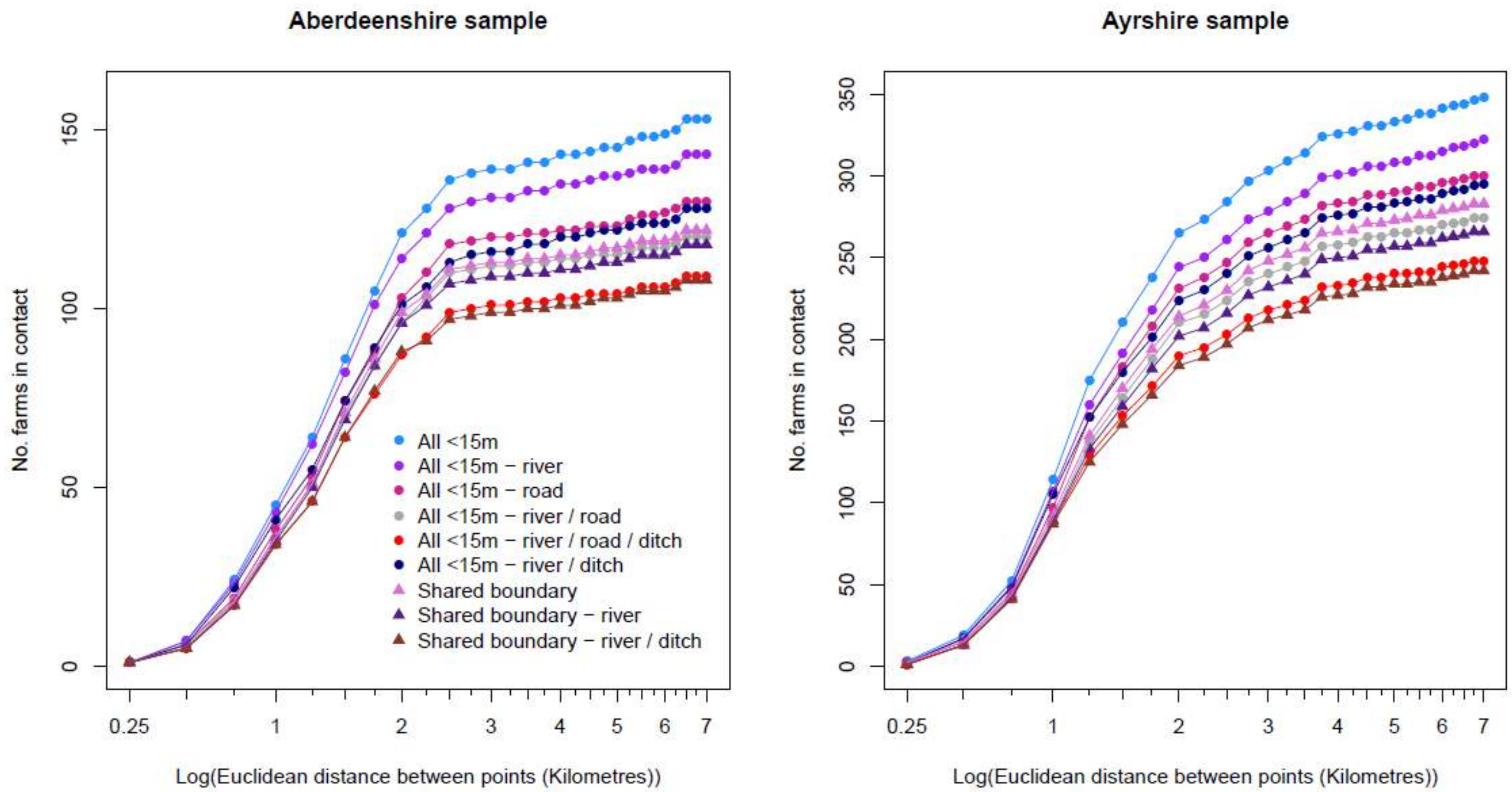



Figure 2.4: Number of premises contiguous under map-based definitions up to 7km point distance.

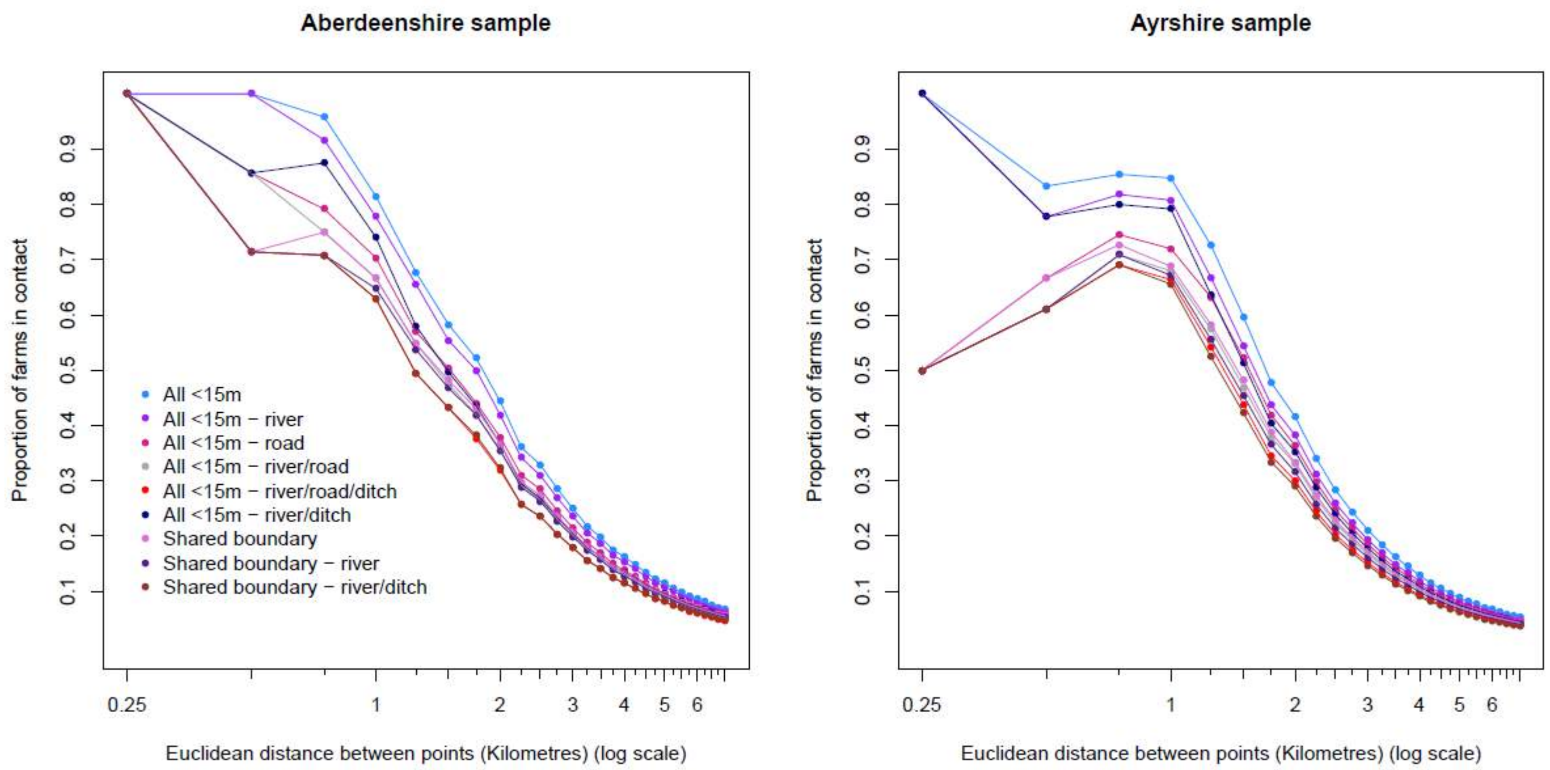



Figure 2.5: The cumulative proportion of premises classified as being contiguous under map-based definitions up to 7km point distance. Where premises pairs exclude those where one or both premises' point locations are ≥100m from their respective field locations.

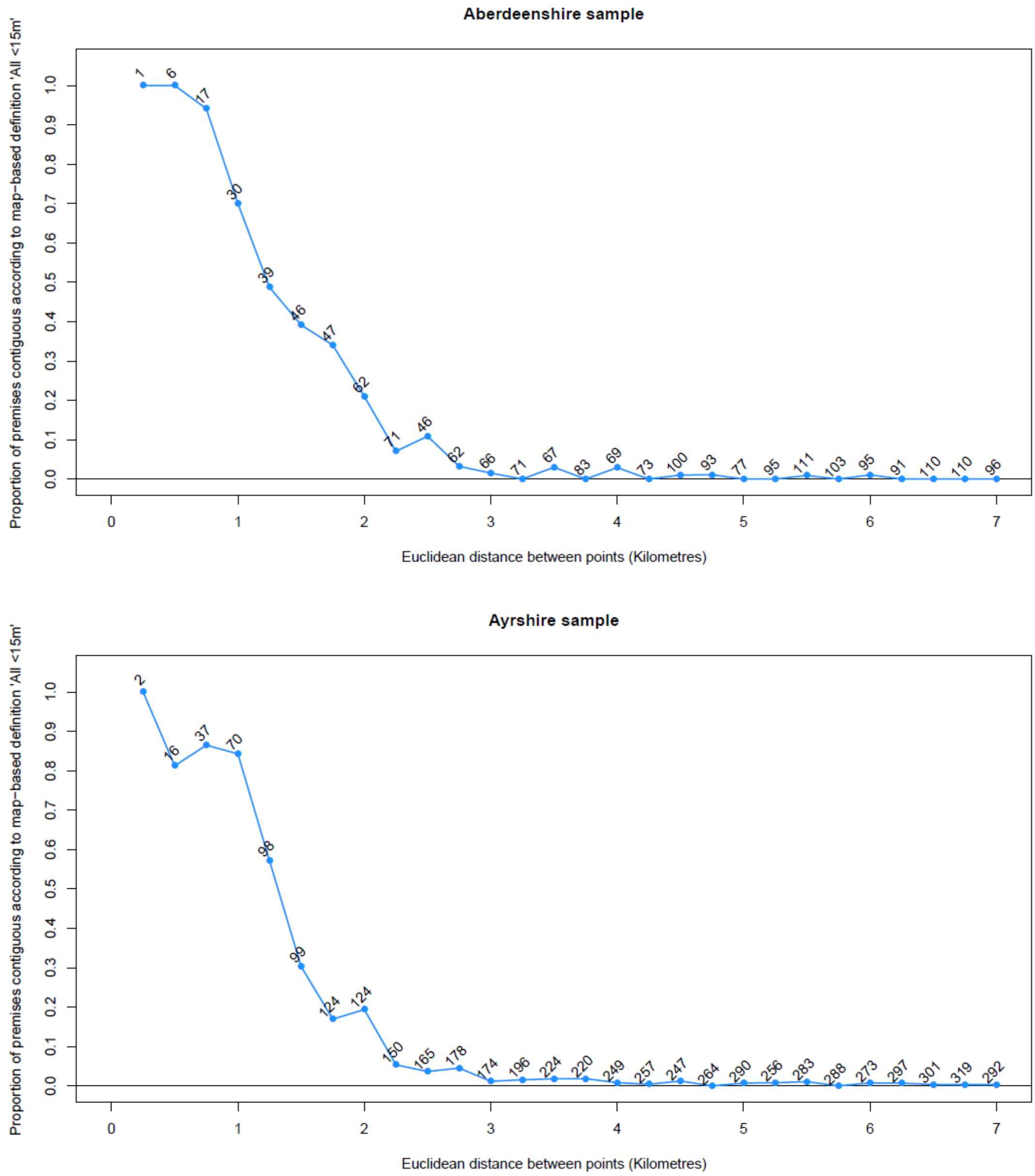



Figure 2.6: The proportion of premises within 0.25km point distance bands that are contiguous under map-based definition 'All <15m'. Numbers indicate total number of premises pairs within the 0.25km distance band. Where premises pairs exclude those where one or both premises' point locations are ≥100m from their respective field locations.

| **Contiguity definition** | **D** | **p-value** |
|---|---|---|
| All <15m | 0.18 | 0.763 |
| All <15m - river | 0.18 | 0.763 |
| All <15m - road | 0.14 | 0.944 |
| All <15m - river/road | 0.14 | 0.944 |
| All <15m - river/road/ditch | 0.14 | 0.944 |
| All <15m - river/ditch | 0.14 | 0.938 |
| Shared boundary | 0.18 | 0.763 |
| Shared boundary - river | 0.18 | 0.773 |
| Shared boundary - river/ditch | 0.18 | 0.773 |

Table 2.5: Kolmogorov-Smirnov test results comparing the distributions shown in Figure 2.5 of the cumulative proportion of premises classified as being contiguous under the various map-based definitions in the two sample areas (in Aberdeenshire and Ayrshire).

### 2.3.2 Agreement between the different CP definitions

Concordance of approximation measures was very high for point distances <1km, field edge distances <1km, and Voronoi and area-weighted tessellation for both Aberdeenshire and Ayrshire (all >87% agreement with map-based contiguity measures) (Table 2.6). This was however distinctly biased towards non-contiguous pair agreements (True Negatives).

Sensitivity was therefore calculated to find the proportion of map-based CPs that were correctly identified by the approximation methods. Sensitivity was fairly consistent between map-based contiguity measures. For measures based on point distances, sensitivity was low for <1km, and only reached >94% at point distances <5km (Table 2.7). Ayrshire had a higher average sensitivity at <1km point distance compared to Aberdeenshire (Ayrshire 33.8%; Aberdeenshire 30.3%), but lower average sensitivity at <3km point distance (Ayrshire 87.4%; Aberdeenshire

92.0%). Both samples reached an average of about 96% sensitivity at 5km point distance. The two tessellation methods identified a higher average of map-based CPs in Aberdeenshire (Voronoi tessellation = 73.6%; area-weighted tessellation = 83.4%) than in Ayrshire (Voronoi tessellation = 63.5%; area-weighted tessellation = 68.0%). Field edge distance measures were 100% sensitive by definition (Table 2.7).

PPV identified the proportion of approximation method CPs that were CPs under map-based methods, so that a low value indicates that only a low proportion of those identified are map-based CPs. For both samples PPV was consistently low (<50%) through the different map-based CP definitions for point distances <3km and <5km, field edge distance <1km, and Voronoi and area-weighted tessellation (Table 2.8). For point distances <1km, Aberdeen had a higher average PPV of 55.1% compared to Ayrshire which had an average PPV of 48.1%. As expected, the highest PPV was for field edge distance <26m, and this was similar between the two samples (Aberdeenshire range 66.3-93.9%; Ayrshire range 66.9-96.1%). That the PPV was lower than the sensitivity for all approximation measures of contiguity except for <1km point distance, indicates that map-based contiguity definitions identify a higher proportion of these approximation measure CPs than these approximation measures identify map-based CPs.

The highest TSS scores were found for the field edge distance measures (Table 2.9). Out of point distance measures, <3km had the highest TSS score (Aberdeenshire range 0.686-0.712; Ayrshire range 0.662-0.680). Point distances of <5km and <1km had average TSS scores of 0.393 and 0.289 in Aberdeenshire and 0.390 and 0.324 in Ayrshire, respectively. Voronoi and area-weighted tessellation had average TSS scores of 0.647 and 0.727 in Aberdeenshire and 0.588 and 0.626 in Ayrshire, respectively.

| Gold standard | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| **Aberdeenshire** | | | | | | | | |
| All <15m | 94.5 | 79.5 | 47.6 | 99.6 | 98.9 | 89.3 | 90.7 | 89.6 |
| All <15m - river | 94.7 | 79.3 | 47.3 | 99.2 | 98.4 | 88.9 | 90.5 | 89.4 |
| All <15m - road | 94.8 | 78.9 | 46.7 | 98.6 | 97.9 | 88.3 | 90.2 | 89.1 |
| All <15m - river/road | 95.1 | 78.7 | 46.4 | 98.2 | 97.5 | 87.9 | 90.0 | 88.9 |
| All <15m - river/road/ditch | 95.4 | 78.2 | 46.0 | 97.7 | 97.0 | 87.4 | 89.7 | 88.6 |
| All <15m - river/ditch | 95.2 | 78.7 | 46.7 | 98.5 | 97.8 | 88.2 | 90.1 | 89.0 |
| Shared fence | 95.0 | 78.7 | 46.5 | 98.3 | 97.6 | 88.0 | 90.3 | 89.0 |
| Shared fence - river | 95.1 | 78.5 | 46.4 | 98.1 | 97.4 | 87.8 | 90.1 | 88.9 |
| Shared fence - river/ditch | 95.4 | 78.1 | 45.9 | 97.7 | 97.0 | 87.4 | 89.9 | 88.6 |
| | | | | | | | | |
| **Ayrshire** | | | | | | | | |
| All <15m | 95.8 | 80.4 | 45.3 | 99.8 | 98.9 | 90.4 | 94.3 | 93.8 |
| All <15m - river | 96.0 | 80.1 | 45.0 | 99.5 | 98.6 | 90.0 | 94.2 | 93.6 |
| All <15m - road | 96.0 | 80.0 | 44.8 | 99.2 | 98.3 | 89.7 | 94.2 | 93.7 |
| All <15m - river/road | 96.2 | 79.7 | 44.5 | 98.9 | 97.9 | 89.4 | 94.1 | 93.6 |
| All <15m - river/road/ditch | 96.5 | 79.5 | 44.2 | 98.5 | 97.6 | 89.1 | 94.1 | 93.4 |
| All <15m - river/ditch | 96.3 | 79.9 | 44.7 | 99.1 | 98.2 | 89.7 | 94.1 | 93.5 |
| Shared fence | 96.1 | 79.8 | 44.6 | 99.0 | 98.1 | 89.5 | 94.0 | 93.5 |
| Shared fence - river | 96.2 | 79.6 | 44.4 | 98.8 | 97.8 | 89.3 | 94.0 | 93.5 |
| Shared fence - river/ditch | 96.5 | 79.4 | 44.1 | 98.4 | 97.5 | 89.0 | 94.0 | 93.4 |

Table 2.6: Concordance (%) of approximation methods versus map-based measures for sample areas in Aberdeenshire and Ayrshire.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | **Aberdeenshire** | | | | | | | | |
| | **All <15m** | 29.4 | 90.8 | 94.8 | 100.0 | 100.0 | 100.0 | 73.2 | 82.4 |
| | **All <15m - river** | 30.1 | 91.6 | 95.8 | 100.0 | 100.0 | 100.0 | 73.4 | 82.5 |
| | **All <15m - road** | 29.2 | 92.3 | 94.6 | 100.0 | 100.0 | 100.0 | 73.1 | 83.1 |
| | **All <15m - river/road** | 30.0 | 93.3 | 95.8 | 100.0 | 100.0 | 100.0 | 73.3 | 83.3 |
| | **All <15m - river/road/ditch** | 31.2 | 92.7 | 95.4 | 100.0 | 100.0 | 100.0 | 72.5 | 83.5 |
| | **All <15m - river/ditch** | 32.0 | 90.6 | 95.3 | 100.0 | 100.0 | 100.0 | 72.7 | 82.8 |
| | **Shared fence** | 29.5 | 92.6 | 95.9 | 100.0 | 100.0 | 100.0 | 75.4 | 84.4 |
| | **Shared fence - river** | 29.7 | 92.4 | 95.8 | 100.0 | 100.0 | 100.0 | 74.6 | 83.9 |
| | **Shared fence - river/ditch** | 31.5 | 91.7 | 95.4 | 100.0 | 100.0 | 100.0 | 74.1 | 84.3 |
| | | | | | | | | | |
| | **Ayrshire** | | | | | | | | |
| | **All <15m** | 32.8 | 87.1 | 95.7 | 100.0 | 100.0 | 100.0 | 62.6 | 67.2 |
| | **All <15m - river** | 33.2 | 86.3 | 95.7 | 100.0 | 100.0 | 100.0 | 62.4 | 67.1 |
| | **All <15m - road** | 32.3 | 88.3 | 96.7 | 100.0 | 100.0 | 100.0 | 64.3 | 69.0 |
| | **All <15m - river/road** | 32.8 | 87.6 | 96.7 | 100.0 | 100.0 | 100.0 | 64.2 | 69.0 |
| | **All <15m - river/road/ditch** | 35.5 | 87.9 | 96.8 | 100.0 | 100.0 | 100.0 | 64.9 | 69.0 |
| | **All <15m - river/ditch** | 35.6 | 86.8 | 95.9 | 100.0 | 100.0 | 100.0 | 63.1 | 67.1 |
| | **Shared fence** | 32.9 | 87.6 | 96.5 | 100.0 | 100.0 | 100.0 | 62.5 | 67.5 |
| | **Shared fence - river** | 33.5 | 87.2 | 96.6 | 100.0 | 100.0 | 100.0 | 63.2 | 68.0 |
| | **Shared fence - river/ditch** | 36.0 | 87.6 | 96.7 | 100.0 | 100.0 | 100.0 | 64.0 | 68.2 |

Table 2.7: Sensitivity (%) of approximation methods versus map-based measures for sample areas in Aberdeenshire and Ayrshire.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | **Aberdeenshire** | | | | | | | | |
| | **All <15m** | 65.2 | 22.7 | 10.4 | 93.9 | 85.0 | 37.4 | 38.1 | 36.4 |
| | **All <15m - river** | 62.3 | 21.4 | 9.9 | 87.7 | 79.4 | 35.0 | 35.7 | 34.1 |
| | **All <15m - road** | 55.1 | 19.6 | 8.9 | 79.8 | 72.2 | 31.8 | 32.3 | 31.2 |
| | **All <15m - river/road** | 52.2 | 18.3 | 8.3 | 73.6 | 66.7 | 29.3 | 29.9 | 28.9 |
| | **All <15m - river/road/ditch** | 49.3 | 16.5 | 7.5 | 66.9 | 60.6 | 26.7 | 26.9 | 26.3 |
| | **All <15m - river/ditch** | 59.4 | 18.9 | 8.8 | 78.5 | 71.1 | 31.3 | 31.6 | 30.6 |
| | **Shared fence** | 52.2 | 18.4 | 8.4 | 74.8 | 67.8 | 29.8 | 31.3 | 29.8 |
| | **Shared fence - river** | 50.7 | 17.8 | 8.1 | 72.4 | 65.6 | 28.9 | 29.9 | 28.6 |
| | **Shared fence - river/ditch** | 49.3 | 16.2 | 7.4 | 66.3 | 60.0 | 26.4 | 27.2 | 26.3 |
| | | | | | | | | | |
| | **Ayrshire** | | | | | | | | |
| | **All <15m** | 56.7 | 17.2 | 7.4 | 96.1 | 80.4 | 32.0 | 41.2 | 39.1 |
| | **All <15m - river** | 53.2 | 15.8 | 6.8 | 89.0 | 74.4 | 29.6 | 38.0 | 36.1 |
| | **All <15m - road** | 48.3 | 15.0 | 6.4 | 82.9 | 69.3 | 27.5 | 36.5 | 34.6 |
| | **All <15m - river/road** | 44.8 | 13.6 | 5.9 | 75.7 | 63.3 | 25.2 | 33.3 | 31.6 |
| | **All <15m - river/road/ditch** | 43.8 | 12.4 | 5.3 | 68.5 | 57.3 | 22.8 | 30.4 | 28.5 |
| | **All <15m - river/ditch** | 52.2 | 14.5 | 6.3 | 81.5 | 68.1 | 27.1 | 35.2 | 33.1 |
| | **Shared fence** | 46.3 | 14.1 | 6.0 | 78.2 | 65.4 | 26.0 | 33.5 | 31.9 |
| | **Shared fence - river** | 44.3 | 13.1 | 5.7 | 73.5 | 61.4 | 24.4 | 31.8 | 30.2 |
| | **Shared fence - river/ditch** | 43.3 | 12.0 | 5.2 | 66.9 | 55.9 | 22.2 | 29.3 | 27.5 |

Table 2.8: PPV (%) of approximation methods versus map-based measures for sample areas in Aberdeenshire and Ayrshire.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | **Aberdeenshire** | | | | | | | | |
| | **All <15m** | 0.283 | 0.696 | 0.391 | 0.996 | 0.988 | 0.885 | 0.651 | 0.725 |
| | **All <15m - river** | 0.289 | 0.701 | 0.400 | 0.991 | 0.984 | 0.881 | 0.650 | 0.724 |
| | **All <15m - road** | 0.279 | 0.705 | 0.385 | 0.985 | 0.978 | 0.876 | 0.643 | 0.725 |
| | **All <15m - river/road** | 0.285 | 0.712 | 0.397 | 0.981 | 0.974 | 0.872 | 0.642 | 0.725 |
| | **All <15m - river/road/ditch** | 0.297 | 0.702 | 0.390 | 0.976 | 0.969 | 0.868 | 0.630 | 0.723 |
| | **All <15m - river/ditch** | 0.308 | 0.686 | 0.392 | 0.984 | 0.977 | 0.876 | 0.638 | 0.722 |
| | **Shared fence** | 0.281 | 0.705 | 0.398 | 0.982 | 0.974 | 0.873 | 0.665 | 0.737 |
| | **Shared fence - river** | 0.282 | 0.702 | 0.395 | 0.980 | 0.973 | 0.872 | 0.655 | 0.730 |
| | **Shared fence - river/ditch** | 0.299 | 0.691 | 0.390 | 0.976 | 0.968 | 0.868 | 0.647 | 0.731 |
| | | | | | | | | | |
| | **Ayrshire** | | | | | | | | |
| | **All <15m** | 0.316 | 0.672 | 0.386 | 0.998 | 0.988 | 0.899 | 0.584 | 0.623 |
| | **All <15m - river** | 0.320 | 0.662 | 0.385 | 0.995 | 0.985 | 0.896 | 0.580 | 0.619 |
| | **All <15m - road** | 0.309 | 0.680 | 0.394 | 0.992 | 0.982 | 0.893 | 0.598 | 0.637 |
| | **All <15m - river/road** | 0.314 | 0.670 | 0.393 | 0.988 | 0.979 | 0.890 | 0.595 | 0.635 |
| | **All <15m - river/road/ditch** | 0.340 | 0.671 | 0.392 | 0.985 | 0.975 | 0.887 | 0.600 | 0.632 |
| | **All <15m - river/ditch** | 0.343 | 0.664 | 0.386 | 0.991 | 0.981 | 0.893 | 0.584 | 0.617 |
| | **Shared fence** | 0.314 | 0.672 | 0.391 | 0.989 | 0.980 | 0.891 | 0.578 | 0.620 |
| | **Shared fence - river** | 0.320 | 0.666 | 0.392 | 0.987 | 0.978 | 0.889 | 0.583 | 0.624 |
| | **Shared fence - river/ditch** | 0.344 | 0.668 | 0.391 | 0.984 | 0.974 | 0.886 | 0.590 | 0.624 |

Table 2.9: TSS of approximation methods versus map-based measures for sample areas in Aberdeenshire and Ayrshire.

### 2.3.3 Network properties

The mean degree (i.e. mean number of CPs) was slightly higher in Ayrshire than in Aberdeenshire for all definitions of contact (Table 2.10). Overall, the mean degree range for the Aberdeenshire sample was 2.67-3.92 and for the Ayrshire sample was 3.21-4.64, for all map-based CP definitions. The mean degree of map-based CPs was 1.22 and 1.34 less in Aberdeenshire and Ayrshire, respectively, when defined as 'All <15m - river/road/ditch' compared to 'All <15m' (distribution shown in Figure 2.7). For map-based CPs contiguous according to definition 'Shared boundary', the presence of rivers and ditches reduced the mean degree by 0.40 and 0.51 in Aberdeenshire and Ayrshire, respectively (distribution shown in Figure 2.7). The distributions of CPs was not, however, significantly different between the definitions 'All <15m' and 'All <15m - river/road/ditch' (Aberdeenshire: K-S D=0.13, p-value=1.00; Ayrshire: K-S D=0.27, p-value=0.855), or 'Shared boundary' and 'Shared boundary - river/ditch' (Aberdeenshire: K-S D=0.26, p-value=0.782; Ayrshire: K-S D=0.15, p-value=0.999). For the point distance CP definitions, <1km considerably underestimated mean degree when compared to map-based CP definitions, particularly in Aberdeenshire, whereas <3km considerably overestimated it, particularly in Ayrshire. Area-weighted tessellation also overestimated mean degree compared to map-based CP definitions, although to a lesser extent than <3km point distance. Premises that kept only sheep had a mean degree between 0.85-1.52 and 1.13-2.07 less than premises that kept cattle only or cattle and sheep, in Aberdeenshire and Ayrshire respectively, across all map-based CP definitions. Area-weighted tessellation (Figure 2.8) and point distance measures (not shown) did not identify this difference.

Aberdeenshire had a higher density than Ayrshire for each definition except <1km point distance, for which the two samples were equal (Table 2.10). The range of density values for all map-based CP definitions were 0.019-0.027 for Aberdeenshire and 0.014-0.021 for Ayrshire. For CPs defined by <1km point distance, density was 0.012 for both samples. This was only slightly less than for CPs in

| Contiguous classification | Aberdeenshire sample | | Ayrshire sample | |
|---|---|---|---|---|
| | Mean degree | Density | Mean degree | Density |
| All <15m | 3.92 | 0.027 | 4.64 | 0.021 |
| All <15m - river | 3.65 | 0.025 | 4.26 | 0.019 |
| All <15m - road | 3.27 | 0.023 | 3.99 | 0.018 |
| All <15m - river/road | 3.01 | 0.021 | 3.61 | 0.016 |
| All <15m - river/road/ditch | 2.70 | 0.019 | 3.29 | 0.015 |
| All <15m - river/ditch | 3.26 | 0.023 | 3.92 | 0.018 |
| Shared field edge | 3.07 | 0.022 | 3.72 | 0.017 |
| Shared fence - river | 2.95 | 0.021 | 3.51 | 0.016 |
| Shared fence - river/ditch | 2.67 | 0.019 | 3.20 | 0.014 |
| <1km distance between point locations | 1.36 | 0.012 | 2.26 | 0.012 |
| <3km distance between point locations | 13.61 | 0.108 | 21.49 | 0.105 |
| Area-weighted tessellation | 5.95 | 0.061 | 6.25 | 0.036 |

Table 2.10: Network properties according to different definitions of contiguity for farm premises in Aberdeenshire and Ayrshire.

Ayrshire defined by a shared boundary excluding those with rivers and ditches between. For Aberdeenshire however, this was about half the density of most of the map-based CP definitions. For CPs defined by $<$3km point distance, density was quadrupled in Aberdeenshire when compared to $<$15m separation of field boundaries, and quintupled in Ayrshire (Table 2.10). Area-weighted tessellation overestimated density less than $<$3km point distance did for both sample networks.

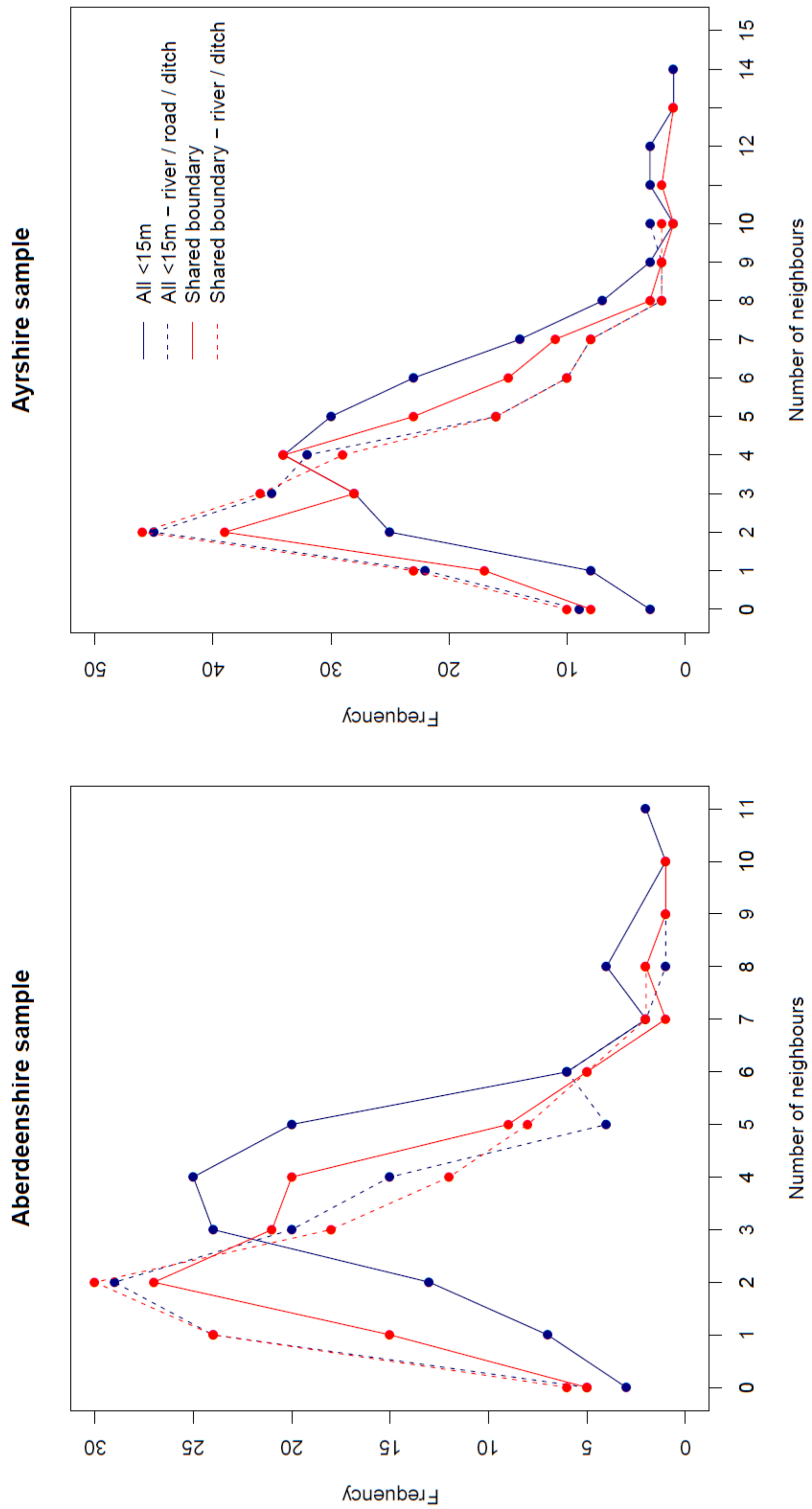



Figure 2.7: Frequency distributions of number of neighbours according to different definitions of map-based contiguity.

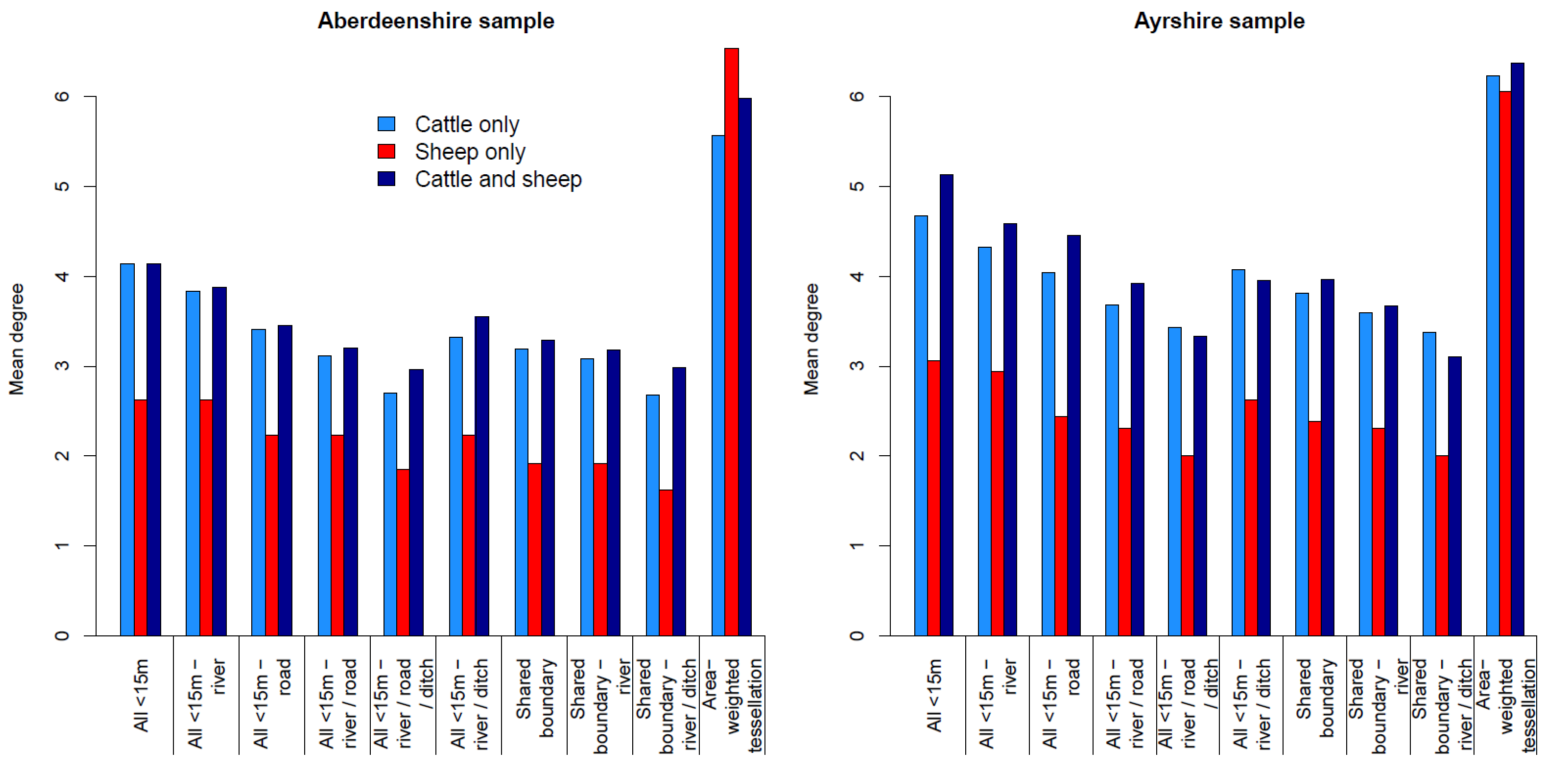



Figure 2.8: Mean degree by species kept on premises, under different definitions of map-based contiguity.

## 2.4 Discussion

The point locations of farm premises were not completely accurate: distances between the CPH-matched point and field locations were $\geq$ 1km in 8.4% and 8.2% of the sample in Aberdeenshire and Ayrshire, respectively. This seemed to particularly affect the agreement between point distances $<$1km and map-based contiguity. For premises pairs within 1km point distance of each other, the proportion of premises pairings, excluding those where one or both premises' point locations are $\geq$100m from their respective field locations, was markedly lower (41.7% in Aberdeenshire; 21.8% in Ayrshire) than among map-based CPs (97.8% in Aberdeenshire; 93.0% in Ayrshire) (Tables 2.3 and 2.4). The inaccuracies of point locations in this way will clearly have a knock-on effect, creating inaccuracies in mathematical model predictions, since 98.6% of premises pairs $<$1km point distance are considered contiguous by area-weighted tessellation (data not shown).

Map-based contiguity definitions identified a higher proportion of approximation measure CPs than the approximation measures identified map-based CPs, for all approximation measures except $<$1km point distance. Thus, approximation measures have a greater tendency to miss map-based CPs than map-based CPs do approximation measure CPs. For $<$1km point distance though, a higher proportion of map-based CPs were identified by this approximation than map-based CPs could identify premises contiguous by $<$1km point distance. This is likely due to the comparatively greater inaccuracy in premises' point locations (relative to their field locations) found among these premises (Tables 2.3 and 2.4). Overall, $<$3km point distance had the most balanced identification of map-based CPs and map-based non-CPs when compared to each the $<$1km and $<$5km categories, and therefore had the highest TSS score of point distances.

Point distance measures do not seek to classify premises within any given distance as contiguous, rather that they are given a weighted level of risk based on the distance from an IP. By comparing these measures against map-based contiguity as if they also defined contiguity does, however, enable us to begin to consider how accounting for map-based contiguity might alter the shape of the transmission kernel. Interestingly, the proportion of premises within 0.25km point distance bands that are contiguous according to map-based definition 'All <15m' (Figure 2.6), follow a very similar pattern in relation to point distance as the transmission risk of the kernel derived from DEFRA contact-tracing during the 2001 outbreak (Figures 1.1 and 1.2). In reality, during the FMD 2001 outbreak, pre-emptive culling was in part determined by identification of CPs on the ground, since they were considered to be at increased risk of becoming infected. Therefore, if contiguous spread does account for a considerable proportion of transmission events IPs would have an elevated rate of transmission relative to true CPs, regardless of point distance between the premises. This would leave transmission events attributable to routes other than those linked to contiguity (e.g. fence line contact), to be captured by the kernel. Crudely, this might be thought of as considering only the relative rate of transmission to map-based non-CPs based on distance between the premises, although in reality map-based CPs would be at risk from these alternative transmission routes as well. Nonetheless this would likely change the shape of the kernel more at small distances than those further away, since at <1km point distance, an average of 44.9% and 51.9% were map-based non-CPs in Aberdeenshire and Ayrshire, respectively, but at <5km these figures were 91.4% and 93.9%, respectively. Indeed, once contiguous transmission is separated out from the kernel, it might be the case that another distance measure such as road distance, as previously considered by Savill et al. (2006), better represents the distance-risk relationship for non-contiguous mechanisms of spread.

In both sample areas, Voronoi tessellation had a slightly lower TSS than for <3km point distance. Area-weighted tessellation on the other hand had a slightly higher TSS than for <3km point distance in Aberdeenshire, but slightly lower TSS in

Ayrshire. This suggests that, in terms of discrimination between map-based CPs and non-CPs, $<$3km point distance and area-weighted tessellation perform similarly, and that the best option may be determined by the landscape of the area that the method is to be applied to. Voronoi and area-weighted tessellation measures performed better overall in Aberdeenshire than in Ayrshire, with somewhat higher TSS scores like-for-like. This may be attributed to sensitivity being considerably poorer in Ayrshire, such that more map-based CPs were being missed by the tessellations. This in turn was likely to be due to the greater density of farm premises in this sample area, leading to a greater distortion of contiguity when tessellating around more tightly packed points. Thus in areas of high livestock farm density, tessellation methods may capture contiguity between farm premises with less accuracy than in lower density areas. While the low levels of accuracy ($\approx$ 20-25%) reported for predicting culled farms by an adapted version of the Keeling et al. (2001) model (Tildesley et al., 2008) are likely due largely to the complex 'on the ground' implementation of culling during the 2001 FMD outbreak, the less than perfect performance of area-weighted tessellation in discriminating between map-based CPs and non-CPs may also have been a contributing factor.

The distances used for field edge based measures in this paper have been used to analyse the persistence of bovine tuberculosis (bTB) (White et al., 2012). These definitions were far superior to either point distance or tessellation approximations in identifying map-based CPs in the two sample areas, reflected in their consistently high TSS scores ($\geq$0.868). By definition they captured all of the map-based CPs as these were also calculated based on field edge distance, only using smaller distances of separation. However, there was up to a 29.4% decrease in PPV when all landscape features were taken into account (for Aberdeenshire, from 93.9% for all separated $<$15m at field edges to 66.3% for all separated $<$15m at field edges excluding those separated by rivers, roads/tracks, and ditches). While this will vary depending on the area of study and the landscape features considered to have an effect on a particular disease's transmission, it suggests that the way in which premises are perceived to be connected may be substantially altered after taking them into account. Indeed, the mechanism of spread of different diseases must be considered when studying the effects of contiguity. For example, the spread of bTB via badger-to-cattle as well as cattle-to-cattle routes means that extended distances between field edges are likely to be appropriate since badgers can roam freely. However, there is some evidence to suggest that bTB prevalence increases following repeated badger culling are less marked when topographical features such as rivers and motorways are present (Woodroffe et al., 2006), as these features act as barriers to isolate badger populations. Such features may therefore be worth incorporating into analyses of bTB in cattle populations since they are likely to affect transmission possibilities.

Mean degree (i.e. mean number of CPs) and density of map-based CP measures were considerably altered by taking landscape features into account in CP definitions. When scaled up to the regional or national scale, taking landscape features into account will likely alter the contact patterns between premises within the network and therefore potentially also affect the pattern of disease transmission through livestock populations. To look at this would require the creation of a reliable and accurate automated method whereby landscape features could be detected, since visual map inspection of larger areas than those studied here would become impractical. Point distance $<$1km created network properties closest to that of map-based CPs, followed by area-weighted tessellation, and then by $<$3km point distance. Of note however, area-weighted tessellation overestimated mean degree by $\approx$1.5-3 compared to map-based CP measures, and was similar (Ayrshire = 6.25; Aberdeenshire = 5.95) to that observed over the whole of GB by Keeling et al. (2001) (6.5, in supplementary information). On a national level this overestimation could therefore introduce considerable inaccuracy into the simulation of culling contiguous premises. This may have the effect of making a contiguous premises culling policy appear to require the culling of more premises than may be identified in reality on-the-ground, and may overestimate its effectiveness by depleting a larger proportion of the population than may be the case in reality.

On balance, however, area-weighted tessellation appears to be better than <3km point distance at capturing map-based contiguity: it has similar ability to discriminate between map-based CPs and non-CPs and better ability to estimate network density and mean degree. Nonetheless, in addition to its overestimation of mean degree, area-weighted tessellation also does not identify the variations in mean degree under map-based CP definitions by livestock species kept on premises (and potentially other predictors of degree as well). In particular, sheep only premises had a fewer map-based CPs compared to cattle only and cattle and sheep premises, which area-weighted tessellation failed to capture (Figure 2.8). This is likely to be important given the differences observed in FMD transmissibility between sheep and cattle during the 2001 outbreak (Keeling et al., 2001), and may have resulted in overestimating the role of culling sheep only premises in controlling predicted spread.

Notably, the two sample areas showed that the different CP measures performed fairly consistently between them. The Ayrshire sample had a much higher number of farm premises than the Aberdeenshire sample however, and this brought to light some differences in the landscapes. Ayrshire had a higher mean degree than Aberdeenshire for map-based CP definitions, indicating that the livestock farming landscape is less fragmented, and that farm premises have, on average, a greater number of CPs. This reflects what is already known about the different farming landscapes of the two areas - Aberdeenshire's being largely composed of mixed cropping and livestock, and Ayrshire's being predominantly dairy cattle farming (Holland et al., 2011). However, network density is lower in the Ayrshire sample. This is because it has about 72% more farm premises compared to the Aberdeenshire sample, meaning that the total number of possible connections is increased disproportionately to the actual number of connections that exist. The proportion of map-based CPs identified was slightly higher in Ayrshire with <1km point distance, and slightly lower with <3km point distance, than compared to Aberdeenshire, both of which may also be attributable to the farming landscape being less fragmented and more tightly-packed with premises in Ayrshire. The relative similarity in results between the two sample areas, despite their counties' differences in farming demographics, suggests that these results may be generalisable to counties with similar farming practices, where livestock production is fairly intensive (although there were some extensive areas captured within the Aberdeenshire sample). The results are likely to be less generalisable to counties with considerable extensive hill grazing, or where common grazing is abundant such that several different premises' livestock may graze within the same land parcel.

The separation distance for map-based contiguity of field edges $<$15m apart was chosen to allow separation of premises by small geographical features, and to reflect the possibility of contaminated material passing between proximal pastures. During the 2001 outbreak however, CPs were defined in Dumfries and Galloway as having shared field boundaries or field boundaries that were separated only by a country road, small river, railway or 20m stretch of woodland (Thrusfield et al., 2005). This is nonetheless very similar, and is unlikely to have affected the results found.

In conclusion, this analysis has demonstrated that none of the point distance, Voronoi tessellation, or area-weighted tessellation measures discriminate particularly well between map-based CPs and non-CPs as identified from premises field boundaries. If an approximation method had to be used, area-weighted tessellation would provide the closest representation of contiguity to map-based identification. Moving forwards though, model accuracy may be improved by basing transmission on map-based contiguity rather than point distances, and by investigating CP control strategies as based on field edges (i.e. map-based) rather than on area-weighted tessellation around farm premises point locations. Furthermore, taking topographic features into account can have a considerable impact on which premises are considered to be contiguous or non-contiguous, and on the resulting mean degree and network density. Thus, if such features are known to prevent transmission between contiguous premises (as has been demonstrated for rivers and railways for FMD (Bessell et al., 2008)), including this level of detail could likely also improve the individual farm-level accuracy of model predictions. The next chapter sees the development of an automated procedure for detecting landscape features between map-based CPs, so that this can be achieved.

# 3 Incorporating a realistic physical landscape into models of FMD spread in Scotland

## 3.1 Introduction

Since disease transmission requires effective contact to occur between susceptible and infected individuals, the underlying spatial distribution of the susceptible population at risk will affect the spatial spread of disease over the course of an outbreak (Highfield et al., 2008). In the case of FMD, models developed during the 2001 UK epidemic assumed FMD risk to be a function of a premises' proximity to an infected premises (IP) (confirmed by subsequent analyses (Bessell et al., 2008; Savill et al., 2006)) and species composition on both the infected and susceptible premises (Ferguson et al., 2001b; Keeling et al., 2001). Thus, the distribution of farm premises' locations and their respective sizes in terms of number of livestock were identified as being key to describing the observed transmission. Subsequent assessment of an adapted version of the Keeling et al. (2001) model, found that this information enabled the overall geographical distribution of disease to be captured, although it had an accuracy of only about 12% in predicting which individual farm premises became IPs over the course of the epidemic (Tildesley et al., 2008). The low level of accuracy in this respect will in part be due to the stochastic nature of the model, but may also be due to how the spatial locations of farm premises were represented which allowed for greater stochasticity than may be realistic.

As discussed in Chapter 2, farm premises' locations were based on point locations (of the main farm buildings, farmer address or postcode or parish centroid), and the Euclidean distance between these was used to construct the transmission kernel (General Introduction, Figures 1.1 and 1.2). This transmission kernel described the decay in risk of transmission with increasing distance from an IP. However, in Chapter 2 it was demonstrated that the distance between point locations is inaccurate in identifying map-based contiguity of farm premises. Being contiguous to an IP during the 2001 FMD outbreak was identified as putting premises at increased risk of becoming infected (Anderson, 2002). During the outbreak these premises were identified on-the-ground as having shared field boundaries or field boundaries separated only by a country road, river, railway track, or 20m stretch of woodland (Thrusfield et al., 2005). Such spatial proximity is thought to have reflected local transmission of the virus by contaminated clothing/boots on people or vehicle wheels, and contaminated material passing between proximal fields (Gibbens et al., 2001). That the model does not capture this level of detail in farm configuration may account for some of the inaccuracy of model predictions at the fine-scale, since accurate representation of both density and connectivity of susceptible individuals through space in key to fully understanding transmission (Cowled and Garner, 2008). Indeed, Highfield et al. (2008) found predicted FMD outbreak impact to be similar but the predicted spatial distribution of spread to be dissimilar, when using different predictions of the spatial distribution of deer density in Texas.

This chapter seeks to assess how mathematical model predictions are affected by making local transmission probability based on contiguity, rather than distance between point locations, as per the kernel. While it will not be possible to demonstrate that a model with transmission based on contiguity will be more accurate in its spatial predictions without validating it against epidemiological data, the comparability of predicted spatial distributions of outbreaks, and the relative stochasticity of IP identification between simulations using two models - where one bases transmission on the kernel, and the other on map-based contiguity - is of interest. Allowing transmission probability to be based on map-based contiguity is likely to reduce the number of premises at high infection risk around an IP, but increase the likelihood of infection to these premises. This could potentially result in a more predictable transmission route of infection between premises. I therefore hypothesise that IPs predicted by the models will be more predictable by using the model that bases local FMD transmission on map-based contiguity, than the model that bases such transmission on point distance (defined by the kernel). Furthermore, I suggest that spatial predictions of the model based on map-based contiguity may result in similar-sized outbreaks being geographically less spread than those predicted by the point distance/kernel-based model. This is because of the difference in how the two models identify CPs of premises with larger areas: the former identifying them solely based on map-based contiguity ($<$15m distance between field edges), and the latter summarising large area premises to single point locations, likely increasing distance to surrounding premises, and consequently reducing transmission risk to them.

## 3.2 Methods

### 3.2.1 Data

Farm premises were selected for inclusion if they had some or all of their fields within the region covering the old Scottish counties of Ayrshire, Wigtownshire, Kirkudbrightshire, Dumfriesshire, Renfrewshire, Lanarkshire, Peebleshire, Roxburghshire, Berwickshire, Selkirkshire, West Lothian, Midlothian and East Lothian. This area was previously identified as being at high risk for FMD spread in the event of a future incursion in Scotland (Porphyre et al., 2013); i.e. the area may not be the highest risk for FMD spread in the UK as a whole, but it is likely the highest risk area within Scotland, and is furthermore bordering Cumbria which was one of the worst FMD-affected counties of England in 2001 Gibbens et al. (2001). The geographical locations of farms' fields were obtained from the Scottish Integrated Administration and Control System (IACS) 2011 dataset. These IACS data were linked to the June 2011 Agricultural Census data based on matching county-parish-holding (CPH) numbers which identify individual farm premises, and premises with any cattle, sheep, pigs, deer or goats recorded in the Census were selected for inclusion. The final sample consisted of 4767 farm premises.

### 3.2.2 Mathematical Modelling

N.B. The mathematical modelling was performed by Thibaud Porphyre. Full methods can be found in Appendix 1, and are written by Thibaud Porphyre, as described in Porphyre et al. (2013).

One thousand simulations of two variations of the Keeling et al. (2001) model were run over the 4767 selected premises. Five premises were selected as seeds within Ayrshire, and were the same across all simulations. Ayrshire was chosen since it was found to be at elevated risk of FMD spread by Porphyre et al. (2013). The first model used was the modified distance-based model shown in Equation (8.1) (Appendix 1) (Tildesley and Keeling, 2009; Tildesley et al., 2008). In this model susceptibility and transmissibility are non-linear in relation to number of cattle and sheep and described by power law parameters in Equations (8.2) and (8.3) (Appendix 1). The relative risk posed by infected premises (IPs) to an uninfected premises was described by the kernel, such that the smaller the distance between the point location of an IP and the surrounding uninfected premises, the greater the risk of transmission to the uninfected premises. In comparison, in the second model used (see Equation (8.4), Appendix 1), the risk posed by an IP to an uninfected premises was based on whether or not it was contiguous to it according to the definition 'All <15m' (as detailed in Chapter 2). Background transmission was also incorporated into this contiguity-based model such that $\delta = 2.81 \times 10^{-6}$ in Equation (8.5) (Appendix 1), to allow for some longer range spread as observed in 2001. This value was used since it was the minimum value of the original Keeling et al. (2001) kernel function, and was used to a distance of 60km outwards from IP point locations.

To ensure consistency in point location derivation, new point locations were generated to enable incorporation of the kernel in the mathematical model simulations. This was necessary since the point locations used in Chapter 2 do not refer to the same point for each premises (i.e. main farm building, postcode centroid, farmer address etc.). These point locations were generated by first creating a 7.5m buffer around farms' fields, and merging these buffered field areas where they overlapped, to create land parcels. The centroid point locations of each land parcel were calculated along with the total area of fields within each parcel. For each premises, the centroid of the land parcel with the largest total field area was taken as the point location.

The outputs from the simulations were studied to examine the differences between the distance-based and contiguity-based models. The five seed premises were removed from these analyses. The distributions of the number of times individual premises became IPs over the course of 1000 simulations were examined for each model, as were the distributions of number of IPs produced by simulation. Contingency tables were used to study the agreement as to which premises became IPs frequently using each of the models.

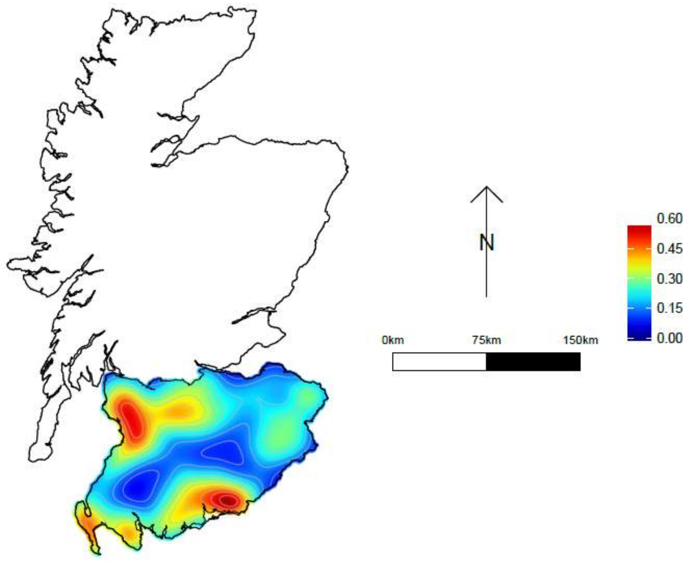



Figure 3.1: Map showing livestock holding density (number of premises per square kilometre) in selected border area within mainland Scotland.

## 3.3 Results

While all 4767 selected premises had fields within the defined area of study, 19 premises' largest land parcel centroids lay outside of it and consequently so did their point locations. The geographical distribution of the livestock premises within the selected area can be seen in Figure 3.1. The majority of the 4767 premises in the study area kept cattle and/or sheep (n=4577; 96.0%) (Table 10.1, in Appendix 3).

While the simulations from the contiguity model were selected on the basis on having a similar mean number of IPs (433.0 for the contiguity model, 450.0 for the distance model) and mean duration, the contiguity model simulations had a much larger interquartile range for the number of IPs (IQR: 83.0-812.0, range: 9-1085) than the distance model (IQR: 225.5-657.0, range: 3-980), and considerably smaller median (269.5 compared to 499.0 for the distance model). Looking at the frequency distribution of number of IPs per simulation indicates that the contiguity model tended to produce smaller outbreaks, but that when it did produce large outbreaks these tended to be larger than those produced using the distance model (Figure 3.2).

Histograms of the distributions of frequency with which premises became IPs over the course of 1000 simulations show that the contiguity model distribution was overdispersed (Figure 3.3). A small number of premises became IPs in the majority of the simulations using the contiguity model, and counter-balance this, a larger number of premises rarely became IPs (in $<5\%$ simulations) compared to in the distance model simulations. The percentage of times premises became IPs over 1000 simulations ranged up to 33.2% using the distance model, and up to 84.6% using the contiguity model. Because the same 5 seed IPs were in each simulation, we expect that premises proximal to these will become IPs on a number of occasions, and the interest is therefore in the frequency with which those premises further from the seed IPs become infected. However, since it is difficult to define the limit within which premises are considered close, the frequency among the sample as a whole was studied. There was little consistency in the number of times premises became IPs between the two models' simulation sets (Figure 3.4). Indeed, agreement of which premises became IPs frequently was poor between the two models at a cut-off of $>14\%$ (Table 3.1, where 14% was approximately between the upper quartile values for each model) and of $>20\%$ (Table 3.2).

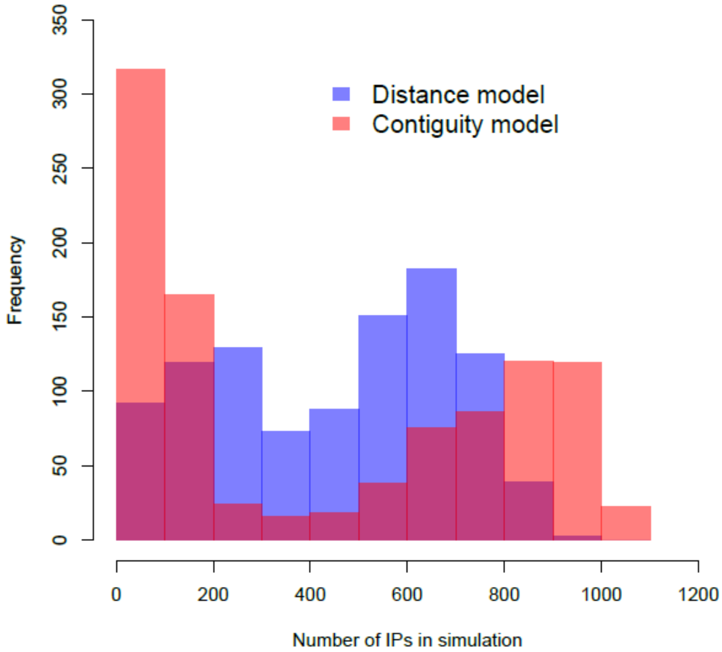



Figure 3.2: Histograms showing the frequency distributions of the number of IPs identified over 1000 simulations for each model.

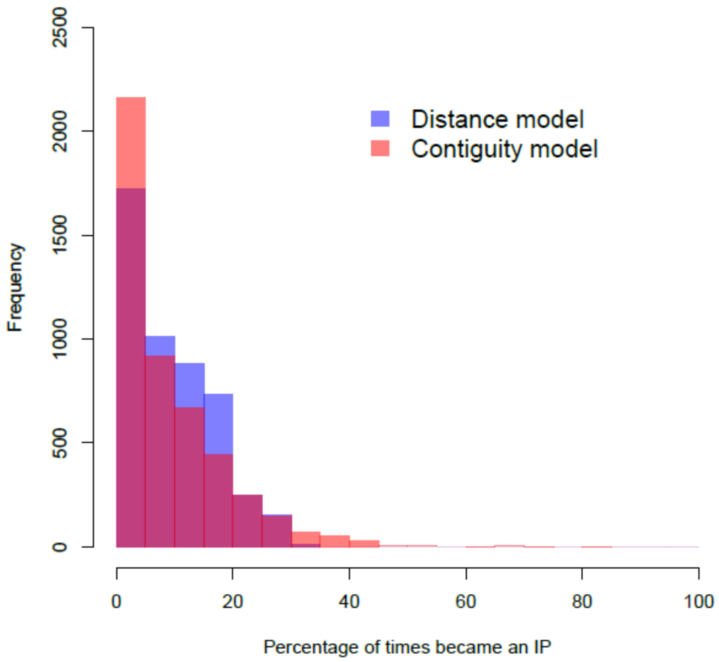



Figure 3.3: Histograms showing the distributions of the percentage of times premises became IPs over the course of 1000 simulations for each model.

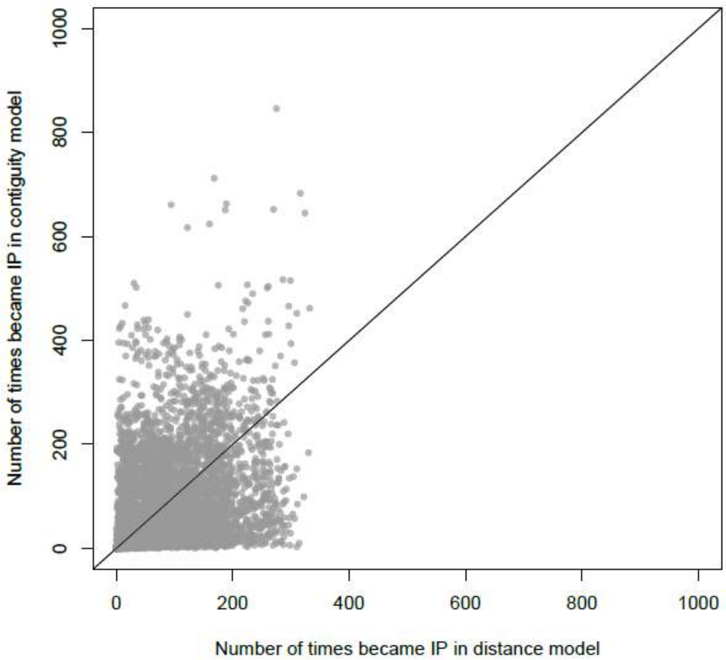



Figure 3.4: Scatter plot showing the number of times premises became IPs using the contiguity model against the number of times premises became IPs using the distance model (over the course of 1000 simulations).

| | | Contiguity model | | Total |
|---|---|---|---|---|
| | | ≤14% | >14% | |
| Distance model | ≤14% | 2728 | 722 | 3450 |
| | >14% | 890 | 422 | 1312 |
| Total | | 3618 | 1144 | 4762 |

Table 3.1: Contingency table for premises that became IPs in $>14\%$ of simulations using the distance and contiguity models. Where the 14% cut-off was chosen as being approximately between the upper quartile values for each model.

| | | Contiguity model | | Total |
|---|---|---|---|---|
| | | ≤20% | >20% | |
| Distance model | ≤20% | 3877 | 473 | 4350 |
| | >20% | 310 | 102 | 412 |
| Total | | 4187 | 575 | 4762 |

Table 3.2: Contingency table for premises that became IPs in $>20\%$ of simulations using the distance and contiguity models. Where the 14% cut-off was chosen as being approximately between the upper quartile values for each model.

## 3.4 Discussion

Simulations of two models each basing local FMD transmission on the point distance as per the transmission kernel of Keeling et al. (2001) (the distance model) and on contiguity (the contiguity model), defined as map-based contiguity as ascertained from map data, provided some evidence for the IPs being identified by the contiguity model being more predictable, and less random. This was shown with the contiguity model generating a higher probability of infection for fewer holdings than in the distance model, and was evidenced by the distribution of number of times each premises became an IP over the course of 1000 simulations (Figure 3.3). It was important for this exercise that the same seed IPs were used for each simulation in order that the pathway of infection through the farming landscape could be compared in terms of the percentage of simulations in which premises became IPs. Had the seeds been different between simulations, it would have been impossible to tell if the percentage of times premises became IPs was due to the differences in transmission parameters, or simply due to the premises' locations in relation to the seed IPs. However, in order to determine which of the models is the most accurate in predicting which premises become IPs during an FMD outbreak would require comparison of predicted IPs with real IP data. Thus, the contiguity model cannot be validated at this point in time.

Although the overall mean outbreak sizes of the simulations for each model were similar, the distributions of outbreak sizes produced by the two model's were different, with the contiguity model tending to produce more small outbreaks than the distance model (Figure 3.2). This is comparable to Highfield et al. (2008) finding that lower spatial continuity of deer population distributions resulted in fewer simulated FMD outbreaks taking off compared to high spatial continuity distributions, since the contiguity model comparatively limits the number of possible premises available to an IP to infect, and hence the continuity of farm premises through the landscape. The fact that the outbreaks did not tend to take-off as often as when using the distance model means that premises had fewer opportunities to become IPs in the contiguity model. That this is the case, and that some premises became IPs in a large proportion of the contiguity model simulations where they did not in the distance model (Figure 3.3), suggests that the distributions of number of simulations that each premises became an IP in may in fact have been even more different than observed between the two models, if they had been calibrated to give similar distributions of outbreak sizes. The priorities for the two models' calibration was that they produced a similar mean number of IPs and similar mean outbreak duration, as well as them having similar probabilities of having an outbreak of >100 IPs and >100 days. To calibrate them in greater detail of distribution of outbreak sizes would have been much more computationally challenging, and therefore not possible in the time available.

There was also some limited evidence to suggest that when an outbreak takes-off, the contiguity model predicts more geographically widespread outbreaks (Appendix 1, Figures 8.3 and 8.4). This may be due to the fact that the contiguity model allows for the fact that large farm premises may, for example, be map-based contiguous to two premises that are far-apart from each other; if it becomes infected by one of its contiguous premises (CPs), it then has a possibility of infecting another of its CPs which is geographically distant from the original 'infecting' CP. On the other hand, in the case of the distance model, large premises may be biased towards having artificially large separation distances from premises that they are actually map-based contiguous to, simply due to their large area being reduced to a single point location. This would result in a lower probability of infection and transmission to surrounding premises than may be likely in reality, and therefore prevent such bridging effects as those which are possible in the contiguity model. Thus, the structure of the contiguity model is such that premises that appear geographically far from each other may actually be close in terms of transmission if they share a common CP - enabling disease to spread more widely. While this observation is based on two simulations from each model, the differences in predicted spatial spread were evident from the poor agreement between the two models' predictions of which premises became IPs in a large proportion of the simulations (Figure 3.4 and Tables 3.1 and 3.2).

Furthermore, large premises may have an increased probability of becoming an IP in the contiguity model, since they are likely to have more CPs, and consequently more potential opportunities for infection. This would appear to be in agreement with premises' area being significantly positively correlated with premises' susceptibility, in a multivariable statistical model which had greater predictive ability for identifying individual premises that became IPs during the 2001 epidemic than the Keeling et al. (2001) model was found to (45.1% versus $\approx 12\%$ (Tildesley et al., 2008)). Additionally larger premises may likely be more fragmented than their smaller counterparts, further increasing the potential for a larger number of CPs. In the contiguity model, a premises' fragmentation is accounted for by map-based CPs being defined as those premises that have any of their land parcels contiguous to any of the premises in questions' land parcels, but in the distance model a premises is represented as one point location regardless of the number of land parcels it has. Ferguson et al. (2001b) found a significant positive correlation between the number of discontinuous fields a farm premises had (i.e. its fragmentation, defined slightly differently to in this thesis) and its FMD risk, and found that this explained a high proportion of geographical variation in transmission in their model. However, because they found correlations between premises' fragmentation and their land area and numbers of livestock, they did not include fragmentation in their final model (Ferguson et al., 2001b). Given that the kernel puts larger premises at lower risk of becoming infected than they possibly ought (due to their size and the nature of point locations), it is possible then that the fragmentation/FMD risk relationship was stronger than that observed by their model. This is because this reduction in risk would mean that fewer larger premises were predicted to become IPs than were likely to become IPs in reality, and, assuming that larger premises may have a greater probability of being fragmented, so the average fragmentation of predicted IPs would be reduced, and consequently the apparent FMD risk associated with fragmentation.

This suggests that an even greater proportion of the geographical variation in transmission may have been achieved had the effect of fragmentation on FMD risk not been effectively dampened by the transmission kernel. Thus, premises' fragmentation, and area, may be important factors contributing to FMD risk that are not currently captured by the distance model.

In conclusion, the contiguity model appears to make less random, more predictable predictions for the spatial spread of FMD, and appears to result in more geographically widespread outbreaks in the event that an outbreak takes-off (the chances of which are reduced compared to the distance model). This is likely due to it accounting for the heterogeneity of the farming landscape, making the potential for transmission more anisotropic dependent on the configuration of CPs around an IP. In this way it increases the potential for infection transmission to a restricted number of specific premises, while still allowing for longer range transmission at a low level of probability. While it cannot be concluded from the results presented here that the contiguity model will be more accurate in its predictions of which premises become IPs during an outbreak given the initial IP locations, it highlights that premises' area and level of fragmentation may be important factors not currently captured in the kernel-based models. Since CPs were considered to be at increased risk of infection during the 2001 outbreak (Anderson, 2002), it may be that the increase in FMD risk observed with larger area (Bessell et al., 2010) and increasing fragmentation (Ferguson et al., 2001b), is due to the corresponding increase in CPs that larger, more fragmented premises are likely to have. Improving the accuracy with which the spatial distribution of the population at risk is described in mathematical models is likely to help to improve the accuracy of predicted spatial patterns of spread. Whether the contiguity model does this, and whether it represents the best way of capturing the relative contributions of premises area, fragmentation, number of CPs and number of livestock to FMD transmission, will need to be evaluated using epidemiological data that arises from any future outbreaks.

What makes some premises become predicted IPs in such a high proportion of simulations using the contiguity model warrants further investigation. Some of this will be accounted for simply by the proximity, in terms of map-based contiguity, of the premises to the seed IPs. However, other factors may contribute and, indeed, affect this, such as premises size and fragmentation. The next chapter will investigate this further by using network analysis to study the network structure of map-based contiguous premises.

# 4 How connected is the farming landscape in Scotland? Implications for FMD

**Key network terminology**

***Node:*** *Individuals within the network. Within this chapter: premises.*

***Edge:*** *Connections between two nodes. In this chapter, two premises are said to share an edge where they are map-based contiguous to one another, according to one of four map-based contiguity definitions.*

***Degree:*** *Network term for the number of edges each node has to other nodes. In the context of this work, is the number of map-based CPs a premises has.*

***Degree assortativity:*** *Assortativity of a network can be calculated for any node value, but in the case of degree assortativity measures the likelihood that nodes share edges more commonly with other nodes that have similar degree.*

***Betweenness:*** *The betweenness, or betweenness centrality, of a node measures the number of shortest paths (i.e. the path between any two nodes in the network that minimises the number of other nodes passed through) between other pairs of nodes in the network that pass through the node in question.*

***Component:*** *A subset of nodes within a network that can be all be reached by one another by passing along any number of edges.*

***Giant Component (GC):*** *The subset of nodes that belong within the largest component of the network.*

## 4.1 Introduction

Networks that use known population contact structures can be constructed to consider the epidemiology of infectious disease spread. A number of animal diseases have been studied in this way: avian influenza (Dent et al., 2008; Fournie et al., 2013; Martin et al., 2011), equine influenza (Firestone et al., 2011b, 2012), tuberculosis in wildlife (Drewe et al., 2011; Porphyre et al., 2008), livestock-associated MRSA (Ciccolini et al., 2012) and foot-and-mouth disease (FMD) in livestock (Green et al., 2006; Kao et al., 2006; Kiss et al., 2006; Ortiz-Pelaez et al., 2006; Shirley and Rushton, 2005). Network analysis can also help explain the pattern of known transmission events, thus providing useful information for future disease outbreaks. Indeed, Firestone and colleagues (Firestone et al., 2012) found close agreement between a distance-based transmission kernel, and a combined movement and proximity network at capturing the geographical pattern of equine influenza spread between premises. Such analyses can provide important information for targeting surveillance and control efforts, by enabling identification of key players that occupy important positions in connecting the network (Albert et al., 2000; Callaway et al., 2000; Carne et al., 2013; Christley et al., 2005; Ciccolini et al., 2014; Fournie et al., 2013; Girvan and Newman, 2002; Jonkers et al., 2010; Kao et al., 2006; Kitsak et al., 2010; Ortiz-Pelaez et al., 2006; Shirley and Rushton, 2005).

To date, most network-based models for livestock disease spread have considered only the networks of animal movements (Fournie et al., 2013; Kao et al., 2007; Kiss et al., 2006; Martin et al., 2011; Ortiz-Pelaez et al., 2006; Tildesley et al., 2011; Woolhouse et al., 2005). However, during the UK's FMD epidemic in 2001 a livestock movement ban was rapidly implemented, and the majority of subsequent transmissions were attributable to local mechanisms of spread (Gibbens et al., 2001). While several network-based models have considered networks of proximity (being within a certain distance of an infected premises (IP)) (Dent et al., 2008; Firestone et al., 2011b, 2012; Webb, 2005) or incorporated local transmission into network-based models (Green et al., 2006; Jonkers et al., 2010), these have been in relation to Euclidean distance between farms' point locations. However, transmission pathways for FMD are likely to be considerably more closely related to farm premises contiguity in terms of field edges being proximal, than to distance between farm premises point locations, since local transmission was thought to be comprised of direct contact of livestock over fence-lines, movement of contaminated fomites by people, vehicles, machinery, or blown by wind between proximal pastures, during the UK's 2001 epidemic (Gibbens et al., 2001). This is supported by contiguous premises (CPs), as found on-the-ground, being considered to be at increased risk of subsequently becoming infected (Anderson, 2002). However, spatial spread was described in mathematical models by a transmission kernel, described in the General Introduction (Figures 1.1 and 1.2), which was also based on distance between premises' point locations. Given that distance between premises' point locations do not accurately reflect premises' contiguity in terms of their fields (Flood et al., 2013), some inaccuracies of the model predictions may be due to point distances not accurately capturing the most-likely local transmission routes.

In this chapter networks are created based on contiguity of premises, constructed using fine-scale maps of the farming landscape for an area of southern Scotland. This was previously identified as being at high risk for FMD spread in the event of a future incursion in Scotland (Porphyre et al., 2013). The presence of landscape features running the length of otherwise shared boundaries were taken into account to study their impact on patterns of contiguity and network structure - in particular rivers and railways for which there is evidence from the 2001 epidemic of them acting as barriers to transmission (Bessell et al., 2008). In order to detect these landscape features over a much larger area than that studied in Chapter 2, a process for automating their identification first had to be created.

Therefore, the initial aim was to create an automated procedure that accurately identified when landscape features separated map-based CPs according to definitions ‘All $<$15m’ and ‘Shared boundary’, as compared to visual identification of the features. Once this had been achieved, the aim was to use this to identify how connected or fragmented the livestock farming landscape was in terms of map-based contiguity, and to see if premises that occupy key positions in the network in terms of connecting sub-populations of contiguous premises clusters existed and could be identified and characterised. Such farm premises could be targeted for disease control efforts in the event of any future FMD outbreaks. The hypothesis was that if premises were highly connected within the map-based CP networks (i.e. a larger proportion of premises were in the Giant Component (GC)), that there would be a small number of premises that could be removed from the network that would result in a considerable decrease in GC size. Whether this removal of premises from the networks translated into an actual decrease in predicted number of FMD infected premises and outbreak duration in the event of an outbreak was then investigated by running stochastic model simulations on the networks.

## 4.2 Methods

### 4.2.1 Automated procedure for detecting landscape features separating map-based CPs

#### Data

The two IACS 2006 datasets used in Chapter 2, covering areas of approximately 15x15km in Aberdeenshire and Ayrshire, were used in the development of the automated procedure. When examined visually, the OS MasterMap® landscape data had been in a single layer of a shapefile, visualised according to the column headings 'DescGroup' or 'Theme'. This meant that while different landscape features (e.g. rivers, roads) could be distinguished from one another visually, they could not be by the computer. Thus, the features needed to be separated into different shapefiles in order that an automated procedure could be created that could detect the difference between landscape feature types. Landscape feature datasets were created using both Ordnance Survey (OS) MasterMap® topographic data (scale 1:2500-1:10,000) and OS Meridian™2 data (scale 1:50,000) provided by the Ordnance Survey.

The rivers dataset was created by first creating datasets where DescGroup='Inland Water' for both OS MasterMap® topographic lines and areas, then selecting out from this where the lines were within the areas (since the areas correspond to where inland water features are double lines in the line features, which in turn indicates where water features are >2m wide). The ditches dataset was created by selecting all the 'Inland Water' OS MasterMap® topographic lines, and removing from the selection where they were within the 'Inland Water' areas (i.e. to get the opposite lines to those selected as being rivers). The railway dataset was the OS Meridian™2 rail line data, with small sections of railway added from the OS MasterMap® topographic line dataset where DescGroup='Rail'. These additions were made where track segments appeared to be missing from the OS Meridian™2 dataset in rural areas and included sections of railway between Airdrie/Bathgate and Linlithgow/Bowness.

Two datasets were created and tested for roads/tracks. The first was composed of OS MasterMap® topographic line data where Theme='Land; Roads Tracks And Paths'. While manageable on a small scale, obtaining such a detailed dataset (composed of >6,000,000 records) was, in the end, computationally not feasible at the national level. Therefore, despite the exclusion of tracks from the dataset, the OS Meridian™2 road data (line shapefiles: motorway, a road, b road, minor_rd) were assessed.

### Description of the automated procedure

The automated procedure was created using Model Builder in ArcGIS version 9.3 (ESRI, Redlands, CA, USA), and is comprised of two processes. It was designed using the Ayrshire sample only, and was subsequently applied to the Aberdeenshire sample.

The first component process works to find the area of intersection between farm premises pairs that are <15m apart at their field edges. It first draws a 7.5m buffer around each farm premises, creates a duplicate layer of these, finds where they intersect, and calculates the area of this (in $m^2$). The resulting shape-file needs to then be opened in ArcGIS, and the intersections extracted only where the intersections were between two *different* farm premises (with different Parish-Holding codes). The second component process draws a buffer around the landscape feature dataset under study, finds the intersection of this with the farm-farm intersection areas (found in the first process), and calculates the area of this new intersection (in $m^2$) over the whole of each farm-farm intersection. For illustration of these processes, see Figure 4.1.

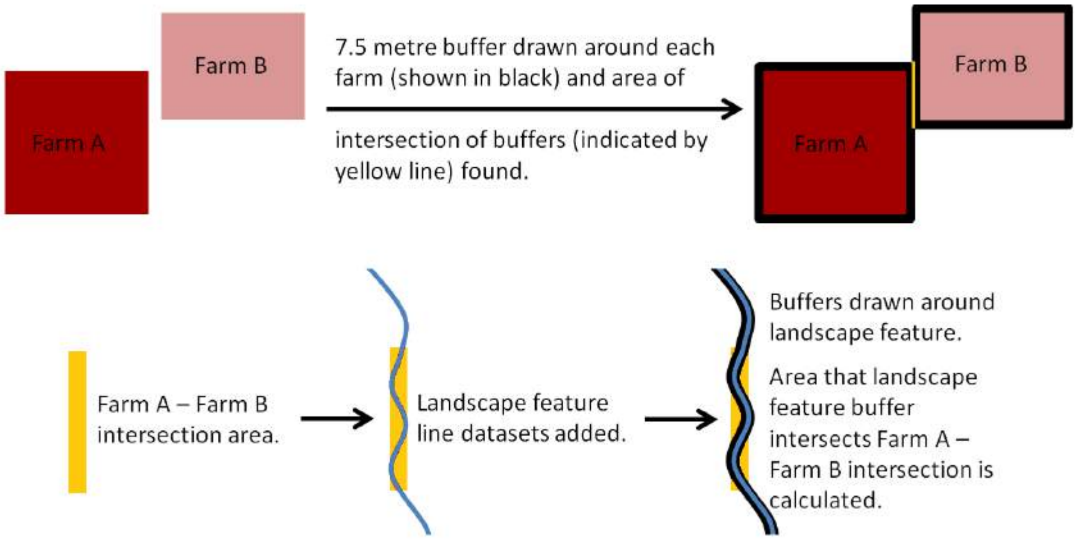



Figure 4.1: Illustration of the component processes used in the automated procedure, using the example of a river between two premises. Top: finding the intersection area between CPs; bottom: finding the intersection of the CP intersection and the landscape feature buffer.

### Identifying optimal conditions

**Objective:** To identify the optimal buffer size to use for each landscape feature, and then to identify the optimal cut-off percentage that the selected buffer takes up of farm-farm intersections to define presence/absence of the landscape feature in question.

Three different buffer sizes were tested for each landscape feature dataset: 15m, 20m and 25m, and for each of these sizes, two buffer 'end' types were tested: flat and round. After running the two processes for the five landscape feature datasets, the datasets were joined, and the percentage proportion that the landscape feature buffer took up of the farm-farm intersection calculated.

Box plots were graphed to visualise the spread of proportions of the CP intersections that the landscape feature buffers took up, according to whether the feature

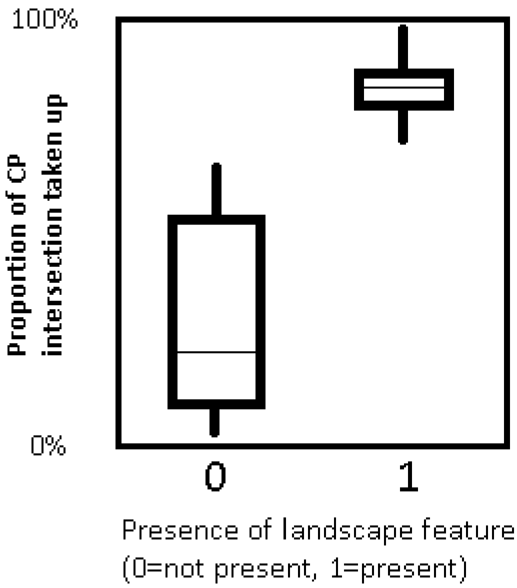



Figure 4.2: Example boxplot showing the spread of proportions of the CP intersections that the landscape feature buffers took up, by feature presence (=1) or absence (=0).

was classified as being present (=1) or absent (=0) under visual inspection, for each buffer size/end type (see example boxplot, Figure 4.2). To identify the best buffer size and end type combination together with the optimal cut-off percentage of the farm-farm intersection that the landscape feature buffer needed to take up to be classified as separating the two premises, several measures were used.

Receiver Operating Characteristic (ROC) curves were plotted in R using package 'ROCR' (Sing et al., 2005). These show the trade-off between the true positive rate (equivalent to sensitivity) and false positive rate (equivalent to 1 - specificity) with different cut-off points for percentage the landscape buffer takes up of the farm-farm intersection. The Area Under the Curve (AUC) (which measures the area under the ROC curve) was calculated using R package 'OptimalCutpoints' (Lopez-Raton and Xose Rodriguez-Alvarez, 2013). The higher the AUC, the better the buffer size/end type at discriminating between the presence/absence of the landscape feature overall. The maximum True Skill Statistic (TSS)/Youden Index (sensitivity + specificity - 1) for each buffer size/end type was also calculated along with the associated cut-off values.

The buffer size/end type combination was chosen first on the basis of which had the highest AUC within each landscape feature dataset. The optimal cut-off percentage was taken to be an integer value between the percentage of farm-farm intersection taken up by the optimal buffer type associated with the highest TSS and the percentage below that, but closest to the observed percentage associated with the highest TSS.

The automated process was then run for the Aberdeenshire sample, using the optimal buffer type and cut-off percentages identified. The identification of landscape features between CPs was then studied for both samples to find the agreements / disagreements between the automated process and visual identification methods. The sensitivity, specificity and concordance were calculated for the automated process, where the gold standard was visual identification of landscape features. Additionally, the True Skill Statistic (where TSS = (sensitivity + specificity - 1)) was calculated in preference to Kappa as it provides a similar measure of accuracy of the discrimination of two methods of landscape feature identification, without being affected by prevalence (Allouche et al., 2006).

#### Comparison of CP definitions using automated procedure and visual inspection

**Objective:** To compare the results obtained for the comparison of approximation measures of contiguity with map-based measures, where identification of landscape features is by visual inspection (as in Chapter 2), and by automated procedure.

The analyses conducted in Chapter 2 were re-run for the two sample areas, with the presence/absence of landscape features now determined by the automated procedure using the optimal conditions outlined above. The same map-based CP definitions (i-ix) were used to compute the sensitivity, PPV and TSS against the approximation methods (a-h), as described in Chapter 2. The difference between these, based on the automated procedure, and the original values, based on visual inspection, was inspected. The number and proportion of map-based CPs captured with increasing Euclidean distance between farm premises point locations was examined, and compared to that of map-based CPs based on visual inspection. For these analyses, only OS Meridian$^{\mathrm{TM}}$2 road data was used, since this would be the dataset used for scaling up the automated procedure.

The network density was calculated for the map-based CP networks based on the automated procedure. The mean degree for each of these networks were also calculated.

### 4.2.2 Networks of map-based CPs for an area of southern Scotland

#### Data

The same dataset as that used in Chapter 3 was used. This is described in more detail in Chapter 3's Methods section. Briefly, 4767 farm premises were selected on the basis of location and having any cattle, sheep, pigs, deer or goats recorded in the June 2011 Agricultural Census. Networks of these premises were then created based on the map-based CP definitions defined in Chapter 2's Table 2.1, such that nodes of the network represent livestock premises that were linked by an edge where they were considered to be contiguous to one another under the map-based definition in question.

### Network analysis

The 'igraph' package (Csardi and Nepusz, 2006) was used in R (R Core Team, 2013) for conducting network analyses. Descriptive analyses were carried out for the networks based on the four contiguity definitions: 'All <15m' (i), 'All <15m - river/railway' (vi), 'Shared boundary' (viii) and 'Shared boundary - river/railway' (ix).

The degree distributions of premises in the networks were examined (i.e. the frequency distribution of number of map-based CPs sample premises had), and the degree assortativity calculated. Degree assortativity is calculated by:

$$r = \frac{\sum_{xy} xy(e_{xy} - a_x b_y)}{\sigma_a \sigma_b},$$

where $e_{xy}$ is the proportion of network edges that join nodes with degree $x$ and $y$, $a_x$ is the proportion of edges that start and end at nodes of degree $x$, and $b_y$ is the proportion of edges that end at nodes of degree $y$. It lies between +1 and -1, where +1 indicates perfect assortative mixing, and shows the degree to which connected nodes share the same characteristics (Newman, 2002). Since IACS data for England were not available, English premises that were CPs of Scottish premises along the Scotland-England boundary could not be identified, and there were consequently imposed edge effects on the data. To get an idea of the likely impact of this edge effect on the degree distribution of the network, the mean degree was calculated first only for premises within the sample, and second including premises contiguous to the sample premises along the top (Scottish) bounding edge of the selected area, since there was available data for this artificial edge. Degree distribution by premises species composition was studied (for categories of cattle only, sheep only, cattle and sheep, cattle/sheep and pigs).

In order to assess the impact different premises had on the connectedness of the premises network, the decay in giant component (GC) size was studied with each premises (node) removal, without replacement. This was first calculated for

1000 simulations where premises were removed in random order, and then where premises were removed in order of the following network centrality measures: betweenness, closeness, degree and eigenvector. The centrality measures were recalculated following removal of each premises, and if more than one premises had the same highest centrality score, one premises was chosen at random to be removed. Farms were also removed from the network in order of k-core membership, where a k-core is a subgraph where each node has a degree of at least k (and hence the cores form layers of subgraphs) (Seidman, 1983). The centrality measure that gave the greatest reduction in GC size was then used in further analyses.

When removing premises in order of the chosen centrality measure, several premises would be removed with little impact on the GC size, but removal of a subsequent premises would result a sudden large decrease. Farms removed preceding the first three significant decreases in GC size, and which did not themselves have a large impact, were visually inspected on maps of the IACS data field locations to ascertain their potential contribution to the large decrease.

Initial GC size was compared between CP definitions to study the fragmentation effect that rivers and railways have on the farming landscape. The decrease in giant component size with removal of the first 100 premises with highest centrality of the chosen measure was studied to ascertain the robustness of the method in breaking up the giant component across different definitions of contiguity. Since the top 100 premises with highest centrality of the chosen measure were not exactly the same, the effect of removing the first 100 under each of the four main contiguity definitions was looked at in turn for each of the definitions. The decision to remove the first 100 farms was arbitrary.

### Mathematical modelling

N.B. The mathematical modelling was performed by Thibaud Porphyre.

In order to examine the importance of the first 100 premises with the highest centrality of the chosen measure in connecting the contiguity network when transmission probability is $<1$, as would be the case in a foot-and-mouth disease outbreak, simulations of a modified version of the Keeling et al. (2001) model were run on the network. First, a model where transmission was only possible between premises contiguous to one another under the contiguity definition of the network in question, with transmission parameter of $\rho$ (and $\delta = 0$ given no background transmission, in Equation (8.5), Appendix 1). Second, with a transmission parameter of $\rho$ between CPs, in addition to a low level rate of transmission at distances up to 60km outwards from an IP point location (transmission parameter $\delta = 2.81 \times 10^{-6}$ in Equation (8.5), Appendix 1). These contiguity-based model formulations are described in detail in Appendix 1.

The mean epidemic size (number of IPs) and duration was calculated for 10,000 simulations for the four networks of contiguity (i, vi, viii and ix, above) for each removal of the 100 premises with highest centrality of the chosen measure identified by the network based on contiguity definition 'All $<$15m' (i, above). A single seed was randomly selected for each simulation.

The distributions of the frequency with which the 100 premises with highest centrality of the chosen measure in the 'All $<$15m' contiguity network became IPs in Chapter 3's simulations were studied for both the distance and contiguity model simulations.

### Statistical analysis

Univariate logistic regression analysis was performed on the dataset using the outcome of being one of the 100 premises with highest centrality of the chosen measure. This was to see whether any premises variables were associated with an increased odds of being one of the top 100 premises with highest centrality. This was performed for the two definitions 'All <15m' (i) and 'All <15m - river/railway' (vi).

The following variables from the June 2011 agricultural census were included in the analysis:

1. Presence/absence of cattle
2. Presence/absence of sheep
3. Number of cattle
4. Number of sheep
5. Species composition (cattle and sheep versus other compositions)
6. Do/do not rent out land seasonally
7. Do/do not rent in land seasonally

Six other variables derived from IACS 2011 were also incorporated:

1. Total premises field area (hectares)
2. Number of contiguous premises (all <15m field edge)
3. Number of fields
4. Number of land parcels (where a parcel is composed of fields <15m apart)
5. Fragmentation index: $FI = 1 - \frac{\sum(a^2)}{A^2}$, where $a$ is the area of each land parcel and $A$ is the total farm area, based on Ilbery (1984). Thus zero indicates no fragmentation, and values tending towards one indicate a high level of fragmentation.

6. Premises is part of a single-/multi- premises farm business

The number of cattle, number of sheep, premises area, and number of land parcels were highly skewed and were therefore categorised based on quartile values. The fragmentation index values were categorised to correspond with those used by Ilbery (1984) (N.B. the fragmentation index used here was the inverse of that used by Ilbery (1984)).

## 4.3 Results

### 4.3.1 Automated procedure for detecting landscape features separating map-based CPs

#### Identifying optimal conditions

Box plots showing the distribution of the percentage proportion the landscape feature buffers take up of the farm-farm intersection area using different buffer sizes and end types, against presence/absence of the feature as determined by visual classification, for each landscape feature dataset, can be seen in Appendix 2 (Figures 9.1 to 9.5). These enable visualisation of whether there is a clear difference in the proportion of a CP intersection area taken up by a landscape feature buffer when the landscape feature is and is not present, respectively.

The AUCs and cut-off percentages associated with the highest TSS values can be seen for the different landscape feature datasets and buffer types in Table 4.1. Different landscape features and datasets had varying best-performing buffer sizes and end-types. This simply reflects the accuracy of the landscape feature data and the shape of the landscape feature in question: given lower resolution data, e.g. OS Meridian™2 compared to OS MasterMap® roads, a wider buffer may be required since the positioning of the roads between CPs is not as accurate; given less linear landscape features, such as rivers compared to roads, a wider buffer may be required since the river may not lie as neatly between any two premises. The following points summarise how the buffer sizes and types performed for each landscape feature dataset:

- Both round- and flat-ended 25m buffers performed the best for discriminating between presence/absence of rivers (both AUC=0.999, 95% CI 0.999-1). Flat-ended 25m buffers were chosen. The maximum TSS for this buffer type (0.991) corresponded with a cut-off value of 69.8% of the farm-farm intersection being taken up by the buffer. The next highest observed percentage of a farm-farm intersection taken up by the flat-ended 25m river buffer was 56.5%.
- Flat ended 25m buffers performed best for ditches (AUC=0.981, 95% CI 0.970-0.992). The maximum TSS for this buffer type (0.933) corresponded with a cut-off of 55.1%, with the next highest observed percentage of a farm-farm intersection taken up being 54.7%.
- For OS MasterMap® roads, both round- and flat-ended 15m buffers had the same, perfect, AUC (1, 95% CI 1,1) and TSS (1). Round-ended 15m buffers were used since the cut-off percentage associated with the highest TSS was higher (99.2%) compared to the flat-ended 15m buffers (95.2%). The next highest observed percentage of a farm-farm intersection taken up was 94.8%.
- For OS Meridian™2 roads, flat-ended 25m buffers were optimal (AUC=0.998, 95% CI 0.995-1.001). The highest TSS value (0.880) corresponded with a cut-off percentage of 71.2%, with the next highest observed percentage of a farm-farm intersection taken up by the buffer being 64.3%.
- Only one CP pair were separated by a railway in the Ayrshire sample, with the result that every buffer size and end type performed perfectly at identifying when the railway was present. The cut-off associated with the

maximum TSS was 100%, with the next highest observed percentage of farm-farm intersection taken up being 35.6%.

| | Flat 15m | | | Round 15m | | | Flat 20m | | | Round 20m | | | Flat 25m | | | Round 25m | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AUC (95% CI) | Cut-off | Max. TSS | AUC (95% CI) | Cut-off | Max. TSS | AUC (95% CI) | Cut-off | Max. TSS | AUC (95% CI) | Cut-off | Max. TSS | AUC (95% CI) | Cut-off | Max. TSS | AUC (95% CI) | Cut-off | Max. TSS |
| **OS Meridian2 Roads** | 0.994 (0.988, 1.000) | 44.4 | 0.847 | 0.994 (0.988, 1.000) | 44.4 | 0.847 | 0.994 (0.988, 1.000) | 53.7 | 0.850 | 0.994 (0.988, 1.000) | 53.7 | 0.850 | 0.998 (0.995, 1.001) | 71.2 | 0.880 | 0.994 (0.988, 1.000) | 44.4 | 0.847 |
| **OS MasterMap Roads** | 1.000 (1.000, 1.000) | 95.2 | 1.000 | 1.000 (1.000, 1.000) | 99.2 | 1.000 | NA | NA | NA | 0.997 (0.994, 1.001) | 100.0 | 0.997 | 0.994 (0.989, 1.000) | 95.2 | 0.993 | 0.992 (0.986, 0.998) | 100.0 | 0.990 |
| **OS MasterMap Rivers** | 0.999 (0.998, 1.000) | 55.7 | 0.991 | 0.999 (0.998, 1.000) | 55.8 | 0.991 | 0.999 (0.998, 1.000) | 64.3 | 0.991 | 0.999 (0.998, 1.000) | 64.3 | 0.991 | 0.999 (0.999, 1.000) | 69.8 | 0.991 | 0.999 (0.999, 1.000) | 69.8 | 0.991 |
| **OS MasterMap Ditches** | 0.985 (0.978, 0.993) | 48.1 | 0.936 | 0.981 (0.973, 0.990) | 48.5 | 0.930 | 0.985 (0.978, 0.993) | 55.1 | 0.933 | 0.981 (0.972, 0.990) | 58.8 | 0.939 | 0.988 (0.982, 0.995) | 55.1 | 0.933 | 0.984 (0.976, 0.992) | 59.5 | 0.936 |
| **OS Meridian2/ MasterMap Railways** | 1.000 (1.000, 1.000) | 100.0 | 1.000 | 1.000 (1.000, 1.000) | 100.0 | 1.000 | 1.000 (1.000, 1.000) | 100.0 | 1.000 | 1.000 (1.000, 1.000) | 100.0 | 1.000 | 1.000 (1.000, 1.000) | 100.0 | 1.000 | 1.000 (1.000, 1.000) | 100.0 | 1.000 |

Table 4.1: For each landscape feature dataset, the Area Under the ROC Curve (AUC) and associated 95% CIs, with optimal cut-off of landscape feature buffer as a percentage of the farm-farm intersection area (where TSS is maximised), and the maximum TSS, for different buffer sizes and end types. NA = process failed to run for flat-ended 20m buffers around OS MasterMap® roads. Ayrshire sample.

Based on the results presented above, the following buffer types and cut-off percentages were chosen for the landscape feature datasets:

- OS MasterMap® roads: round-ended 15m buffers, 98% cut-off;
- OS MasterMap® rivers: flat-ended 25m buffers, 68% cut-off;
- OS MasterMap® ditches: flat-ended 25m buffers, 55% cut-off;
- OS Meridian™2/MasterMap® railways: flat-ended 15m buffers, 98% cut-off;
- OS Meridian™2 roads: flat-ended 25m buffers, 70% cut-off.

These classifications resulted in perfect identification of OS MasterMap® roads and OS Meridian™2/MasterMap® railways in the Ayshire sample dataset (Appendix 2, Table 9.1). For OS MasterMap® rivers, three CP pairs were misclassified as having a river separating them when using the automated process (resulting in a TSS of 0.991); twenty-two CP pairs were misclassified as having a ditch separating them using OS MasterMap® ditches data (TSS=0.933). Six CP pairs were incorrectly classified as not being separated by a road using OS Meridian™2 roads data (TSS=0.880). When applied to the Aberdeenshire sample dataset, there were a small number of disagreements in landscape feature identification for all feature types (Appendix 2, Table 9.2).

The sensitivity of the automated process compared to the gold standard of visual identification was 100% for all landscape feature datasets in Ayrshire except OS Meridian™2 roads which had 88.0% sensitivity (Table 4.2). This was slightly lower in Aberdeenshire, with all landscape feature datasets having >85% sensitivity, apart from OS Meridian™2 roads which had 69.6%. The impact of this lower sensitivity in Aberdeenshire is that a larger number of false negatives are being picked up - i.e. landscape features are not identified as being present between two CPs, when in reality (by visual map inspection) they are. This in turn will result in a larger number of CPs remaining classified as such when the map-based CP definition is restricted from 'All <15m' to exclude where premises are separated by a landscape feature. Specificity was perfect for both road datasets in both sample areas, and all other datasets had specificities >85%. Concordance was >85% for all datasets within both samples. However, TSS was <0.850 for OS Meridian™2 roads and OS MasterMap® ditches (0.696 and 0.739, respectively)(Table 4.2).

| | | Sensitivity | Specificity | TSS | Concordance |
|---|---|---|---|---|---|
| Ayrshire sample | OS MasterMap Roads | 100.0 | 100.0 | 1.000 | 100.0 |
| | OS MasterMap Rivers | 100.0 | 99.1 | 0.991 | 99.2 |
| | OS MasterMap Ditches | 100.0 | 93.3 | 0.933 | 93.8 |
| | OS Meridian2/ OS MasterMap Railways | 100.0 | 100.0 | 1.000 | 100.0 |
| | OS Meridian2 Roads | 88.0 | 100.0 | 0.880 | 98.3 |
| | | | | | |
| Aberdeenshire sample | OS MasterMap Roads | 91.3 | 100.0 | 0.913 | 98.7 |
| | OS MasterMap Rivers | 90.0 | 97.9 | 0.879 | 97.4 |
| | OS MasterMap Ditches | 86.7 | 87.2 | 0.739 | 87.2 |
| | OS Meridian2/ OS MasterMap Railways | NA | NA | NA | NA |
| | OS Meridian2 Roads | 69.6 | 100.0 | 0.696 | 95.5 |

Table 4.2: Sensitivity, specificity, TSS and concordance for identification of landscape features by automated process, where visual identification of features is the gold standard, Ayrshire and Aberdeenshire samples. NA = there were no railways in the Aberdeenshire sample area.

### Comparison of CP definitions using automated procedure and visual inspection

The number of map-based CPs captured with increasing distance between point locations of farms where identification of landscape features was by automated procedure, captured the overall trend well, but not perfectly, compared to when features were identified by visual inspection, in both the Ayrshire and Aberdeenshire sample areas (Figures 4.3 and 4.4). Map-based CP definitions including ditches underestimated the number of farm premises in contact, while definitions excluding CPs separated by roads or rivers/roads overestimated them, compared to when features were identified visually. Plotting the agreement of the number of premises that were map-based CPs with increasing point distance between the sample when landscape features were identified by automated procedure and by visual inspection, clearly supported this, with map-based CP definitions including ditches having lines falling further from the x=y line than did the other definitions (Figures 4.5 and 4.5). Similar trends were observed for the automated procedure in determining the proportion of farms in contact within 0.25km distance bands between farm premises point locations, in both the Ayrshire and Aberdeenshire sample areas (Figures 4.7 and 4.8).

Using the automated procedure to classify presence of landscape features to inform map-based CP definitions, resulted in similar sensitivity values for comparison with approximation methods for defining CPs, when compared to identifying features by visual inspection. Map-based CP definitions based on the automated procedure resulted in differences in sensitivity of between -0.7 and 1.6, and -1.7 and 0.0 for definitions including ditches in Ayrshire and Aberdeenshire, respectively, and -0.1 and 0.8, and -1.5 and 0.6 for map-based CP definitions that did not include ditches, in Ayrshire and Aberdeenshire, respectively (Appendix 2, Tables 9.3 and 9.4).

The PPVs of map-based CP definitions against approximation methods were more affected by the identification of landscape features by automated procedure compared to visual identification, than sensitivity. The difference between PPVs of map-based CPs based on the automated procedure and on visual identification had a considerably larger range for definitions including ditches (Ayrshire: 0.4 to 6.9; Aberdeenshire: 0.7 to 11.0), than definitions not that did not include ditches (Ayrshire: -1.6 to 1.5; Aberdeenshire: -4.2 to 1.4) (Appendix 2, Tables 9.5 and 9.6).

TSSs of map-based CPs based on the automated procedure were only slightly different from the TSS values of map-based CPs where landscape features were identified visually. There was however a wider range of differences in TSS for CP definitions that included ditches (Ayrshire: -0.005 to 0.017; Aberdeenshire: -0.014 to 0.008) than for definitions that did not include ditches (Ayrshire:-0.001 to 0.008; Aberdeenshire: -0.015 to 0.004) (Appendix 2, Tables 9.7 and 9.8).

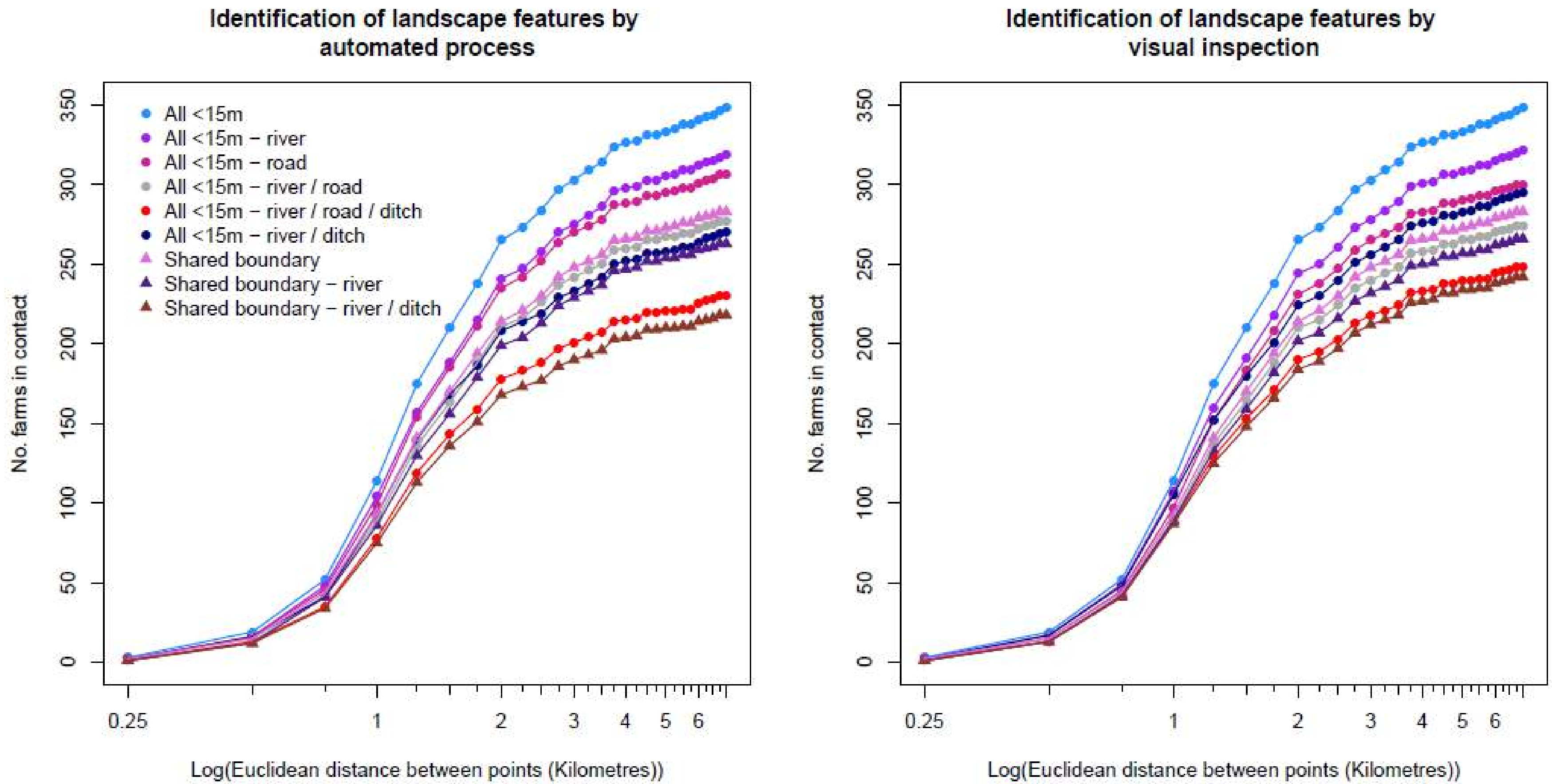



Figure 4.3: Number of premises in contact by map-based measures up to 7 km point distance, Ayrshire. Road data used was from OS Meridian$^{TM}$2.

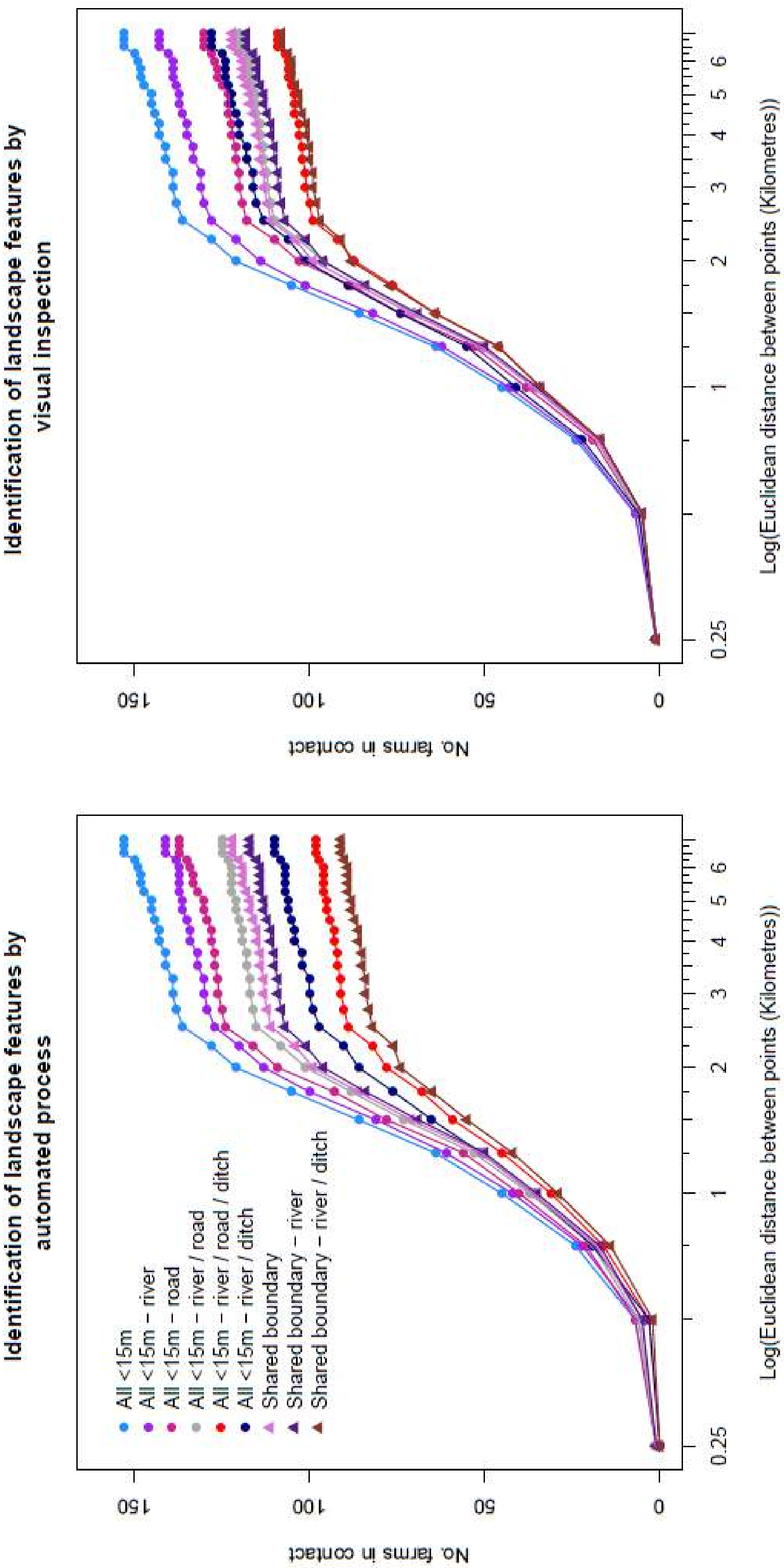



Figure 4.4: Number of premises in contact by map-based measures up to 7 km point distance, Aberdeenshire. Road data used was from OS Meridian$^{TM}$2.

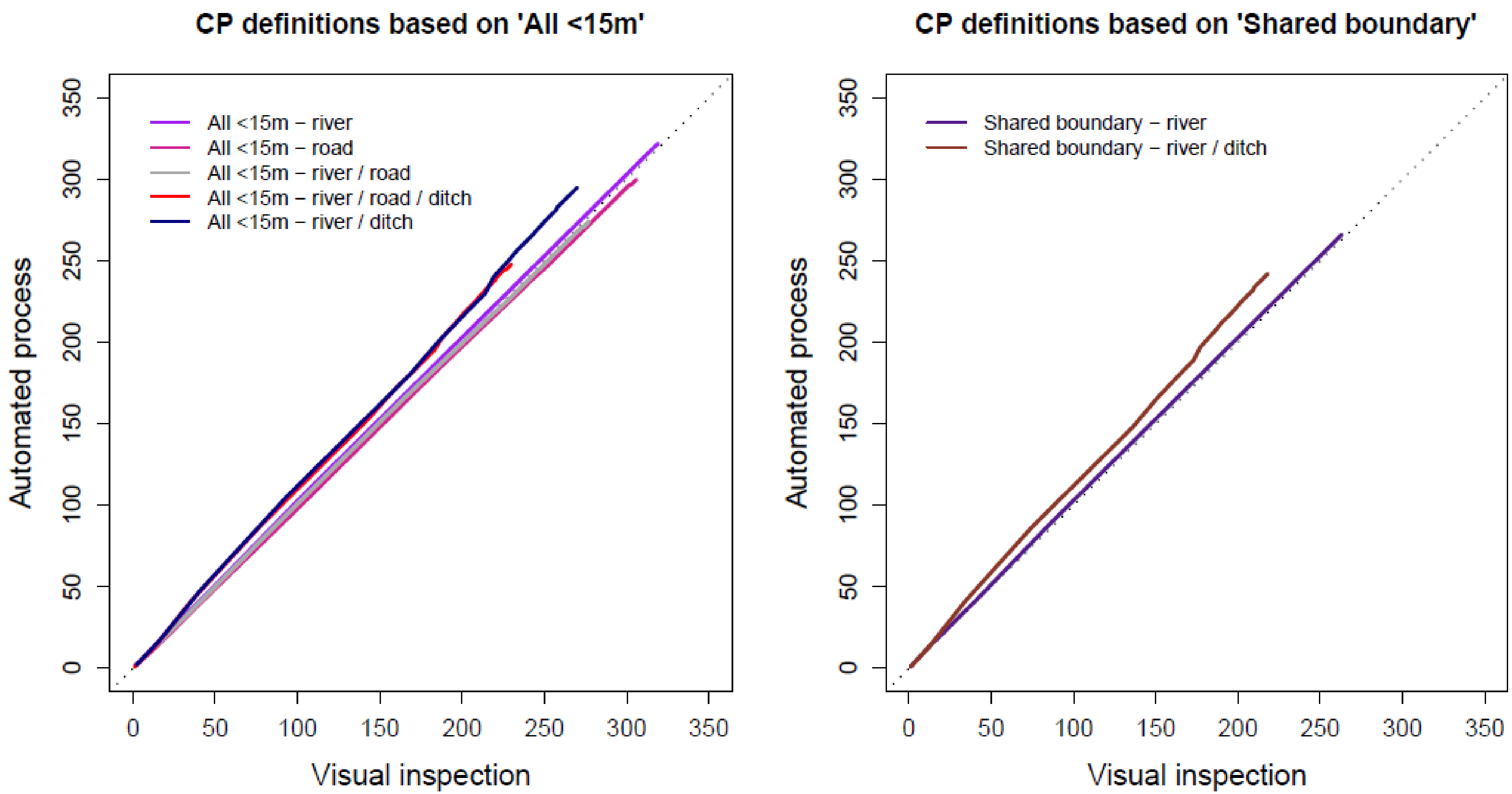



Figure 4.5: Agreement between visual inspection and automated process in the number of premises in contact by map-based measures up to 7 km point distance, Ayrshire. Road data used was from OS Meridian$^{TM}$2. The x=y line represents agreement between the 'All <15m' and 'Shared boundary' definitions, respectively, since these are unaffected by presence of landscape features.

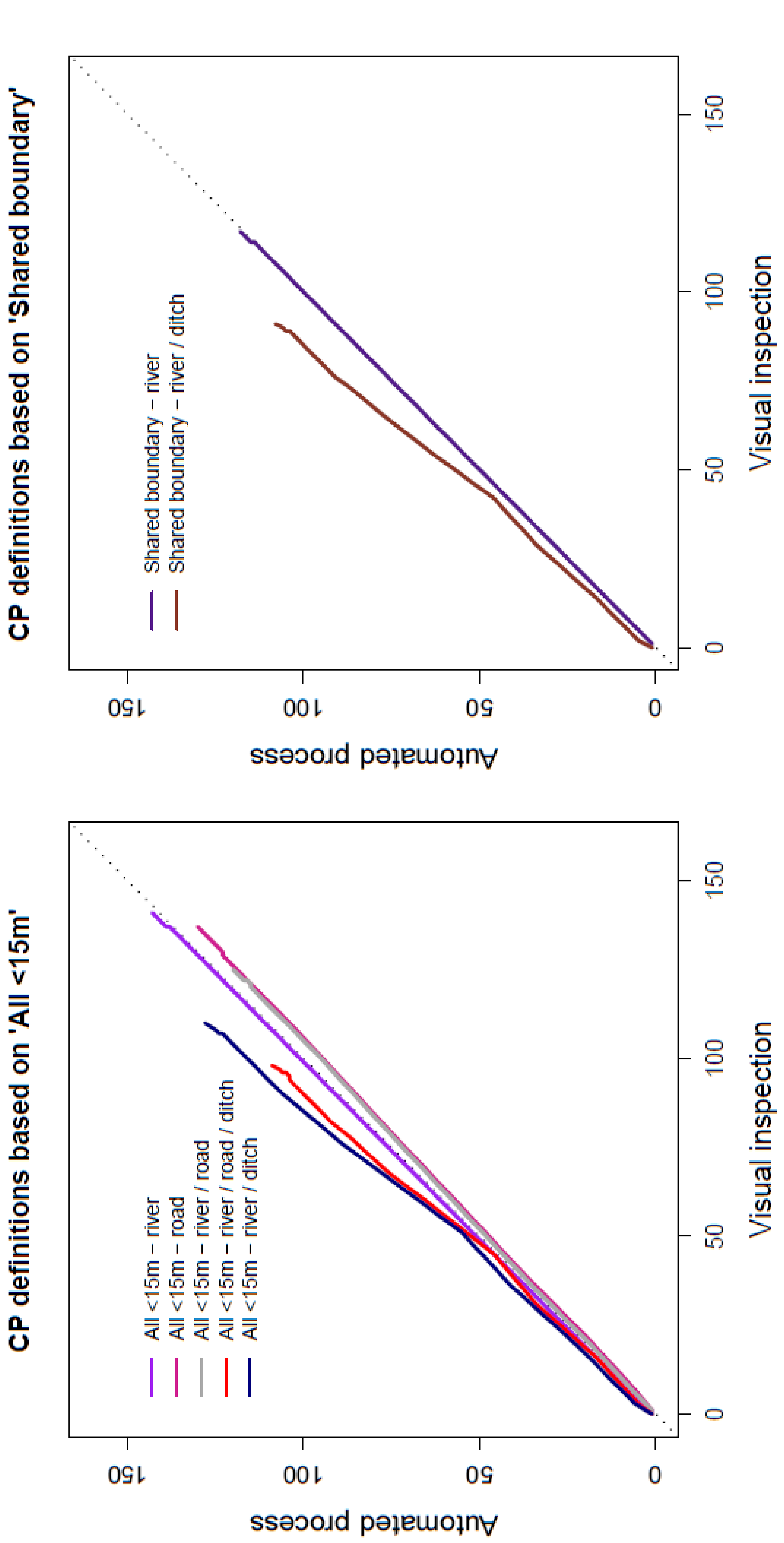



Figure 4.6: Agreement between visual inspection and automated process in the number of premises in contact by map-based measures up to 7 km point distance, Aberdeenshire. Road data used was from OS Meridian™2. The x=y line represents agreement between the 'All <15m' and 'Shared boundary' definitions, respectively, since these are unaffected by presence of landscape features.

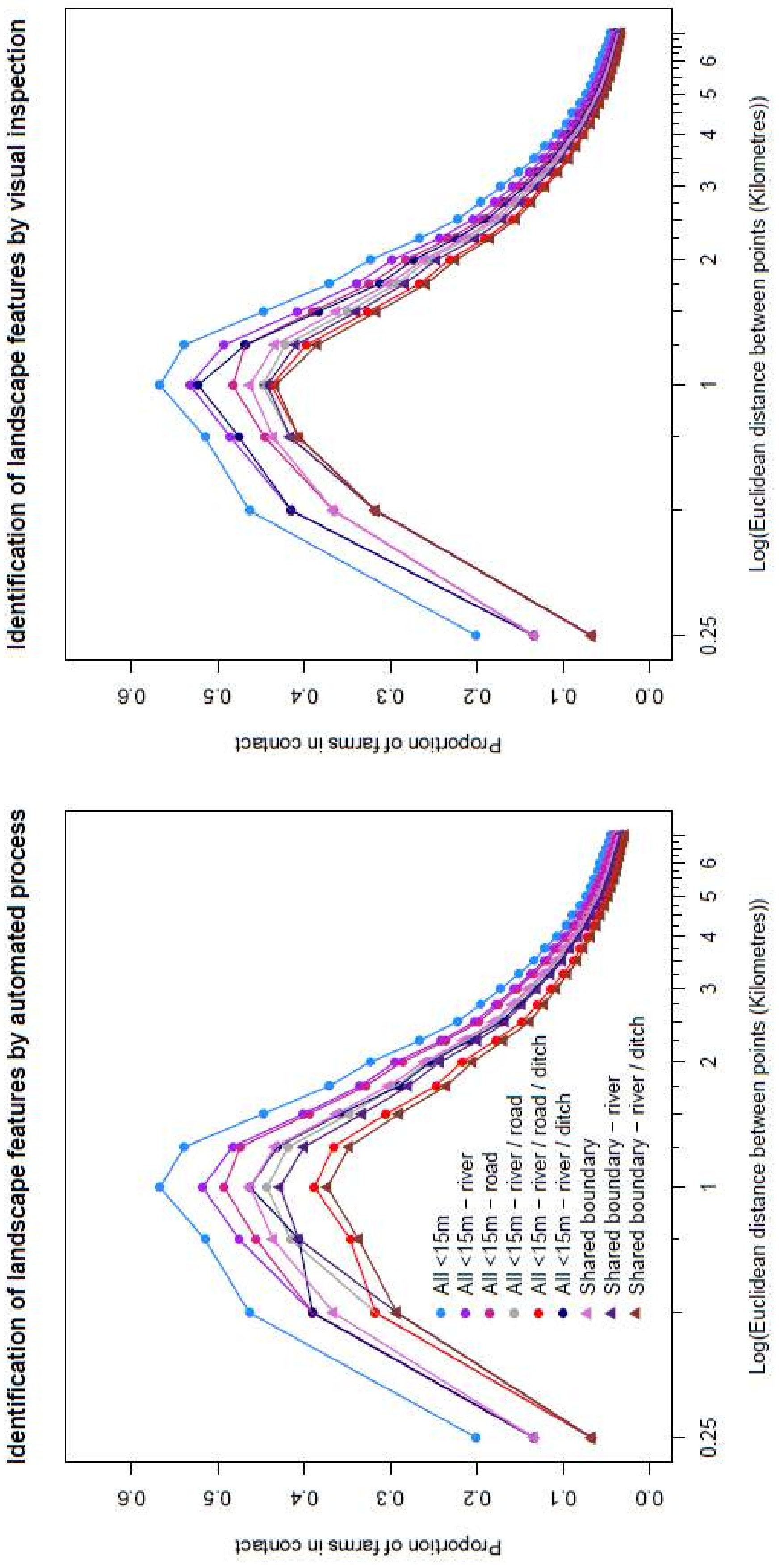



Figure 4.7: Proportion of premises in contact by map-based measures up to 7 km point distance, Ayrshire. Road data used was from OS Meridian$^{TM}$2.

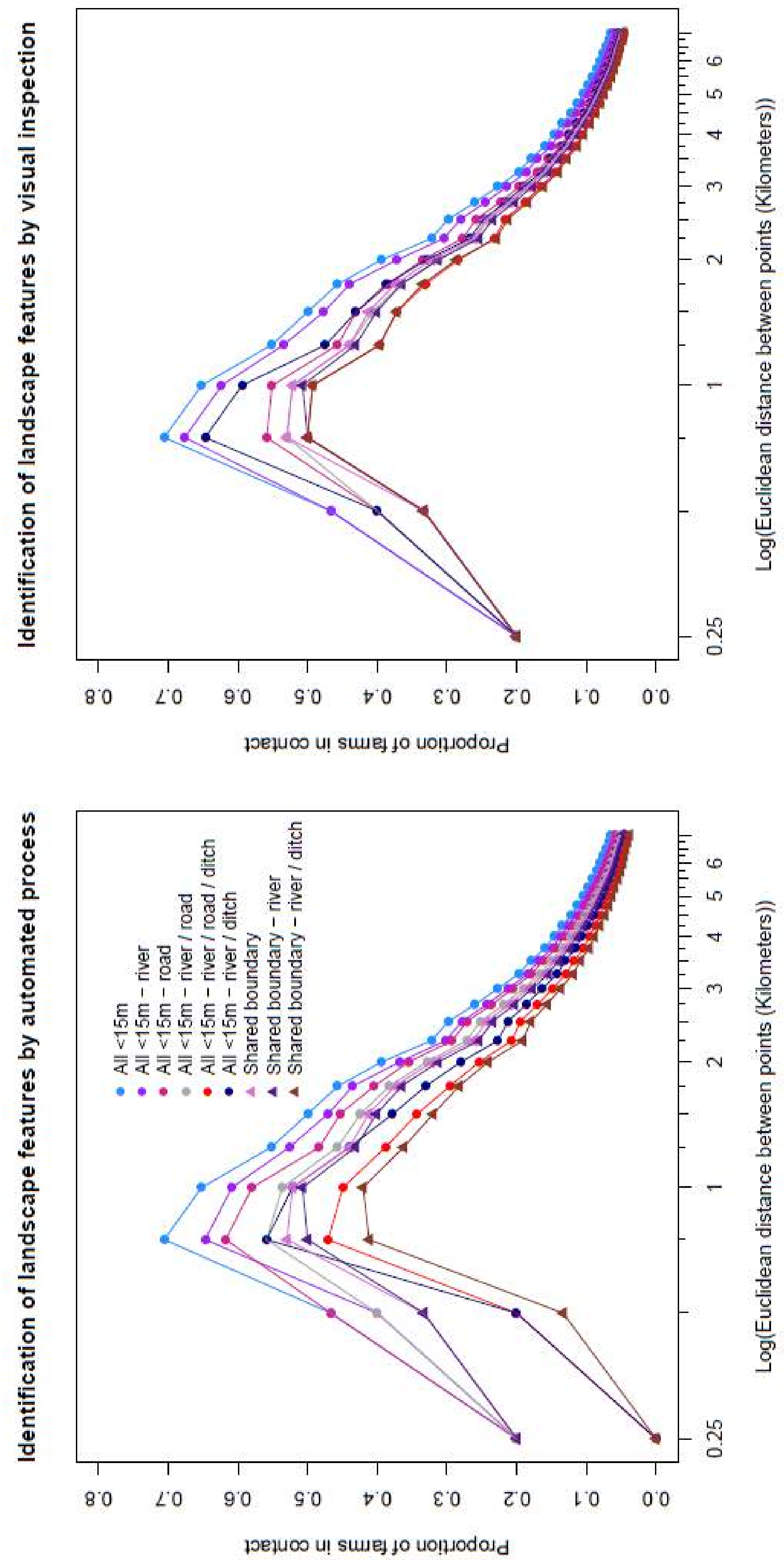



Figure 4.8: Proportion of premises in contact by map-based measures up to 7 km point distance, Aberdeenshire. Road data used was from OS Meridian$^{\mathrm{TM}}$2.

The mean degree of map-based contiguity networks was similar between CP definitions based on landscape feature identification by automated process and by visual inspection (Table 4.3). Definitions including ditches had the largest differences between mean degree using visual and automated methods of landscape feature identification in Ayrshire, with the smallest differences among cattle and sheep premises, and largest differences among cattle only premises within each of these definitions (Table 4.4). Similarly in Aberdeenshire, definitions including ditches had the largest differences between mean degree using visual and automated methods of landscape feature identification, but with the smallest differences observed among sheep only premises, and largest differences among cattle only premises within each of these definitions (Table 4.5). Unsurprisingly given that the automated procedure was developed on the Ayrshire data, the Ayrshire sample mostly had smaller percentage differences in mean degree between those calculated for landscape feature identification by visual and automated procedure (for definitions not including ditches, Ayrshire had between -1.14% to 2.51% change, and Aberdeenshire -1.64% to 6.73% change; for definitions including ditches, Ayrshire had between -6.36% to -9.35% change, and Aberdeenshire -5.56% to -12.73% change) (Table 4.3).

The densities of map-based contiguity networks where landscape feature identification was by automated procedure were identical to the densities where feature identification was by visual inspection for all definitions in Ayrshire, except for those including ditches (with maximum difference in density of -0.002 - an 11.11% change). In Aberdeenshire, definitions including ditches had differences of up to -0.004 (-17.39% change), and those including roads but not ditches had differences of 0.001 (which constituted changes of 4.35% and 4.76% for CP definitions 'All <15m - roads' and 'All <15m - rivers/roads', respectively) (Table 4.6).

| | Ayrshire | | Aberdeenshire | |
|---|---|---|---|---|
| | Visual inspection | Automated process | Visual inspection | Automated process |
| **All <15m** | 4.64 | 4.64 | 3.92 | 3.92 |
| **All <15m – rivers** | 4.27 | 4.23 | 3.65 | 3.59 |
| **All <15m – roads** | 3.98 | 4.08 | 3.27 | 3.49 |
| **All<15m – rivers / roads** | 3.62 | 3.68 | 3.01 | 3.16 |
| **All <15m – rivers / roads / ditches** | 3.30 | 3.09 | 2.70 | 2.55 |
| **All <15m – rivers / ditches** | 3.94 | 3.62 | 3.26 | 2.90 |
| **Shared boundary** | 3.72 | 3.72 | 3.07 | 3.07 |
| **Shared boundary – rivers** | 3.51 | 3.47 | 2.95 | 2.91 |
| **Shared boundary – rivers / ditches** | 3.21 | 2.91 | 2.67 | 2.33 |

Table 4.3: Mean degree of different map-based contiguity networks, when landscape features are identified by visual inspection or automated process. Road data used was from OS Meridian$^{\text{TM}}$2.

| | Cattle only | | Sheep only | | Cattle and sheep | |
|---|---|---|---|---|---|---|
| | Visual inspection | Automated process | Visual inspection | Automated process | Visual inspection | Automated process |
| **All <15m** | 4.68 | 4.68 | 3.06 | 3.06 | 5.13 | 5.13 |
| **All <15m – rivers** | 4.33 | 4.29 | 2.94 | 2.88 | 4.62 | 4.62 |
| **All <15m – roads** | 4.04 | 4.14 | 2.44 | 2.56 | 4.44 | 4.51 |
| **All<15m – rivers / roads** | 3.69 | 3.74 | 2.31 | 2.38 | 3.92 | 4.00 |
| **All <15m – rivers / roads/ ditches** | 3.44 | 3.19 | 2.00 | 1.88 | 3.36 | 3.26 |
| **All <15m – rivers / ditches** | 4.09 | 3.73 | 2.62 | 2.31 | 4.00 | 3.82 |
| **Shared boundary** | 3.81 | 3.81 | 2.38 | 2.38 | 3.97 | 3.97 |
| **Shared boundary – rivers** | 3.61 | 3.57 | 2.31 | 2.25 | 3.67 | 3.67 |
| **Shared boundary – rivers / ditches** | 3.39 | 3.04 | 2.00 | 1.75 | 3.13 | 2.95 |

Table 4.4: Mean degree of different map-based contiguity networks by species kept on holding, when landscape features are identified by visual inspection or automated process, Ayrshire. Road data used was from OS Meridian$^{\text{TM}}$2.

| | Cattle only | | Sheep only | | Cattle and sheep | |
|---|---|---|---|---|---|---|
| | Visual inspection | Automated process | Visual inspection | Automated process | Visual inspection | Automated process |
| **All <15m** | 4.14 | 4.14 | 2.62 | 2.62 | 4.14 | 4.14 |
| **All <15m – rivers** | 3.84 | 3.78 | 2.62 | 2.54 | 3.88 | 3.8 |
| **All <15m – roads** | 3.41 | 3.57 | 2.23 | 2.46 | 3.45 | 3.73 |
| **All<15m – rivers / roads** | 3.11 | 3.22 | 2.23 | 2.38 | 3.2 | 3.39 |
| **All <15m – rivers / roads/ ditches** | 2.7 | 2.41 | 1.85 | 1.85 | 2.96 | 2.88 |
| **All <15m – rivers / ditches** | 3.32 | 2.86 | 2.23 | 2 | 3.55 | 3.2 |
| **Shared boundary** | 3.19 | 3.19 | 1.92 | 1.92 | 3.29 | 3.29 |
| **Shared boundary – rivers** | 3.08 | 3.03 | 1.92 | 1.92 | 3.18 | 3.12 |
| **Shared boundary – rivers / ditches** | 2.68 | 2.24 | 1.62 | 1.46 | 2.98 | 2.63 |

Table 4.5: Mean degree of different map-based contiguity networks by species kept on holding, when landscape features are identified by visual inspection or automated process, Aberdeenshire. Road data used was from OS Meridian$^{TM}$2.

| | Ayrshire | | Aberdeenshire | |
|---|---|---|---|---|
| | Visual inspection | Automated process | Visual inspection | Automated process |
| **All <15m** | 0.021 | 0.021 | 0.027 | 0.027 |
| **All <15m – rivers** | 0.019 | 0.019 | 0.025 | 0.025 |
| **All <15m – roads** | 0.018 | 0.018 | 0.023 | 0.024 |
| **All<15m – rivers / roads** | 0.016 | 0.016 | 0.021 | 0.022 |
| **All <15m – rivers / roads / ditches** | 0.015 | 0.014 | 0.019 | 0.017 |
| **All <15m – rivers / ditches** | 0.018 | 0.016 | 0.023 | 0.019 |
| **Shared boundary** | 0.017 | 0.017 | 0.022 | 0.022 |
| **Shared boundary – rivers** | 0.016 | 0.016 | 0.021 | 0.021 |
| **Shared boundary – rivers / ditches** | 0.014 | 0.013 | 0.019 | 0.016 |

Table 4.6: Density of different map-based contiguity networks, when landscape features are identified by visual inspection or automated process. Road data used was from OS Meridian$^{TM}$2.

### 4.3.2 Networks of map-based CPs for an area of southern Scotland

#### Network analysis

There were no railways found to separate any contiguous premises where they were defined as having a shared boundary. Mean degree for the contiguity networks ranged between 2.73 and 3.65 for the four map-based CP definitions considered (Table 4.7). However, the degree distributions were overdispersed (Figure 4.9), with degree ranging from 0 to 47 for the network based on definition (i) ‘All <15m’, and from 0 to 46 for the network based on definition (vi) ‘All <15m - river/railway’. The degree-assortativity of the contiguity networks were 0.047 for definition ‘All <15m’, and 0.029 for definition ‘Shared boundary’.

The densities of all the networks were very small (<0.0008, Table 4.7), however, the giant components (GCs) contained between 57.1% (for ‘Shared boundary - river/railway’) and 90.6% (for ‘All <15m’) of the premises (Table 4.8). Taking rivers and railways into account in the definitions of contiguity caused a considerable reduction in initial GC size (Table 4.8).

Compared to random removal of premises from the network, removal based on network centrality measures reduced the GC size considerably more rapidly (Figure 4.10). Removal of premises based on core membership was not however always an improvement on random removal, although it performed better on the networks based on having a shared boundary than those based on being within 15m (Figure 4.10). Between network centrality measures, degree and eigenvector centrality performed similarly, and not as well as closeness and betweenness, in reducing GC size with premises removal. The most rapid reduction in GC size was achieved by removing premises in order of their betweenness. Removal of the first 100 premises in order of betweenness in the ‘All <15m’ network resulted in a 93.6% decrease in GC size from 4318 to 278 (results for the other CP definition networks can be seen in Table 4.8).

The proportion of GC size reduction for the networks, with premises removed in order of betweenness, was consistent between all definitions (Appendix 3, Figure 10.4). However, there was poor agreement between the top 100 premises with highest betweenness under each definition (Table 4.9). Despite this, a significant decrease in GC size was achieved across all four contiguity networks considered by removing the 100 premises with highest betweenness (network locations shown in Figure 4.11) identified in the 'All <15m' contiguity network (Figure 4.12).

Farms with sheep and no cattle had consistently lower mean degree than premises with cattle or cattle and sheep (Appendix 3, Figure 10.1). However, when looking more closely at the distribution of degree, this difference only held up consistently for the median against premises with cattle and sheep (Figure 4.13 and Appendix 3, Figure 10.2). Cattle only premises had higher median degree compared to sheep only premises for map-based CP definitions of premises <15m apart including rivers and roads only (Figure 4.13).

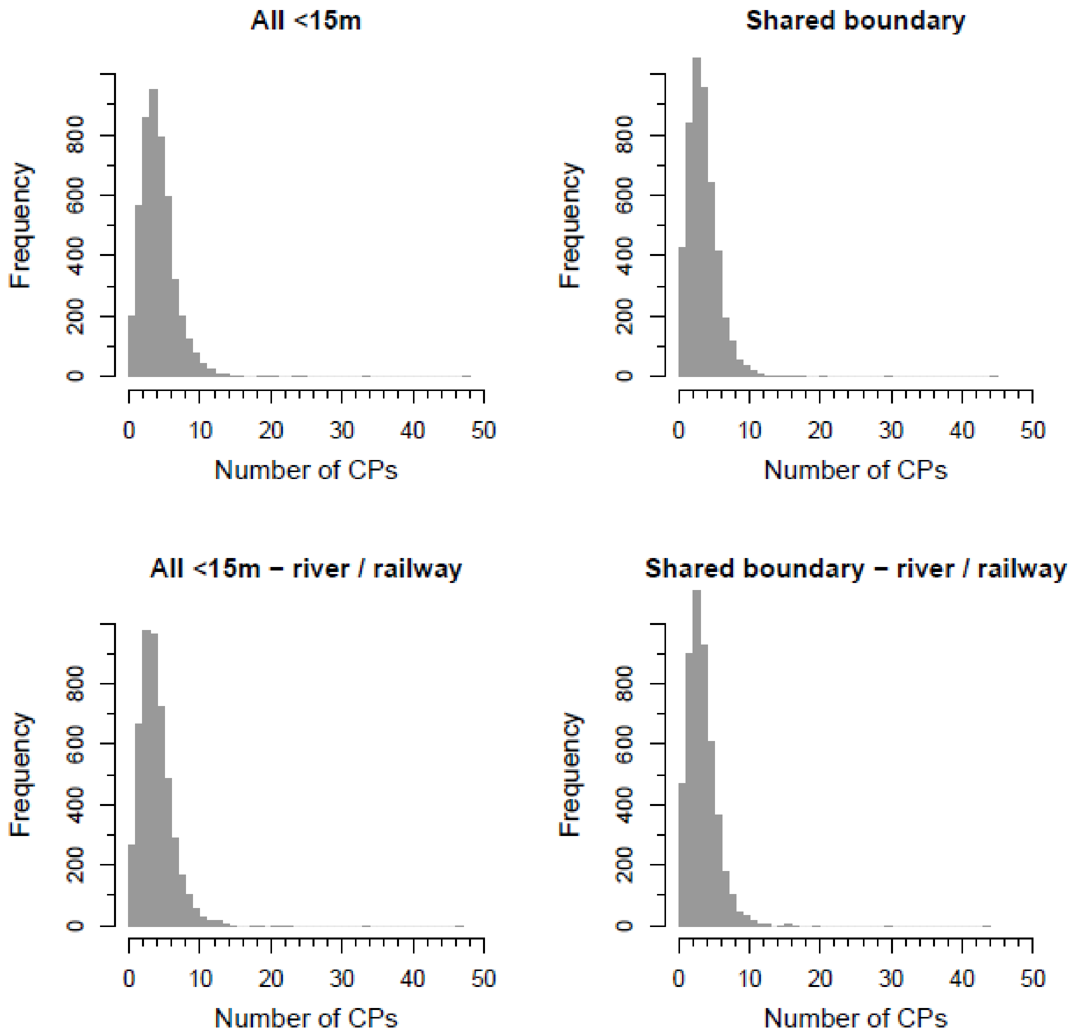



Figure 4.9: Distribution of degree, under different map-based CP definitions.

| Contiguous classification | Density | Mean degree (standard deviation) |
|---|---|---|
| All <15m | 0.00077 | 3.65 (2.44) |
| All <15m – river/railway | 0.00070 | 3.34 (2.35) |
| Shared boundary | 0.00060 | 2.86 (2.14) |
| Shared boundary – river/railway | 0.00057 | 2.73 (2.09) |

Table 4.7: Mean degree and density of networks based on different definitions of contiguity.

| Contiguous classification | Initial GC size | GC size after 100 premises with highest betweenness removed |
|---|---|---|
| All <15m | 4318 | 278 |
| All <15m – river/railway | 3982 | 229 |
| Shared boundary | 3592 | 158 |
| Shared boundary – river/railway | 2721 | 142 |

Table 4.8: Initial giant component (GC) size, and GC size following removal of the 100 premises with highest betweenness from the networks constructed based on different contiguity definitions.

| Contiguous classification | All <15m | All <15m – river/railway | Shared boundary |
|---|---|---|---|
| All <15m | - | - | - |
| All <15m – river/railway | 48 | - | - |
| Shared boundary | 34 | 39 | - |
| Shared boundary – river/railway | 33 | 40 | 66 |

Table 4.9: Agreement of number of premises removed as the 100 premises with highest betweenness under each of the contiguity definitions studied.

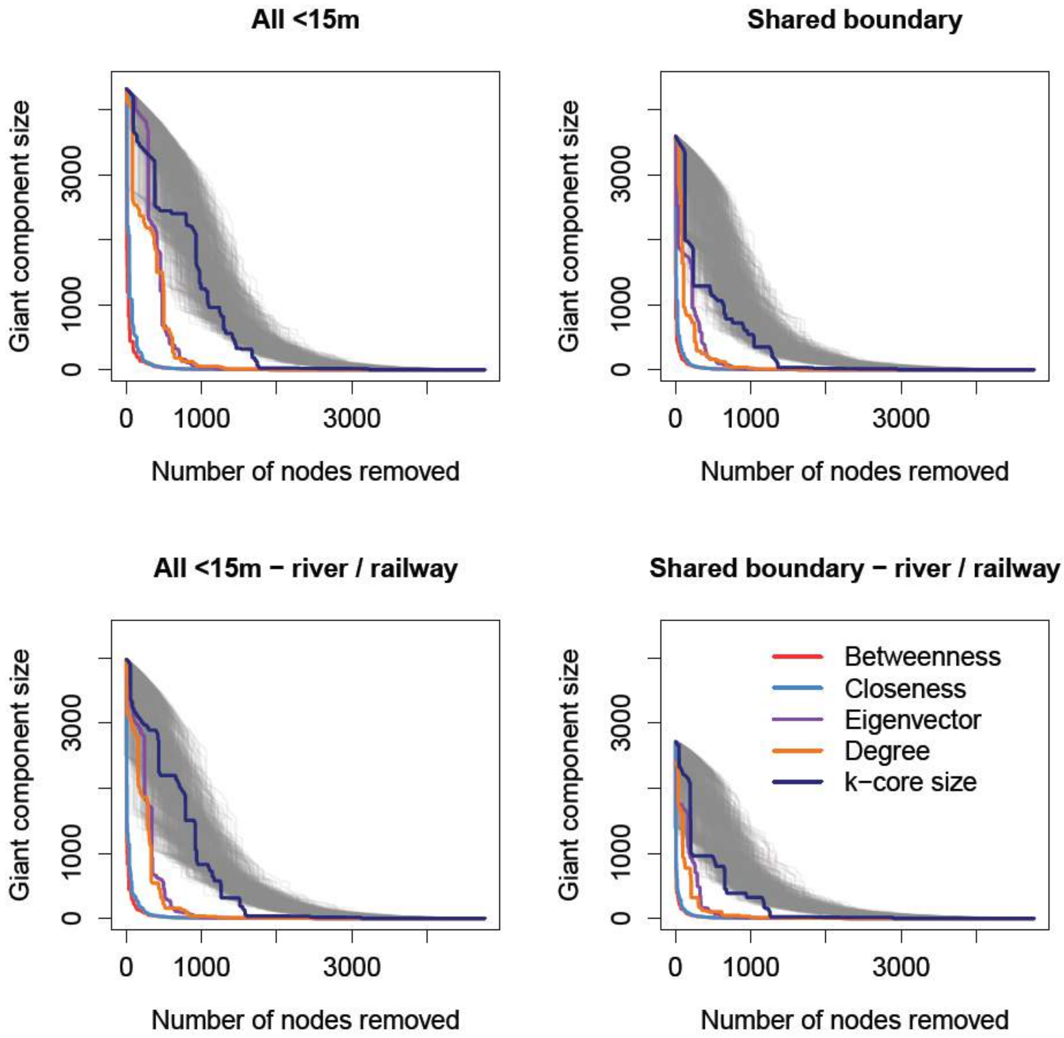



Figure 4.10: Graphs showing decrease in giant component size when premises are removed from networks based on different contiguity definitions at random (grey lines), and in order of centrality measures.

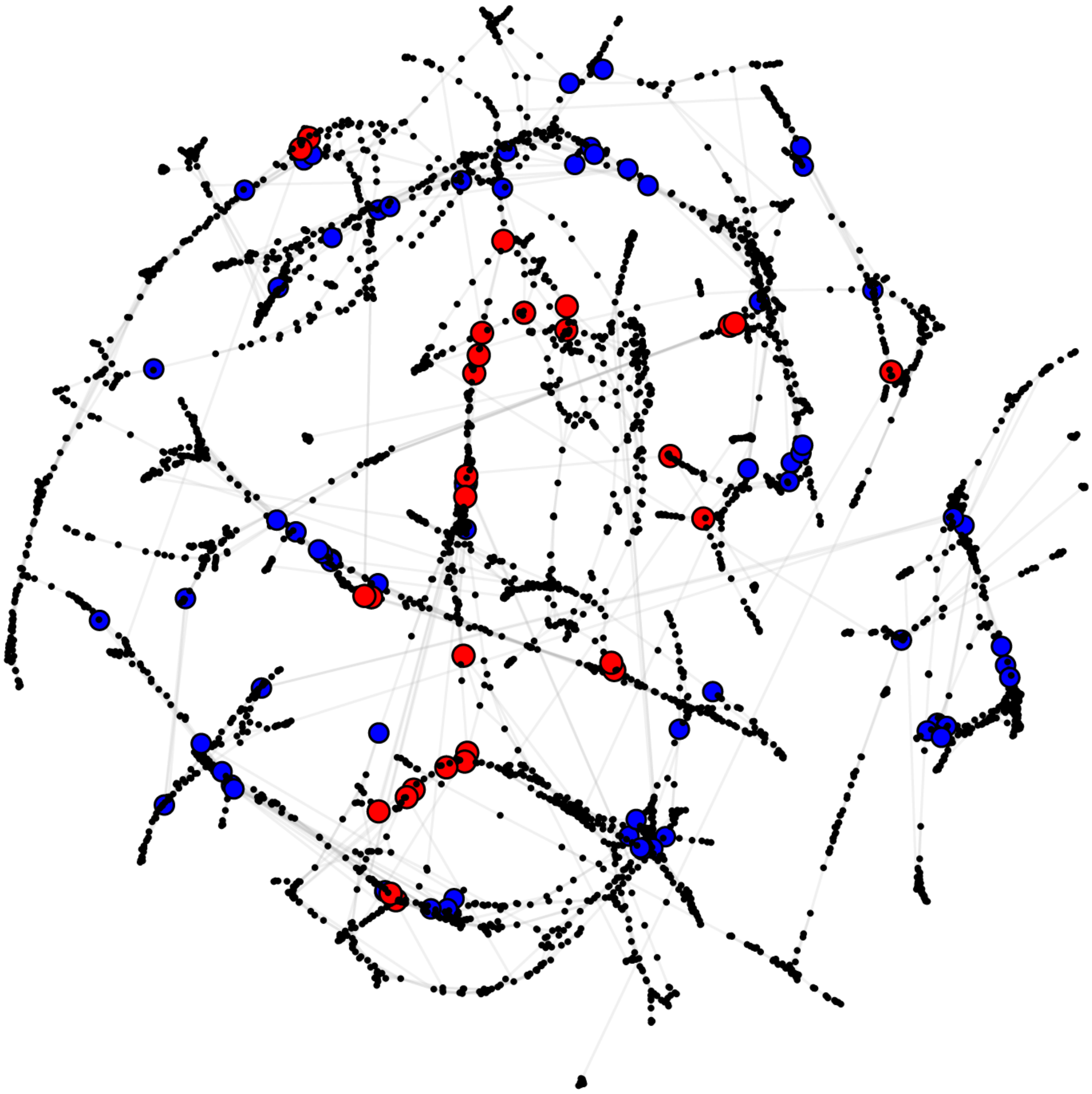


Figure 4.11: Network graph showing the location of the 30 (red circles) and remaining 100 (blue circles) livestock premises with highest betweenness within the giant component, where contiguity is defined as 'All <15m'. Grey lines represent edges between premises vertices (small black circles), where premises are contiguous.

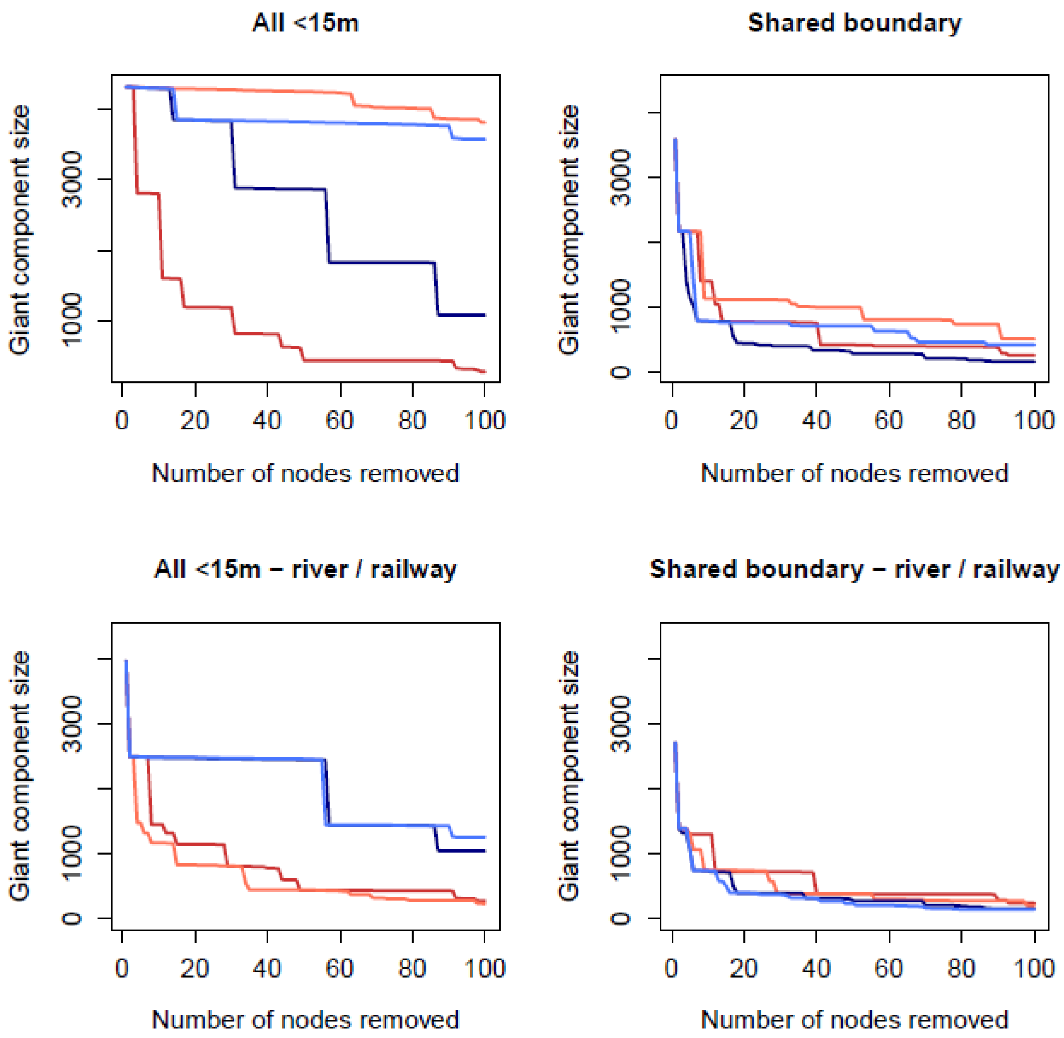



Figure 4.12: Graphs showing decrease in giant component (GC) size for each of the networks based on different CP definitions, when the 100 premises with the highest betweenness, as found under each of the different CP definitions (Red = 'All <15m'; pink = 'All <15m - river/railway'; dark blue = 'Shared boundary'; light blue = 'Shared boundary - river/railway'), are removed from each of the networks.

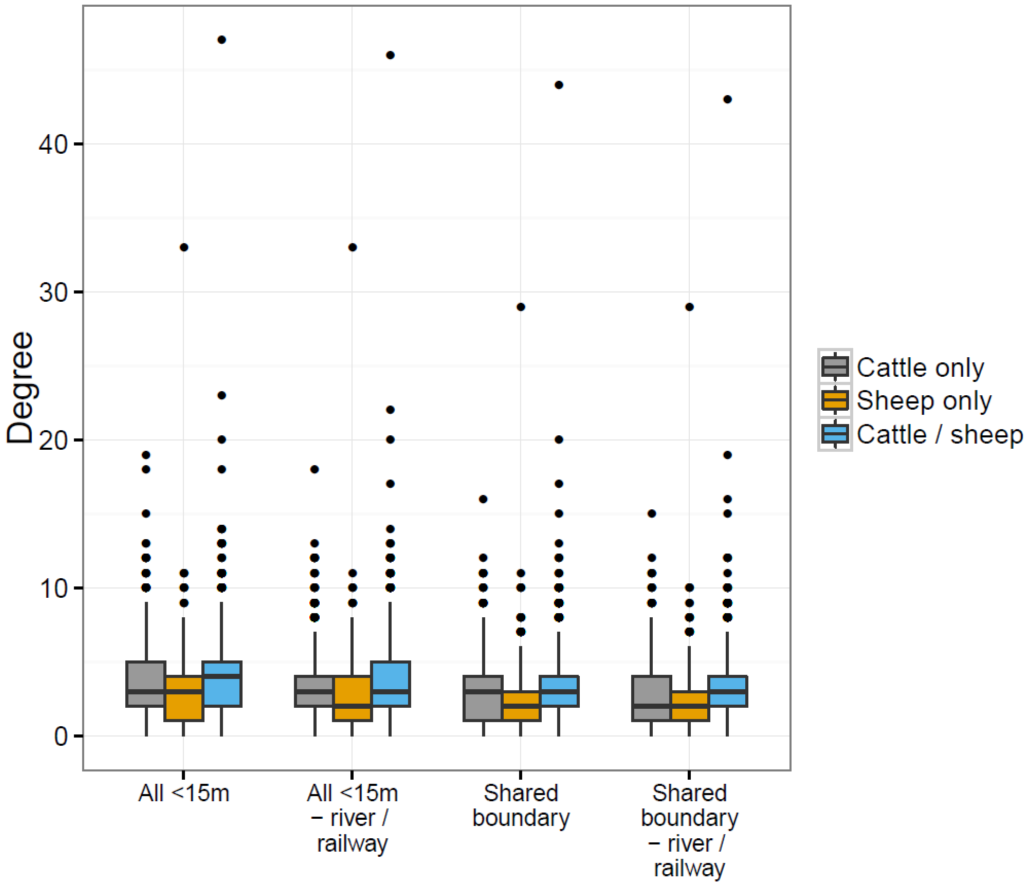



Figure 4.13: Box plots of degree distribution by species kept on premises, where CPs are considered to be premises within 15m.

### Mathematical modelling

Considered in terms of disease transmission, the network analyses essentially assume that a contact between two premises (i.e. contiguity) results in a successful transmission event. Given that this is not the case, it was felt important that mathematical model simulations were run to ascertain whether the method of removing high betweenness premises was still effective: the contiguity model with no background transmission to examine the effect of introducing stochasticity to transmission between CPs; and the contiguity model with a low level of background transmission to examine the effect of introducing long-distance stochastic transmission events (i.e. between non-CPs) in addition to stochastic transmission between CPs. The simulation results from the contiguity model with $\delta = 0$ (i.e. no background transmission, such that transmission is only possible between CPs) can be seen in Figure 4.14. With the introduction of stochasticity, the impact of removing premises with the highest betweenness in the contiguity network 'All $<$15m' from each network based on different contiguity definitions, remains similar to that observed for the decrease in network GC size: there is a steep decline in mean number of infected premises (IPs) with the first removals, which becomes more gradual (but continues) with successive removals (Figure 4.14). A similar decline is observed for the mean duration (in days) of the predicted outbreaks (Figure 4.14). Removing the 100 premises with highest betweenness results in a drop in mean number of IPs from 70.4 to 15.8, and of mean duration from 60.5 to 31.6 days. When incorporating a low level of longer-range transmission into the model (where $\delta = 2.81 \times 10^{-6}$), similar relationships are observed as for when $\delta = 0$ with removal of premises with the highest betweenness in the contiguity network 'All $<$15m' from the different contiguity networks (Figure 4.15). Although the lines within each plot in Figures 4.14 and 4.15 differ from one another, they all follow the same pattern, and all show a considerable decrease in either mean number of IPs or mean duration with removal of premises in order of their betweenness. Interestingly, when Chapter 3's simulations of each the distance and contiguity models are considered, the 100 premises with highest betweenness in the 'All $<$15m' network tended to become IPs more frequently in the contiguity model simulations (Figure 4.16).

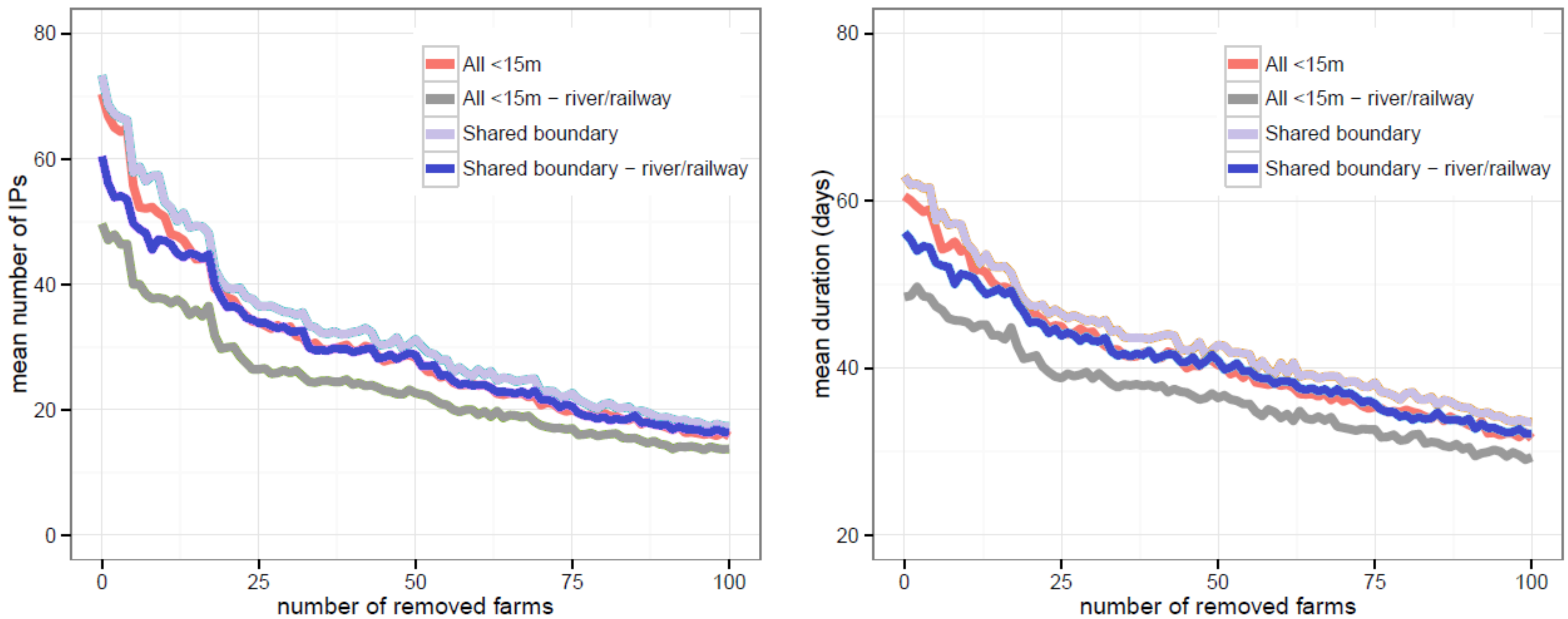



Figure 4.14: Impact of removing the 100 premises with highest betweenness as defined from the network based on contiguity definition 'All <15m' from contiguity networks based on different definitions. Change in the mean number of infected premises (IPs) (left panel), and the mean duration (days) (right panel) with each holding removal. Transmission is based on the best fitting estimate of $\hat{\rho}$ given no background transmission ($\delta = 0$) for each definition of contiguity shown. This figure was provided by Thibaud Porphyre.

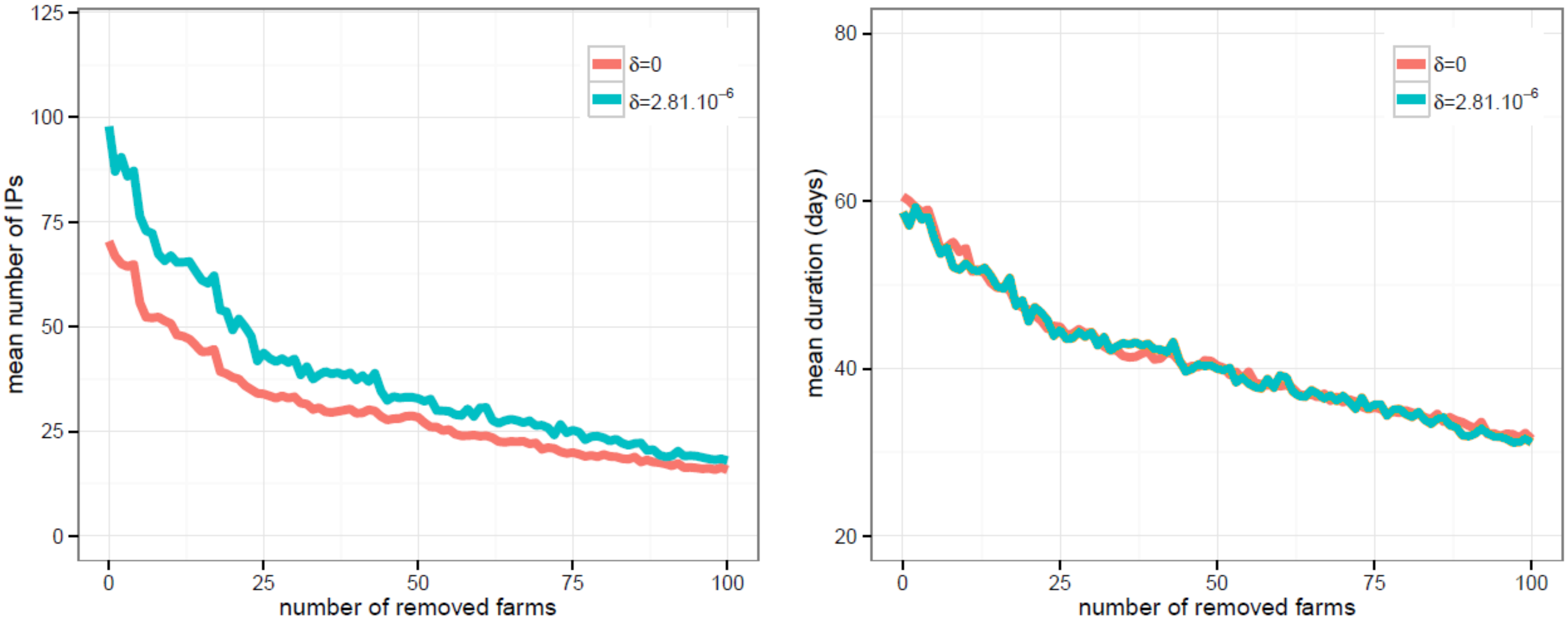



Figure 4.15: Impact of removing the 100 premises with highest betweenness as defined from the network based on contiguity definition 'All <15m' from the 'All <15m' contiguity network. Change in the mean number of infected premises (IPs) (left panel), and the mean duration (days) (right panel) with each holding removal, for two values of $\delta$. Transmission is considered for the 'All <15m' definition of contiguity, using the best fitting estimate of $\hat{\rho}$ given the tested value of $\delta$. This figure was provided by Thibaud Porphyre.

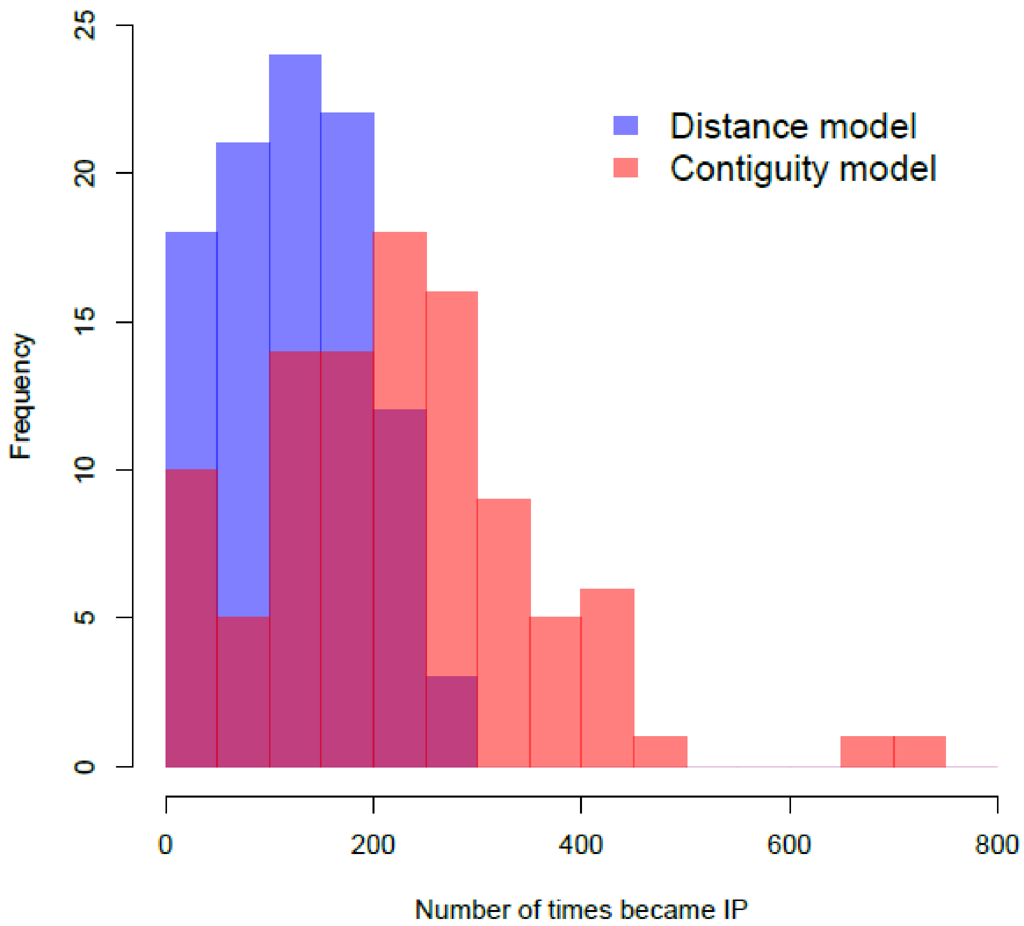



Figure 4.16: Histograms showing the distribution of the number of times the 100 premises with highest betweenness in the contiguity network for the area (based on definition ‘All <15m’) became IPs over the course of 1000 simulations for each model.

### Statistical analysis

The univariate logistic regression analyses indicate that several premises variables are associated with the odds of being a premises with the 'top 100' betweenness in the two networks based on the definitions 'All $<$15m' and 'All $<$15m - river/railway'. In terms of species composition, having any sheep or cattle present on the premises significantly increased the odds of being in the 'top 100', and having $\geq$ 270 cattle or $\geq$ 946 sheep had a larger, and significant effect compared to the other size categories (Table 4.10). Having both species present was also associated with being a premises with 'top 100' betweenness, with premises of other species compositions (cattle only, sheep only, deer/goats only) having 0.49 the odds of being a premises with 'top 100' betweenness compared to those with both cattle and sheep. Other significant positive associations were found with the number of CPs, the premises area, its fragmentation index (as defined in section 4.2.2, with a higher fragmentation index indicating greater fragmentation of land), and the number of fields and land parcels (Table 4.10). The same effect directions were found for the two outcomes studied (having the 'top 100' betweenness values in the two networks based on definitions 'All $<$15m' and 'All $<$15m - river/railway'), except in the case of the two middle categories for number of cattle where they had different directionality but were both non-significant.

| Variable | All <15m | | | | All <15m - river/railway | | | |
|---|---|---|---|---|---|---|---|---|
| | Odds ratio | Z | P-value | 95% CI | Odds ratio | Z | P-value | 95% CI |
| **Species composition** (baseline = cattle and sheep) | | | | | | | | |
| Other species mix | 0.49 | -3.388 | 0.001 | (0.33-0.74) | 0.61 | -2.416 | 0.016 | (0.41-0.91) |
| **Any cattle present** | 2.77 | 2.583 | 0.010 | (1.37-6.59) | 2.39 | 2.351 | 0.019 | (1.23-5.37) |
| **Number of cattle** (baseline = <24) | | | | | | | | |
| <129 | 1.20 | 0.418 | 0.676 | (0.51-2.85) | 0.73 | -0.796 | 0.426 | (0.32-1.58) |
| <270 | 1.71 | 1.346 | 0.178 | (0.79-3.90) | 0.93 | -0.180 | 0.857 | (0.44-1.96) |
| ≥270 | 6.33 | 5.367 | <0.0001 | (3.38-13.18) | 4.13 | 4.860 | <0.0001 | (2.39-7.58) |
| **Any sheep present** | 1.41 | 1.570 | 0.116 | (0.93-2.19) | 1.17 | 0.746 | 0.455 | (0.78-1.79) |
| **Number of sheep** (baseline = 0) | | | | | | | | |
| <98 | 0.65 | -0.949 | 0.343 | (0.24-1.47) | 0.48 | -1.526 | 0.127 | (0.16-1.13) |
| <946 | 0.89 | -0.375 | 0.707 | (0.49-1.59) | 0.75 | -0.986 | 0.324 | (0.41-1.32) |
| ≥946 | 2.29 | 3.503 | 0.000 | (1.45-3.67) | 1.93 | 2.849 | 0.004 | (1.23-3.05) |
| **Number of CPs** | 1.64 | 13.980 | <0.0001 | (1.54-1.77) | 1.84 | 15.180 | <0.0001 | (1.70-1.99) |
| **Area** (baseline = <48 hectares) | | | | | | | | |
| <97 hectares | 2.33 | 1.222 | 0.222 | (0.65-10.82) | 1.99 | 1.125 | 0.260 | (0.63-7.49) |
| <184 hectares | 9.66 | 3.725 | <0.001 | (3.41-40.46) | 5.92 | 3.273 | 0.001 | (2.27-20.23) |
| ≥184 hectares | 21.76 | 5.198 | <0.0001 | (8.05-89.27) | 17.14 | 5.498 | <0.0001 | (7.06-56.53) |
| **Fragmentation index** (baseline = 0) | | | | | | | | |
| <0.4 | 5.53 | 5.067 | <0.0001 | (2.94-11.18) | 7.06 | 4.876 | <0.0001 | (3.38-16.62) |
| <0.7 | 7.42 | 6.083 | <0.0001 | (4.02-14.79) | 13.37 | 6.778 | <0.0001 | (6.69-30.59) |
| ≥0.7 | 13.84 | 6.314 | <0.0001 | (6.06-31.62) | 22.67 | 6.835 | <0.0001 | (9.42-58.00) |
| **Number of land parcels** (baseline = 1) | | | | | | | | |
| 2 | 3.49 | 3.403 | 0.001 | (1.72-7.37) | 3.38 | 2.704 | 0.007 | (1.42-8.57) |
| >2 | 9.80 | 7.246 | <0.0001 | (5.49-19.10) | 17.26 | 7.644 | <0.0001 | (8.85-38.90) |
| **Number of fields** | 1.04 | 11.300 | <0.0001 | (1.03-1.04) | 1.04 | 11.650 | <0.0001 | (1.03-1.04) |
| **Multi-premises farm business** | 1.51 | 1.722 | 0.085 | (0.92-2.39) | 1.26 | 0.917 | 0.359 | (0.75-2.03) |
| **Area rented in (hectares)** | 1.34 | 1.433 | 0.152 | (0.90-1.99) | 1.28 | 1.228 | 0.220 | (0.86-1.91) |
| **Area rented out (hectares)** | 1.55 | 1.455 | 0.146 | (0.82-2.70) | 1.14 | 0.400 | 0.689 | (0.55-2.11) |

Table 4.10: Univariate logistic regression results for the outcome being a premises with top 100 betweenness, for each of the two networks based on CP definitions ‘All <15m’ and ‘All <15m - river/railway’.

## 4.4 Discussion

Combining network analysis with fine-scale maps of the landscape has highlighted the high connectivity of the livestock farming landscape in southern Scotland, with the vast majority of premises (90.6%) being within the giant component (GC) of the 'All <15m' contiguity network. This suggests there is the potential for a large outbreak should there be an incursion of FMD in Scotland in the future. In terms of reducing the GC size of the network, node removal in order of betweenness centrality was the most (and indeed, hugely) effective of the measures of network centrality investigated. This implies that outbreak size could be limited to some extent by fragmenting the farming landscape by ensuring that those premises with the highest betweenness do not become infected - by enhanced biosecurity and surveillance. Indeed, mathematical model simulations of FMD, where the model is adapted to incorporate the contiguity networks, show a considerable reduction in mean predicted epidemic size (in terms of number of infected premises (IPs)) and duration by removing premises from the networks in order of their betweenness centrality. This finding was maintained when long range transmission was incorporated alongside contiguous spread at the level identified during the 2001 epidemic. As stated in the methods, the choice to look at the 100 premises with highest betweenness was arbitrary, and, in fact, limiting this to fewer than 30 premises would appear to have a considerable impact on both GC size (Figure 4.12) and mean number of predicted IPs and duration (Figures 4.14 and 4.15). Such targeted control is similar to the rabies vaccination strategy proposed by Haydon et al. (2006) to aim vaccination at wolves occupying corridor habitats that connect the wider population: rather than lowering the overall basic reproduction number, R0, the potential outbreak size is reduced by fragmenting the population. While the key premises identified here may not cause a disproportionate number of secondary FMD cases themselves, by facilitating spread between otherwise separated sub-populations of premises they may increase the chances that disease will reach a premises which does, which in turn would increase the likelihood of a successful epidemic taking hold (Lloyd-Smith et al., 2005).

An automated method, whereby landscape features that may act as barriers to FMD transmission can be reliably detected and therefore taken into account in construction of the network, was developed as part of this work. The computational difficulty of processing OS MasterMap® road data required OS Meridian™2 data to be used in their place. This replacement data source resulted in a reduced accuracy of identification. As expected given the lack of tracks in the OS Meridian™2 road data, in all cases of mis-matched identification, visual map inspection had identified a road as being present, and the automated procedure had identified them as absent. Whilst using this data source for roads was not perfect, it nonetheless did not have a large impact on the results when comparing approximation and map-based measures of contiguity. The use of automated procedure for identifying ditches did however have a considerable impact on the results of this analysis, compared with ditch identification by visual inspection. This inaccuracy, together with the fact that it seems likely that ditches do not pose so much of a barrier to foot-and-mouth disease transmission compared to other features, meant that identification of ditches was no longer considered worthwhile. The following data sources, landscape feature buffer types and cut-off percentages that the buffers take up of the farm-farm intersections in order to be classified as present, were therefore found to be optimal, and useful for application in further work:

- OS MasterMap® rivers: flat-ended 25m buffers, 68% cut-off;
- OS Meridian™2/MasterMap® railways: flat-ended 15m buffers, 98% cut-off;
- OS Meridian™2 roads: flat-ended 25m buffers, 70% cut-off.

Studying the GC decay under different definitions of contiguity that included information on whether premises had shared or close (<15m) field boundaries as well as presence of rivers and railways (according to detection by automated method described above) enabled the consideration of different transmission networks that may reflect FMD transmission (given that Bessell et al. (2008) found these features to protect against transmission). It also brought to light that in order to best use this method of network analysis to target control measures at premises occupying key locations in the network, it seems that the widest definition of contiguity (‘All <15m’) should be used to identify these key premises, since this resulted in the most consistent rapid reduction in GC size across the networks constructed based on different definitions of contiguity (Figure 4.12). Indeed, the results from the model simulations indicate that regardless which contiguity network is considered to reflect FMD transmission, removing premises from the network based on definition ‘All <15m’ results in a decrease in both mean number of IPs and epidemic duration (Figures 4.14 and 4.15). This suggests that the method is robust even in the event contiguity has been imperfectly specified in terms of transmission possibility. Given that the definition of contiguity used here likely differed slightly from that used during the 2001 outbreak (during which, in Dumfries and Galloway, CPs were identified as having shared field boundaries or field boundaries that were separated only by a country road, small river, railway or 20m stretch of woodland (Thrusfield et al., 2005)), this provides confidence in the method described for fragmenting CPs within the farming landscape.

That the contiguity networks’ GC’s could be easily fragmented supports the finding of Newman (2002) that the GC is harder to fragment in highly assortative networks than more neutral or disassortative ones, since the contiguity-based networks were neutral rather than assortative in terms of degree (with values of assortativity close to zero). Betweenness has similarly been found to be effective for identifying key nodes in other networks (Carne et al., 2013; Christley et al., 2005; Fournie et al., 2013; Ortiz-Pelaez et al., 2006) and for identifying nodes responsible for linking otherwise separate communities (Girvan and Newman, 2002). On the other hand, Kitsak et al. (2010) suggested k-coreness better identifies efficient spreaders because it incorporates information regarding network position (e.g. nodes may be central and therefore have high betweenness, but be on the periphery in terms of position). For the contiguity networks studied here, removal of nodes in order of their k-core membership was only sometimes an improvement on random node removal (Figure 4.10).

Results of univariate analyses suggest that premises with high betweenness in the map-based contiguity network are generally larger in area ($\geq$ 184 hectares), keep a large number of cattle ($\geq$ 270) and sheep ($\geq$ 946), have several land parcels and are consequently more highly fragmented (with a fragmentation index of $\geq$ 0.7), and are part of a multi-premises farm business (Table 4.10). Thus, premises likely to contribute considerably to ongoing FMD transmission during an outbreak could potentially be crudely identified as having these features. Furthermore, a consequence of premises having larger areas is that their point locations are likely to be further away from those of surrounding premises, despite possibly being contiguous (indeed they also tend to have more CPs). As a result, larger premises may be classified as having a lower transmission probability in the distance model, due to the nature of the transmission kernel. Since larger premises have increased odds of being among the 100 premises with highest betweenness (Table 4.10), premises with high betweenness may therefore be likely to become IPs more frequently in reality than is predicted by the distance model. Indeed, simulations show that the 100 premises with highest betweenness become IPs more frequently using the contiguity model than the distance model (Figure 4.16). Therefore, premises with the characteristics detailed above may not only contribute disproportionately to continued spread but also be at increased risk of becoming an IP in the first place.

Given that having larger area is correlated with having larger numbers of cattle and sheep as well as CPs, it is possible that the effect of such premises being at decreased risk of becoming infected according to the kernel was counteracted in the original model parameterisation by the susceptibility parameters. These define an increase in susceptibility with increasing numbers of cattle and sheep. Some of this increase could be due instead to the increase in susceptibility that would come from being contiguous to a larger number of premises that could potentially become infected. Furthermore, in agreement with previous findings (Flood et al., 2013, Chapter 2), premises with cattle and sheep tended to have more CPs than premises with sheep but no cattle. It is possible then that sheep appeared less susceptible than cattle to FMD in the UK's 2001 epidemic (Keeling et al., 2001) partly because they tended to be less exposed as a result of having fewer CPs. The finding that cattle and sheep premises on average have more CPs than cattle only and sheep only premises may account for the observed dominance of premises that kept both cattle and sheep in the 2001 epidemic - they accounted for 71% of all IPs (Gibbens et al., 2001). These findings therefore call into question the relative contributions of numbers of cattle and sheep and premises' area/fragmentation/number of CPs/betweenness to FMD transmission. Examination of the performance of a contiguity based model against new epidemiological data in the event of a future FMD outbreak may go some way to answering this.

The work presented here implies that ensuring that the top 100 (or even the top 30) premises with highest betweenness in the 'All <15m' contiguity network do not become infected would considerably reduce the likely outbreak size, by helping to limit natural spread of FMD via local transmission mechanisms through the landscape. This offers a much more manageable response effort given the limited number of people and resources available to respond to an outbreak at short notice. Biosecurity measures used on these premises may include compulsory boot-dips at farm entrances and disinfectant mats for vehicles coming onto the premises, as well as other measures that have found to be associated with FMD risk (Ellis-Iversen et al., 2011). Additionally, restriction of grazing fields such that perimeter fields are not stocked and avoidance of herding stock down the surrounding roads may aid disease prevention on these premises. Farmers working on these premises should be targeted to ensure they have good knowledge of signs to look out for, and regular checks of stock made compulsory. Pre-emptive vaccination of the premises' stock may also want to be considered by policy makers. In this way, the results presented suggest that a huge impact on FMD outbreak size and duration can be achieved - even allowing for a low level of long-range transmission. Indeed, it is likely that for other diseases that have a significant local spread component to their transmission, such as bovine tuberculosis (White et al., 2013), bovine viral diarrhoea (Gates et al., 2013), and rabies (Haydon et al., 2006), similar network approaches may offer a huge gain in terms of impact on spread, for a very targeted control response and hence limited resource use.

This chapter has demonstrated that the farming landscape in southern Scotland is extremely connected by map-based contiguity, and therefore potentially vulnerable to an extensive FMD epidemic should there be a future incursion into the area. A reliable automated procedure for the detection of rivers, roads and railways between map-based CPs has been created. This enabled different definitions of map-based contiguity including landscape feature presence to be examined for a large area of Scotland. Increasing distances between different premises' land parcels would enable the farming landscape to be less connected, and more fragmented in terms of contiguity that is likely to reflect FMD transmission pathways. Network analysis can be used in combination with fine-scale maps to identify key premises that act to connect the farming landscape using betweenness centrality. Additionally, analysis of the demographic factors associated with being one of these key premises highlights premises' characteristics that can be used to broadly identify which premises these are on-the-ground. In ensuring that these key premises remain free of infection the farming landscape may be effectively fragmented in terms of FMD transmission, and consequently, to some extent, epidemic's may be naturally contained by the landscape itself - supported by the reduction in mean epidemic size and duration predicted by the model simulations, even with inclusion of some long-range transmission. It has also brought to light the question of the relative contributions of area (and hence number of CPs) and number of livestock to the susceptibility and transmissibility of premises. Implementation of strict biosecurity practices as well as vaccination of all susceptible animals on the identified key premises would help to prevent them becoming infected in the event of any future FMD incursions in the UK, potentially substantially limiting outbreak size. Such biosecurity measures include, but are not limited to, restriction of livestock grazing in perimeter fields, strict use of premises-specific clothing and footwear, boot dips, and restriction of vehicle access.

# 5 Investigating social patterns in the farming landscape in relation to FMD-biosecurity risk

**Key terminology**

***Spatial autocorrelation:*** *The degree of similarity between observations in space. Positive spatial autocorrelation indicates that observations close together in space are more similar than those further away, whereas negative autocorrelation indicates that observations close together are more different to those further away.*

***Assortativity:*** *Assortativity of a network can be calculated for any node (premises) value (within this chapter, this value is the biosecurity risk score), and measures the likelihood that nodes share edges more commonly with other nodes that have similar value (here, biosecurity risk score). It lies between +1 and -1, where +1 indicates perfect assortative mixing, i.e. premises share an edge (are map-based CPs) with only those premises that have the same biosecurity risk score.*

***Spatial weights matrix:*** *Here, a matrix of premises where the cells take a value of 1 where premises are map-based CPs and 0 where they are not.*

***Moran's I:*** *Measures the spatial autocorrelation in a spatial dataset. It takes a value between +1 and -1, where a positive value indicates positive spatial auto-*

*correlation, and a negative value indicates negative autocorrelation.*
***Neighbour lag distance:*** *The distance by CPs between two premises, e.g. a lag distance of 1 indicates that the two premises are CPs, a lag distance of 2 indicates that they are separated by one CP etc.*

## 5.1 Introduction

This chapter and the following chapter will present analyses of survey data collected via 200 interviews with farmers in Ayrshire and Aberdeenshire. The two chapters are based on the same datasets but have different focuses: this chapter on social/spatial patterns in biosecurity risk, and the next on farm demographics in relation to biosecurity risk.

During the silent spread phase of an FMD incursion - before it has been diagnosed on any affected farm premises - the 'peace-time' biosecurity practices undertaken on farms will affect how disease spreads via local mechanisms. Biosecurity practices relevant to FMD aim to reduce potential spread by contaminated fomites carried by people or vehicles, which are thought to have been the transmission pathways responsible for the majority of infected premises in Dumfries and Galloway in 2001 (Thrusfield et al., 2005). How implementation of such biosecurity practices vary between farm premises may affect the observed transmission patterns. It is possible that if imitation behaviour of such biosecurity practices occurs between proximal farms this could account for some of the spatial clustering of cases, since imitation could result in formation of farm clusters with higher/lower levels of biosecurity. Indeed, spatial clusters of farms with high and low biosecurity, respectively, have previously been identified among Canadian pig farms (Lambert et al., 2012).

Farm biosecurity has parallels with people's health-seeking behaviours: much like vaccination reduces the chances of individual infection, on-farm biosecurity reduces the chances of farm-level infection. There is considerable evidence in the literature for imitation of others in the adoption of vaccination (May and Silverman, 2003; Parker et al., 2006; Sugerman et al., 2010) as well as for other health-related behaviours within social networks (Centola, 2010; Christakis and Fowler, 2007). Furthermore, those in closer proximity appear to have greater influence on an individual's behaviour: in social and/or geographical terms (Centola, 2010; Christakis and Fowler, 2007; May and Silverman, 2003; McPherson et al., 2001; Parker et al., 2006; Sugerman et al., 2010).

Among the farming community, there is mixed evidence for imitation behaviours between farmers but, to the best of my knowledge, no research to date regarding the degree to which farmers do or do not imitate others' biosecurity practices. On one hand, farmer adoption of new technology has been found to be influenced by others living within the same district (Case 1992), and poultry exhibitors report to find each other to be the most useful sources of information on biosecurity matters (Hernandez-Jover et al., 2013). On the other hand, a study looking at neighbouring land parcels found little evidence for imitation between farmers in terms of land use (Schmit and Rounsevell, 2006).

For behaviours related to factors that influence infectious disease susceptibility, such as biosecurity practices, imitation can have serious knock-on effects to the outbreak potential. This is due to imitation resulting in the creation of social and geographical clusters of susceptible individuals, as has been observed in relation to vaccine refusal (May and Silverman, 2003; Parker et al., 2006; Sugerman et al., 2010). Models incorporating social networks have been used to study the effect of imitation, and the resulting clusters of susceptibility, on disease dynamics. They find that clusters of susceptible individuals enable sizeable outbreaks despite high vaccination coverage in the population (Ndeffo Mbah et al., 2012), and that such clusters may be created even with weak imitation, resulting in increased outbreak probability (Salathe and Bonhoeffer, 2008). Research has also found that when social reinforcement (i.e. exposure to behaviour from multiple neighbours) is necessary for behaviour adoption, while fewer clusters form compared to an assumption of simpler behaviour spread, outbreaks tend to occur more often, to be larger, and are possible at higher population vaccination coverage levels (Campbell and Salathe, 2013). As with imitation in vaccinating behaviour, such an effect for FMD biosecurity risks could affect the potential for outbreak take-off and size.

Farm biosecurity is comprised of many dimensions, including factors related to livestock purchasing, livestock movement, wildlife control and staff and visitor management. Different biosecurity measures help to target prevention and control of different diseases in various farm species (Enticott et al., 2012; Firestone et al., 2011a, 2013; Lambert et al., 2012; Themudo et al., 2012). However, following the UK's 2001 FMD epidemic, Brennan and Christley (2013) found that amongst cattle farmers in northwest England, the term 'biosecurity' was most commonly associated with practices aimed at reducing indirect contact transmission mechanisms. Indeed, it was such practices that largely comprised the composite biosecurity risk score, developed by the AHVLA during the 2007 FMD outbreak in Surrey, which was found to be significantly related to premises' probability of becoming a secondary FMD case (Ellis-Iversen et al., 2011). The composite biosecurity risk score was composed of the following 12 dimensions relating to fomite transmission routes:

1. No main gate is present, or kept open some/all of the time;
2. There is no physical separation between public access areas and livestock areas;
3. There are gates onto public land, or some/all gates onto public land are not locked;
4. There is no sign prohibiting entry at the entrance to the farm;
5. Car parking is not away from the areas that livestock access;
6. A boot dip is not used at the entrance to the farm;

7. Farm-specific boots are not provided for all staff and family;
8. Farm-specific overalls are not provided for all staff and family;
9. There is no clothes-changing area available;
10. There is a farm shop or other enterprise on the premises;
11. Dogs are free-roaming and/or accompany staff around the farm premises;
12. 'Unusual events' occurred in the 'risk period' (in 2007 this ranged between 14 and 33 days).

Each element took a value of 1 if there was a perceived risk present and 0 if there was no risk, except for farm-specific boots and overalls (elements 7 and 8) which took a value of 0.5 each. Thus, the scores could range from 0 (excellent biosecurity) to 11 (poor biosecurity in the dimensions considered).

It is important that the influence of social networks on the interdependence of individuals' health-related behaviours is taken into account when considering population health outcomes (Christakis, 2004). By identifying whether or not any spatial patterns in FMD biosecurity risk exist, the landscape epidemiology of FMD can be better understood in terms of factors underlying the observation of geographical clustering of cases during outbreaks. This chapter aimed to investigate potential patterns in farm premises' FMD biosecurity risks across the farming landscape. Since the AHVLA's composite biosecurity risk score had been validated in terms of its association with FMD status, the same risk score was used to assess farm premises' FMD biosecurity risk in this study. Specifically then, the hypothesis of this chapter is that premises' biosecurity risk scores (as assessed by Section B of the questionnaire shown in Appendix 4) are related to those of their map-based CPs.

## 5.2 Methods

### 5.2.1 Data collection

#### Devising a questionnaire

The questions regarding biosecurity were kept as close to the original AHVLA questionnaire as possible so as to try to limit any differences in perception by the farmers. Since the surveys were not outbreak-related, the period of time asked for in relation to unusual events happening (element xii) was in the 3 weeks prior to the survey. The survey was pilot tested with four farmers: two running primarily dairy premises, one a beef holding and one a sheep holding.

#### Obtaining Approval

A survey approval form was submitted to the Scottish Government's Rural and Environment Science and Analytical Services Division (RESAS) on 22/03/2013 (see Appendix 4, section 11.2). This was approved on 22/04/2013. In compliance with the University Health and Safety regulations, an University of Edinburgh Health and Safety form was completed.

#### Sample size and selection

This study's sample size was calculated based on the amount of time that was available to collect the data in. The estimated participation rate, based on Brennan & Christley's (Brennan et al., 2008) research which also involved running questionnaires through with British farmers in person, was ≈70%. From pilot testing the questionnaire it was found that it took about 30 minutes to complete. Taking into account travelling between farms and other practicalities, one farm visit was estimated to take 1-1.5 hours, translating into a possible 6-9 farm visits per day. Fieldwork weeks were given 4 days per week to allow other administrative tasks to be completed. Over the available 8 weeks, this gave an estimate of 108-162 farm visits possible in Ayrshire (which was given 4.5 weeks because of it's greater density of farms per area), and of 84-126 farm visits possible in Aberdeenshire (see Appendix 4, Section 11.1 for details on actual farm visits).

IACS data from 2011 was linked to 2011 Agricultural Census data in ArcGIS version 9.3, by premises' CPH numbers, and sheep and/or cattle farms across Scotland were identified. Land parcel IDs (LPIDs) (which denote individual fields) among this subset of the 2011 IACS data were then selected where they lay in an approximately square area that lined up with that of the 2006 IACS Aberdeenshire and Ayrshire samples used in Chapter 2. This resulted in a sample selection of 154 CPH premises in Ayrshire and 104 in Aberdeenshire. The Agricultural Statistics Department in the Scottish Government provided the names and addresses of the farmers associated with the list of selected CPH premises.

### Undertaking farm visits

Ayrshire was visited between 1st-31st July 2013, and Aberdeenshire between 5th-16th and 26th-30th August 2013. The list of CPHs for the two locations were ordered alphanumerically, and attributed ID numbers so that premises could not be identified by their CPH in any documentation relating to the farm visit. A letter was sent out to all sample premises in Ayrshire at the end of June, and to all sample premises in Aberdeenshire at the beginning of August, to inform farmers about the research, and that visits would follow (Appendix 4, section 11.2).

Telephone numbers were searched for online using the BT telephone directory (www.bt.com/phonenetuk/). Where a telephone number could be found, calls were made to try to arrange a convenient time to visit. Farms without telephone numbers were visited around the scheduled visits. These un-arranged visits were prioritised by distance from the previous farm. A list of premises IDs and addresses were taken to the field locations. Telephone numbers could not be found for 14.9% (23/154) of farms in the Ayrshire sample, and for 50.0% (52/104) in Aberdeenshire.

At each visit, the purpose of the survey was explained to the farmer, and if they were happy to consider participating they were asked to read through the consent form (Appendix 4, section 11.2), and sign if they agreed to take part. A copy of the consent form was left with them so that they had contact details of the project manager should they decide to withdraw at a later date. The questionnaire was then completed with the farmer (Appendix 4, section 11.2). In the vast majority of cases, the questions were read out by the interviewer, enabling standardisation of the way in which the question was asked and of prompting. In several cases this was not possible due to hearing difficulties, and in these cases the farmer read through the questions themselves, with some verbal communication if possible.

### 5.2.2 Examining patterns in biosecurity risk

Data was entered into a Microsoft Access database, and then checked. All analyses were conducted in R (R Core Team, 2013). Correlations between the elements which made up the composite biosecurity risk score (collected in Section B of the questionnaire) were tested for using the phi coefficient to see if data-reduction could be performed. The phi coefficient was used as it measures the correlation between two binary variables. Radar charts were plotted to visualise the similarities and differences in individual dimensions of biosecurity risk in the two areas. Radar charts are a useful way of visualising proportions of interest among a number of variables on the same plot, and were therefore used for easy visualisation to compare the proportion of premises undertaking the various biosecurity risks. To test the null hypothesis of no difference in proportion of farm premises undertaking each biosecurity risk dimension being undertaken between the two county study areas, Pearson's $\chi^2$ test statistic was calculated using Yates' continuity correction. The Mann-Whitney test was used to test for any difference in composite biosecurity risk score distributions between the two county study areas.

The spatial pattern of biosecurity risk was studied in terms of map-based holding contiguity according to the definition 'All <15m'. Networks were constructed based on contiguity for the two county study areas, and the assortativity of each calculated using the 'igraph' package (Csardi and Nepusz, 2006). This was first calculated for each individual element of biosecurity risk, and then for the overall risk scores. Assortativity is calculated by:

$$r = \frac{\sum_{xy} xy(e_{xy} - a_x b_y)}{\sigma_a \sigma_b},$$

where $e_{xy}$ is the proportion of network edges that join nodes with values $x$ and $y$, $a_x$ is the proportion of edges that start and end at nodes of value $x$, and $b_y$ is the proportion of edges that end at nodes of value $y$. It lies between +1 and -1, where +1 indicates perfect assortative mixing, and shows the degree to which connected nodes share the same characteristics (Newman, 2002).

Moran's I was also calculated for the biosecurity risk scores within each county study area, where the spatial weights matrix took a value of one where premises were contiguous and zero where they were not. Moran's I was calculated using the moran.test and sp.correlogram functions in the 'spdep' package (Bivand, 2014) for a neighbour lag distance of up to 8 (since both areas had sufficiently high premises pairings to this lag (Appendix 5, Figure 12.1)). It is calculated using the following equation:

$$I = \left[\frac{n}{\sum_{i=1}^{n}(y_i - \bar{y})^2}\right] \times \left[\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(y_i - \bar{y})(y_j - \bar{y})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}}\right],$$

where $y_i$ is the data value (in this case biosecurity score) at premises $i$, $\bar{y}$ is the overall mean value, $n$ is the number of observations (premises), and $w_{ij} = 1$ if the premises $i$ and $j$ are contiguous, and 0 if they are not. Moran's I takes a value between +1 and -1, where a positive value indicates positive spatial autocorrelation, and a negative value indicates negative autocorrelation.

## 5.3 Results

An 81.2% participation rate was achieved in Ayrshire (n=125), and 72.1% participation rate was achieved in Aberdeenshire (n=75). The higher participation rate in Ayrshire was probably attributable to the dominance of dairy production, meaning that farms were more easily identified from the road, and farmers were nearly always on the premises throughout the day (see Appendix 4, section 11.1). Brief summaries of data collected in the questionnaire can be found in Appendix 6.

Although farm premises were surveyed at the level of the CPH, multiple premises can be joined under one farm business. Out of 104 premises selected in Aberdeenshire, 91 (87.5%) were stand-alone premises, 11 belonged to a pair of premises under one farm business, and two premises belonged to multi-premises farm businesses each composed of 3 and 4 premises. Of the standalone premises, 27 (29.7%) were not surveyed, compared to 2 (18.2%) of the premises that were part of multi-premises farm businesses. Only two of the premises within the sample were part of the same farm business (i.e all other premises that were part of a multi-premises farm business had their joined premises outside of the sample), and these were both surveyed.

Out of 154 premises selected in Ayrshire, 127 (82.5%) were stand-alone premises, 18 belonged to a pair of premises under one farm business, and 6 and 3 premises belonged to a farm business composed of 3 and 4 premises, respectively. Of the standalone premises, 27 (21.3%) were not surveyed, whereas only 2 (7.4%) of the multi-premises farms were not surveyed. Three pairs and one triplet of premises were part of the same farm business within the sample (two of which had one additional premises under the farm business not included in the sample), all of which were surveyed.

This meant that 2 premises in Aberdeenshire and 9 premises in Ayrshire were non-independent observations, under one and four farm businesses, respectively. This was deemed too few values to consider accounting for in the analyses.

### 5.3.1 Biosecurity practices in the two sample areas

The biosecurity risks reported on surveyed premises in the two locations can be seen in Table 5.1 and Figure 5.1. Since Aberdeenshire had a higher percentage undertaking biosecurity risks in the majority of the dimensions, this was used as the base for the radar plot (Figure 5.1), and biosecurity risk dimensions were placed in decreasing order of percentage undertaken in Aberdeenshire. The vast majority of premises in both areas had no sign prohibiting entry, no/open main gate, and no routine boot-dip at the entrance to the farm. Few premises in either area had another enterprise on the premises (n=14 in Aberdeenshire; n=19 in Ayrshire). At the individual level of each biosecurity risk, Pearson's $\chi^2$ provided some evidence against the null hypothesis of no difference between county of farm premises and whether or not a biosecurity risk dimension was undertaken for several of the dimensions (Table 5.1). These dimensions were whether or not: there is a physical separation between public access areas and livestock areas; any gates onto public land are locked; there is car parking away from livestock areas; farm-specific boots are provided for all staff and family; farm-specific clothing is provided for all staff and family; there is a clothes-changing area available; any 'unusual events' occurred in the 3 weeks preceding survey. In all of these dimensions, apart from 'unusual events', Aberdeenshire had a considerably higher proportion undertaking the biosecurity risk than in Ayrshire (Table 5.1).

The phi coefficient indicated that only two elements of the composite biosecurity risk score were moderately correlated: whether farm-specific boots and farm-specific clothes were provided for all staff and family (Aberdeenshire phi = 0.61; Ayrshire phi = 0.59) (Figure 5.2), therefore data-reduction of the composite score was deemed inappropriate. Since no premises had signs prohibiting entry in the Aberdeenshire sample this element was excluded from the phi coefficient calculations.

The distributions of the biosecurity risk scores can be seen in Figure 5.3. The Ayrshire sample had a slightly lower distribution of biosecurity risk scores (Mann-Whitney W=3053, $p<0.0001$), with scores ranging between 3-9 and a mean of 5.98, compared to a range of 4-10, and mean of 6.90 in Aberdeenshire.

| | Aberdeenshire | | Ayrshire | | $\chi^2$ statistic | p-value |
|---|---|---|---|---|---|---|
| | Number | Percentage | Number | Percentage | | |
| **No/open gate at main entrance to farm** | 74 | 98.7% | 122 | 97.6% | 0.00 | 1.000 |
| **No physical separation between public access areas and livestock areas** | 54 | 72.0% | 69 | 55.2% | 4.90 | 0.027 |
| **There are gates onto public land which are not locked** | 26 | 34.7% | 15 | 12.0% | 13.42 | <0.001 |
| **There is no sign prohibiting entry at entrance to farm** | 75 | 100.0% | 119 | 95.2% | 2.25 | 0.134 |
| **There is no car parking away from livestock areas** | 23 | 30.7% | 15 | 12.0% | 9.43 | 0.002 |
| **There is no boot dip used at the entrance to the farm (for visitors that come into contact with animals)** | 67 | 89.3% | 115 | 92.0% | 0.15 | 0.702 |
| **Farm-specific boots are not provided for all staff and family** | 44 | 58.7% | 40 | 32.0% | 12.61 | <0.001 |
| **Farm-specific clothing are not provided for all staff and family** | 37 | 49.3% | 38 | 30.4% | 6.38 | 0.012 |
| **There is no clothes-changing area available** | 63 | 84.0% | 60 | 48.0% | 24.16 | <0.001 |
| **There is a farm shop/other enterprise on the premises** | 14 | 18.7% | 19 | 15.2% | 0.20 | 0.658 |
| **Dogs are free-roaming on the farm/accompany staff around the farm premises** | 52 | 69.3% | 75 | 60.0% | 1.38 | 0.240 |
| **'Unusual events' occurred in the 3 weeks preceding survey** | 29 | 38.7% | 100 | 80.0% | 33.19 | <0.001 |

Table 5.1: Table showing breakdown of biosecurity risks on premises by county, and Pearson's $\chi^2$ statistic and associated p-values for the difference between counties.

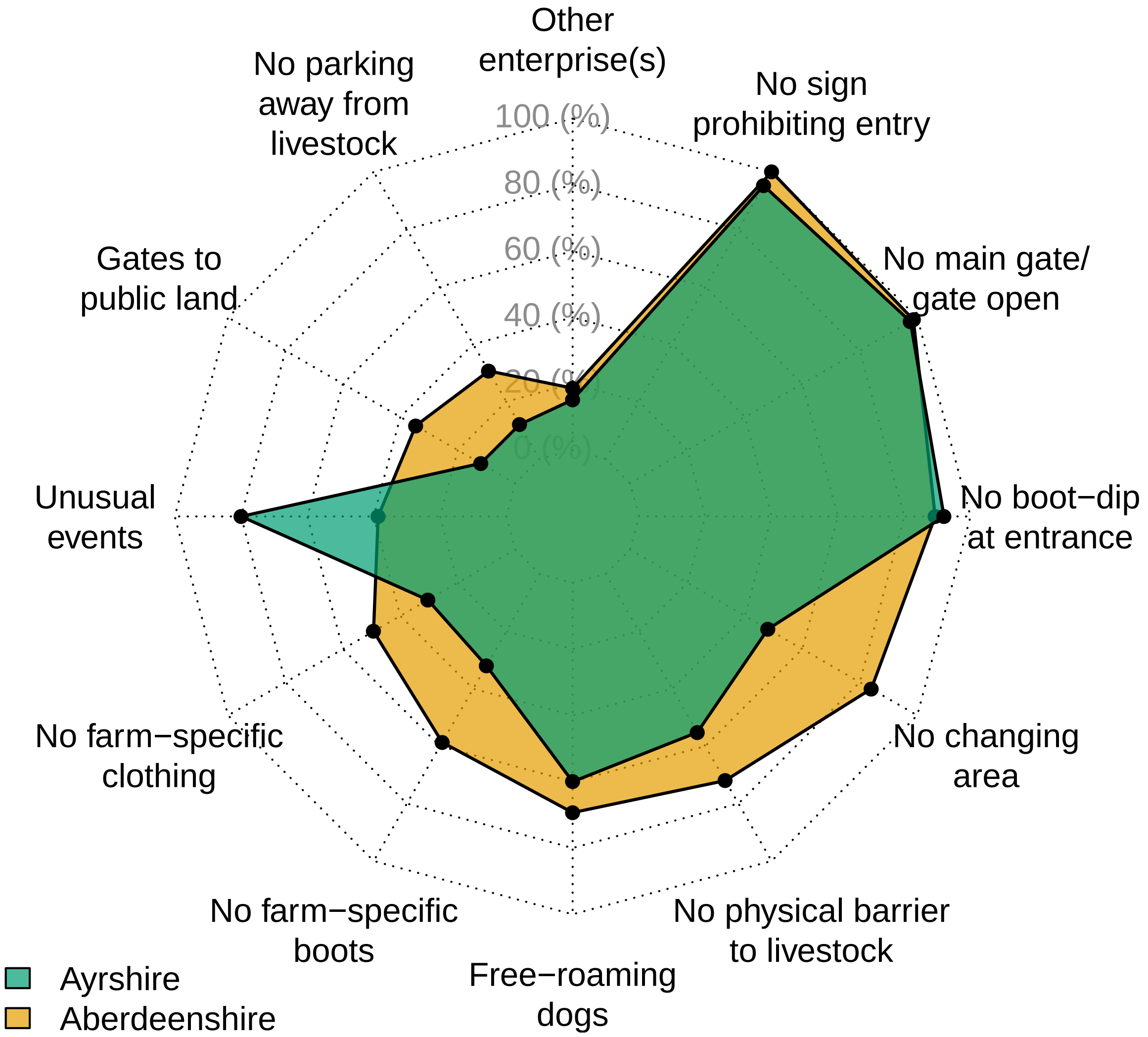



Figure 5.1: Radar chart showing proportion of premises undertaking each biosecurity risk component in each county area.

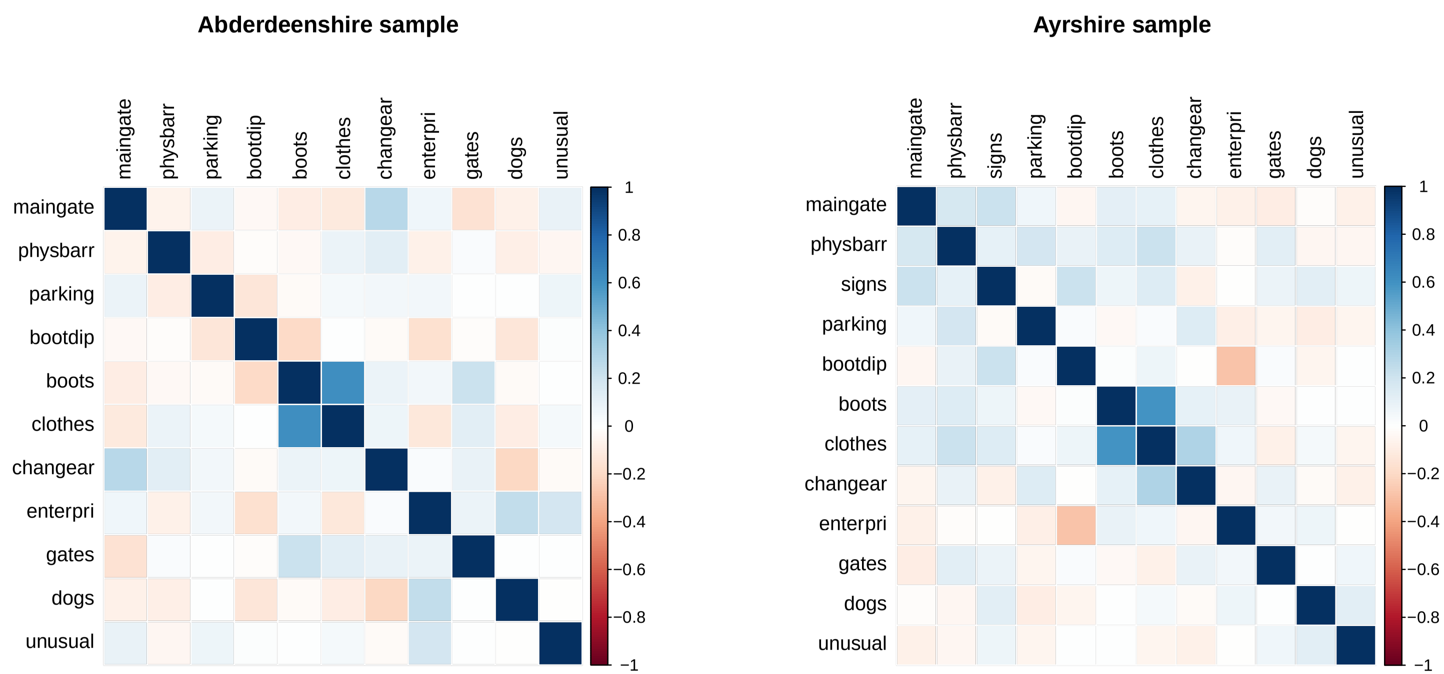



Figure 5.2: Correlation plots showing the phi coefficient between the individual biosecurity measures. No premises had signs prohibiting entry in the Aberdeenshire sample, therefore this element was excluded. (Definitions: maingate = There is a gate at main entrance to farm which is kept closed all the time; physbarr = There is a physical separation between public access areas and livestock areas; signs = There is a sign prohibiting entry at entrance to farm; parking = Car parking is away from livestock access areas; bootdip = Boot dip used at entrance to farm (for all visitors that come into contact with animals); boots=Farm-specific boots are provided for all staff and family; clothes = Farm-specific clothing are provided for all staff and family; changear = There is a clothes-changing area available; enterpri = There is no farm shop/other enterprise on the premises; gates=There are no gates onto public land or all gates onto public land are closed and locked; dogs = Dogs are not free-roaming on the farm/do not accompany staff around the farm premises; unusual = No 'unusual events' occurred in the 3 weeks preceding survey)

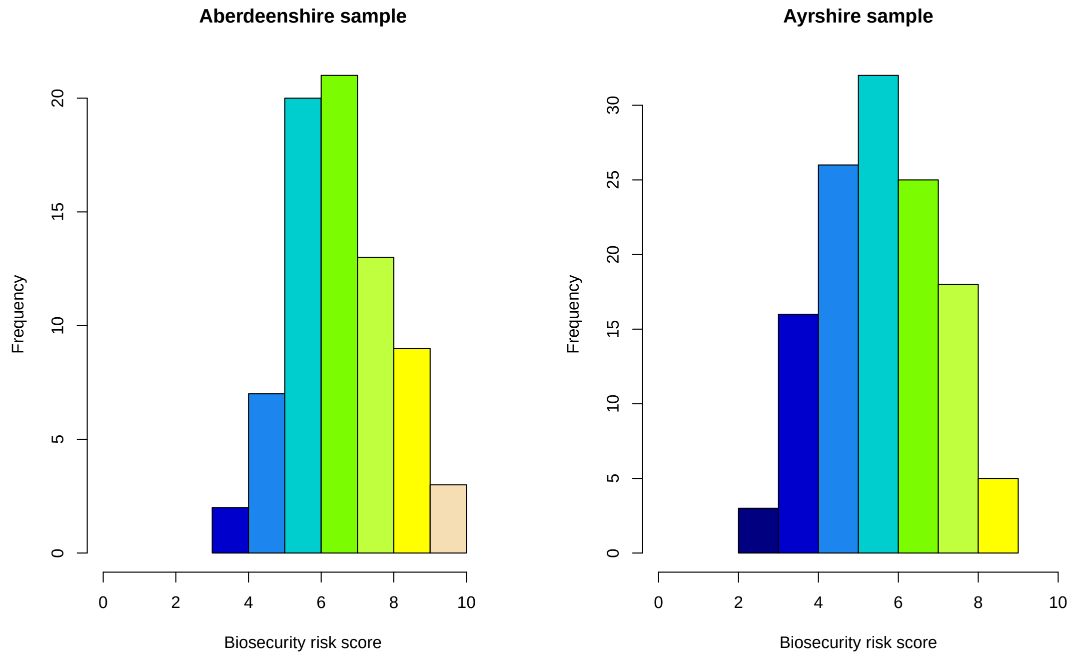



Figure 5.3: Histograms showing distribution of biosecurity risk scores in each county area.

### 5.3.2 Biosecurity practices on contiguous premises

The constructed contiguity networks for the two sample areas can be seen in Figure 5.4. Had there been any imitation behaviour in biosecurity risk practices between CPs we would expect to see clusters of premises with the same score (and therefore colour) within this network plot, but this was not observed. None of the individual biosecurity risk dimensions were assortative in either of the two county areas (Table 5.2). The Moran's I statistics were not suggestive for spatial autocorrelation in composite biosecurity risk scores in either area at any neighbour (CP) lag distance investigated (for 1st CP lag: Aberdeenshire Moran's I = 0.115, p = 0.099; Ayrshire Moran's I = 0.053, p = 0.174, Table 5.3 and Figure 5.5). This was in agreement with the assortativity values for the risk scores over the networks which were close to neutral: 0.122 in Aberdeenshire and 0.060 in Ayrshire.

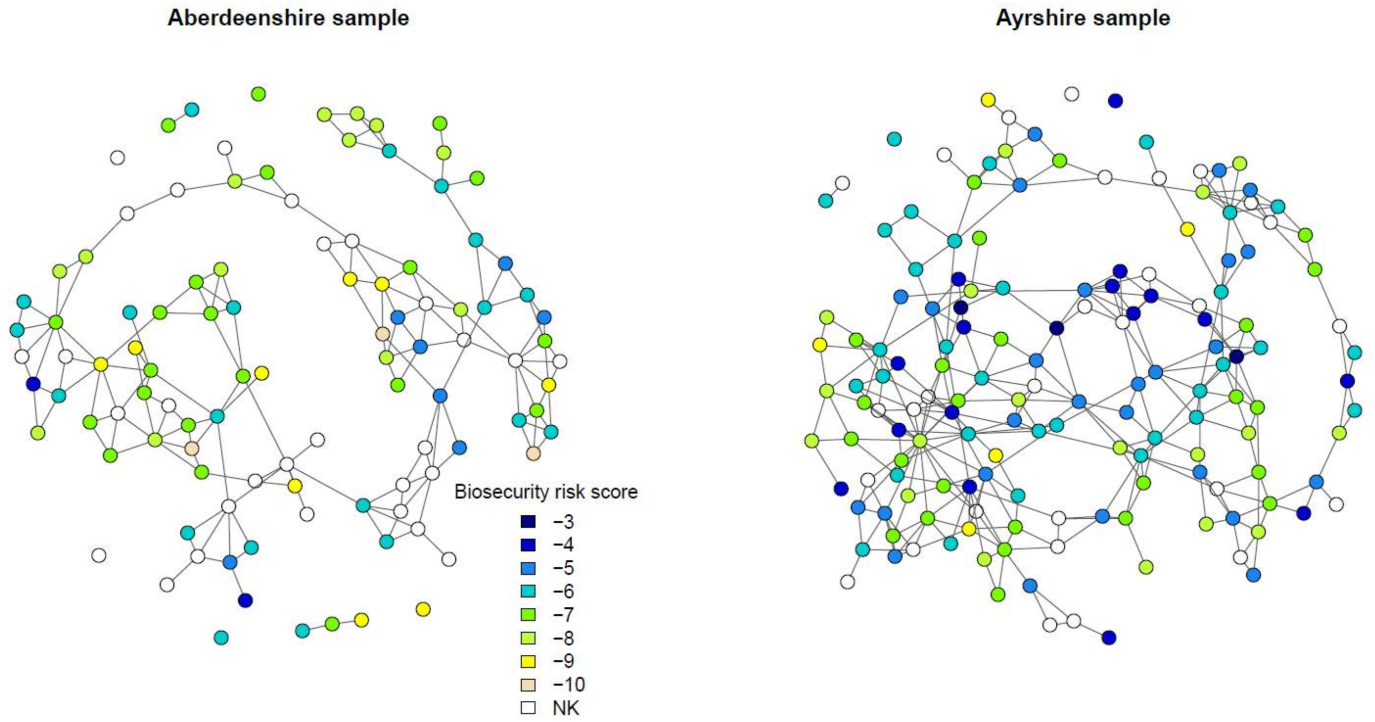



Figure 5.4: Network of premises and their biosecurity risk scores in the two county areas, displayed using a Fruchterman-Reingold layout. The circles represent farm premises, and the colour of these their biosecurity risk score. Lines between the circles are the network edges and indicate that the premises are map-based contiguous according to the definition 'All <15m'.

| Biosecurity practice: | Assortativity | |
|---|---|---|
| | Aberdeenshire | Ayrshire |
| Is there a gate at the main entrance to the farm which is kept closed all the time? | -0.011 | -0.021 |
| Is there a physical separation between public access areas and livestock areas? | 0.047 | 0.053 |
| Are there any gates onto public land, and if so are they closed and locked? | 0.014 | 0.080 |
| Is there a sign prohibiting entry at the entrance to the farm? | NA | -0.042 |
| Is car parking avaliable away from livestock access areas? | -0.011 | -0.086 |
| Is a boot dip used at entrance to farm (for all visitors that come into contact with animals)? | 0.003 | -0.010 |
| Are farm-specific boots provided for all staff and family? | 0.066 | 0.086 |
| Are farm-specific clothing provided for all staff and family? | -0.104 | 0.113 |
| Is there a clothes-changing area available? | -0.083 | -0.102 |
| Is there a farm shop/other enterprise on the premises? | 0.003 | -0.079 |
| Are dogs free-roaming on the farm/do they accompany staff around the farm premises? | -0.132 | 0.030 |
| Any 'unusual events' occurring in the 3 weeks preceding survey? | 0.057 | -0.082 |

Table 5.2: Assortativity of the networks in relation to each biosecurity risk element for each county area.

| Sample area | Moran's I | Expected value (E) | Variance of E | Standard deviate | p-value |
|---|---|---|---|---|---|
| **Aberdeenshire** | | | | | |
| 1st lag | 0.115 | -0.014 | 0.010 | 1.286 | 0.198 |
| 2nd lag | -0.101 | -0.016 | 0.008 | -0.956 | 0.339 |
| **Ayrshire** | | | | | |
| 1st lag | 0.053 | -0.009 | 0.004 | 0.937 | 0.349 |
| 2nd lag | 0.062 | -0.009 | 0.002 | 1.729 | 0.084 |

Table 5.3: Moran's I statistics for composite biosecurity risk scores in the two county areas.

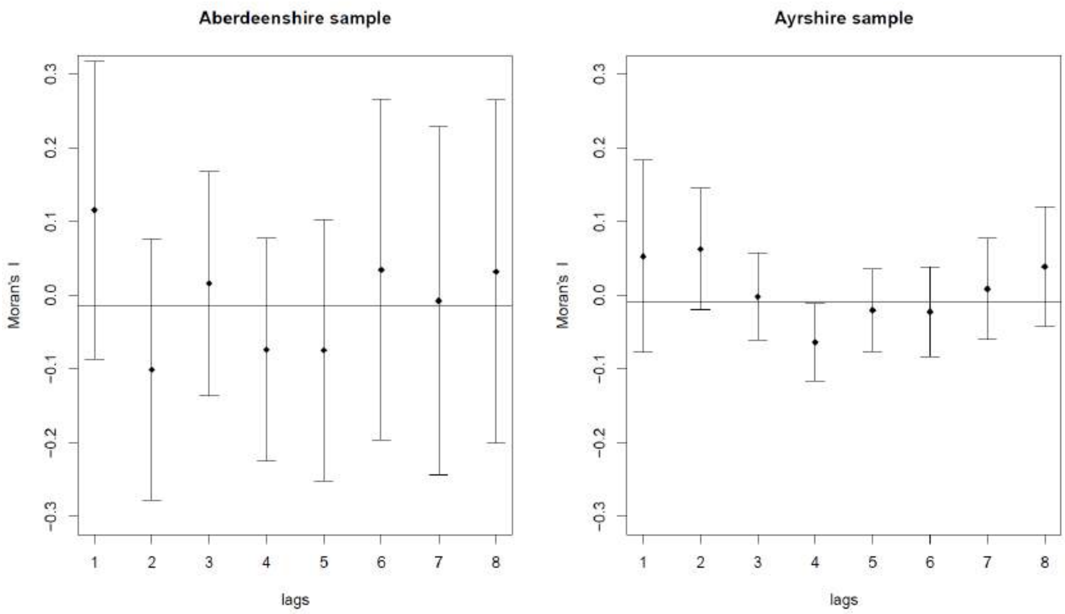



Figure 5.5: Spatial correlogram (Moran's I) of biosecurity risk scores, Ayrshire and Aberdeenshire. Error bars show +/- two standard deviations. Lags are based on map-based contiguity definition 'All <15m'.

## 5.4 Discussion

At the time of writing, this study is the largest of its kind known to have been conducted in the UK. It provided no support for the presence of imitation behaviour among farmers on contiguous premises (CPs) in terms of their FMD-related biosecurity practices. The Moran's I estimates and assortativity values for the composite FMD-biosecurity risk score showed little evidence for similarity of scores between farmers on CPs, with values <0.12 (Table 5.3). Additionally, the assortativity values for the individual risk score dimensions were between -0.132 and 0.113, meaning that there did not appear to be any increased similarity in individual practices undertaken on CPs either (Table 5.2). This is in agreement with Schmit and Rounsevell (2006) who did not find evidence supportive of land use imitation between farmers on contiguous land parcels (defined as fields <50m apart) in Belgium.

It is still possible that imitation of biosecurity practices does exist, but that contiguity of farm premises is not an accurate representation of the social network that it operates over. Indeed, Christakis and Fowler (2007) found that while social distance was associated with weight-gain in individuals, geographic distance was not. With the rise of the internet, McPherson et al. (2001) suggest that where before social distance and physical distance were similar, social distance has become more homogenised over small-medium physical distances. The findings from this study suggest this is possible in terms of farmer-communication, given that there appeared to be a slight difference in biosecurity risk score distributions between the two sample areas, with risk scores tending to be higher in Aberdeenshire. It is possible that farmers in Aberdeenshire felt less of a need to undertake biosecurity practices (at least those under study), since they felt less at risk of disease incursion from other premises because of the lower farm density compared to in Ayrshire.

There was considerable variability (6 risk 'points') in biosecurity risk scores within the two sample areas (3-9 in Ayrshire, and 4-10 in Aberdeenshire). Such variability in biosecurity between premises is not currently accounted for - at least directly - within mathematical models, but is likely to affect a premises' susceptibility. During the 2007 outbreak, after controlling for other variables, a difference of 1 risk score 'point' was found to have a 6.2 (95% CI 1.2-32.0) fold increase in risk of becoming a secondary FMD case (Ellis-Iversen et al., 2011). While the study's power was low, and the possible effect size varied substantially, this nonetheless indicates the potential for considerably increased risk of infection with just a small difference in biosecurity risk. Even taking the lower 95% CI bounding value means that premises with the highest values of biosecurity risk score would have at least $\approx 3$ times the odds of becoming infected compared to the premises with the lowest biosecurity risk scores (given a difference of 6 risk 'points', $1.2^6$). This may consequently render some areas considerably more susceptible to secondary transmissions once disease has been introduced to the area. However, more work is needed to examine whether this is the case.

Furthermore, it is possible that different dimensions of the biosecurity risk score pose different levels of risk in relation to FMD infection. When analysed in a univariate screening analysis in 2007, only four of the risk score dimensions were found to be associated (at $p<0.2$) with secondary case farms: absence of physical barriers between public access areas and livestock areas, no car parking available away from livestock access areas, free-roaming dogs, and unusual events during the risk period (Ellis-Iversen et al., 2011). That the proportion of farm premises undertaking three of these four risk dimensions was significantly different between the two sample county areas (no physical barriers, no car parking and unusual events), might make a real difference in terms of actual secondary transmission of FMD in the event of disease incursion in an area. In addition to spatial location, time of year may also make a real difference to probability of secondary transmissions in relation to FMD-related biosecurity risk. The difference in proportion of premises reporting an 'unusual event' within the 3 weeks prior to the survey between the two counties could be attributed to the timing of surveys: Ayrshire's period of survey coincided with intensive silage-making weeks and therefore an increase in use of contractors, whereas the period of surveys in Aberdeenshire fell after the silage-making period. Since having contractors on the premises was classified by Ellis-Iversen et al. (2011) as counting as an unusual event, Ayrshire had higher overall biosecurity risk scores than it would otherwise have had were the surveys conducted after the silage-making period. Ideally, the surveys in the two areas would have been conducted at the same time to avoid this confounding effect, but was not possible given the resources available for this study.

Analysis of correlations between the individual dimensions that make up the composite biosecurity risk score found only moderate correlation between provision of farm-specific boots and clothing for staff and family members. While this was not mentioned as the reason for giving a 0.5 risk point for each of these dimensions by Ellis-Iversen et al. (2011), it suggests there is good reason for weighting them less than the other dimensions, since they are clearly related. Firestone et al. (2013) also found a correlation between individuals changing clothes and changing shoes before contacting horses during an equine influenza outbreak. It is somewhat surprising that no other correlations were found between the biosecurity risk dimensions, and suggests that the score cannot be reduced in the number of dimensions information is required on, if biosecurity risk in relation to FMD is to be studied during any future outbreaks. It is also possible that the wrong questions are being asked.

The mean values of biosecurity risk scores in the two areas (6.90 in Aberdeenshire, 5.98 in Ayrshire), were higher than those of both the secondary case and control farms in Surrey in 2007 (5.6 and 4.5, respectively), although the range of risk scores were similar (3-8 in Surrey in 2007, compared to 3-9 in Ayrshire and 4-10 in Aberdeenshire during this survey). Some of the difference in mean risk scores, and the slightly smaller range in values in 2007, is likely to be due to the original study being undertaken during the outbreak period when farmers would have increased their biosecurity measures. However, the low overall levels of biosecurity measures undertaken on farms to decrease risk seem to be consistent with other findings of small proportions of farmers undertaking various biosecurity practices (Brennan and Christley, 2012; Garforth et al., 2013; Lambert et al., 2012; Noremark and Sternberg-Lewerin, 2014; Racicot et al., 2012). Additionally, not even all vets consistently undertake the biosecurity measures that they have control over (Sayers et al., 2014). Looking at vaccination uptake decisions, Fu et al. (2011) found that imitation of observed successful 'strategies' resulted in the overall vaccination levels lower than the rational optimum. Thus it is possible that biosecurity risk is higher than an economically-derived optimum, and that this may be related to imitation of biosecurity practices, at some level, among farmers.

Biosecurity advice provided by the government has been found to be negatively viewed by some farmers (Enticott et al., 2012; Heffernan et al., 2008). This is likely because of the blanket-level recommendations across the country and different production types, and individual farmers making their own observations and associations that undermine belief in the reasons behind these recommendations (Enticott et al., 2012). It is not realistically possible to always make sure that clothes are clean and boots, equipment and vehicles disinfected prior to contact with livestock (DEFRA, 2012). For example, when stock escape into neighbouring fields in which a different farm's livestock are present, it is impossible to change clothes and boots while moving the escaped stock back into their rightful field. Furthermore, different biosecurity practices are more applicable to, and realistic for, different farm production types and sizes: e.g. keeping the main gate closed all the time is not generally feasible for dairy premises due to the coming and going of milk tankers, and small premises may not be able to provide car parking away from livestock areas. How biosecurity risk scores vary with farm demography will be examined in the following chapter.

Given that farmers most commonly report to take advice on biosecurity from their local vet (Brennan and Christley, 2013; Ellis-Iversen et al., 2010; Heffernan et al., 2008), it may be that there is clustering of biosecurity relating to vet practice membership. This may not manifest as spatial clustering, since vet membership may be different between CPs, and may be more linked to production type rather than local spatial location. This is worthy of investigation, since locally-derived biosecurity recommendations are likely to result in higher levels of implementation (Enticott et al., 2012), meaning local vets could be a useful route to increase biosecurity measures during non-outbreak periods. Additionally, if levels of FMD-related biosecurity risk do cluster with vet practice membership, this may enable clusters of increased FMD-susceptibility to form in the farming landscape, and thus account for some clustering of cases in the event of any future incursions. In repeating any such surveys, ideally they would be conducted on a wider sample from across Scotland to have more confidence in the external validity of the results, and be conducted within a smaller window of time to avoid potential confounding by e.g. silage-making season.

The high level of participation in both areas suggests that this study has good internal validity. While biosecurity risk may well have been underestimated due to recall bias, it is likely that this will have been similar throughout the study samples, and therefore that the patterns in biosecurity risk observed are valid. Surveys were mostly conducted with the farm manager however, so it is possible that premises employing regular farm workers may have slightly lower implementation of biosecurity measures than reported: there is a difference between provision of e.g. farm-specific clothing and boots, and actual use of them. In this way it is possible that farm managers' biosecurity measures are different to those implemented by employees, as found by Racicot et al. (2012) in their study of poultry farms. This would however be limited to the dimensions of the risk score which employees could have any control over.

In conclusion, this study conducted in two sample areas in Scotland has found no evidence for imitation of FMD-biosecurity risks among farmers on CPs. This suggests CPs can be considered independent in terms of their FMD-biosecurity risks during the silent phase of future outbreaks and that clustering of case premises are not due to clustering of biosecurity risks. However, there was a great deal of variability of biosecurity risk scores between premises within each area, which is not currently accounted for mathematical models, but is likely to have a considerable impact on which premises become infected during an outbreak. Additionally, it is possible that imitation does occur, but over a social network different to that of the physical landscape investigated here. One possibility is that biosecurity behaviours may cluster according to local vet practice membership. This warrants investigation. As emphasised by Enticott et al. (2012), it is important that biosecurity recommendations should be at the local level, assessing relative costs and benefits of different biosecurity practices at the local social and physical landscape level. Only by being realistic about what practices make sense for different farmers in different areas to undertake, will FMD-related biosecurity measures be increased during 'peace-time' and therefore the silent spread phase in the event of a future incursion.

# 6 Farm demography in relation to FMD-biosecurity risk

## 6.1 Introduction

During all phases of an FMD outbreak, local transmission of infection will depend in part on the farm premises' level of biosecurity measures aimed at reducing transmission by indirect contact. Indeed, the majority of FMD infected premises (IPs) in Dumfries and Galloway in 2001 were likely via contaminated fomites carried by people and vehicles (Thrusfield et al., 2005): mechanisms of spread that can be prevented by biosecurity measures. While individual premises will most likely increase the biosecurity measures in place once the outbreak has been confirmed, some variation is likely to remain, and high levels of biosecurity are unlikely to be consistently applied across all premises. As discussed in the preceding chapter, during the 2007 FMD outbreak in Surrey the AHVLA created a composite biosecurity risk score which was found to be strongly positively associated with premises' infection status (Ellis-Iversen et al., 2011).

Individual biosecurity measures applied on livestock premises are likely to depend on the type of production and size of the operation. It is possible too that this will translate into different levels of overall biosecurity of a premises, and consequently their potential susceptibility to disease. In terms of production type, surveys of professionals who visit farms in their line of work suggested that pig farms were better than cattle farms, which in turn were better than sheep/goat farms at implementing biosecurity (Noremark and Sternberg-Lewerin, 2014). This was in line with Garforth et al. (2013) who found pig farms tended to have higher biosecurity in relation to staff and visitor management than did sheep farms. There is also evidence for variations in biosecurity between different production types within species. For example, among pig farms in Canada, Lambert et al. (2012) found a generally lower level of biosecurity among growing than among breeding sites, though growing sites were better at implementation of some individual biosecurity measures. This appears to contrast with fattening farms being at lower risk of infection compared to other types of pig farm during Japan's 2010 FMD outbreak (Muroga et al., 2013), which could suggest higher levels of biosecurity, although it is likely that there is variation between countries in their practices within different production types.

Regarding the economics of the balance of costs and perceived benefits of implementing biosecurity measures, it is possible that the size of the operation may determine whether or not they are undertaken: the more animals kept, the greater the potential loss in the event of disease occurrence, and hence the more cost-effective biosecurity measures may be. Indeed, Ellis-Iversen et al. (2010) found that intent to make changes in disease control behaviours was stronger among farmers with larger herds; Can and Altug (2014) found increasing herd size was significantly associated with better biosecurity practices among small-scale dairy farms in Turkey. Additionally, among pig farms, larger herd size has been found to be associated with better biosecurity practices (Boklund et al., 2004; Laanen et al., 2013). In contrast however, a large study of Welsh cattle farms identified larger herd size as being significantly associated with increased odds of having one of a number of diseases under study, which was interpreted as indicating reduced biosecurity (Ortiz-Pelaez and Pfeiffer, 2008).

The FMD models developed on the UK's 2001 outbreak include a term that describes premises' increasing susceptibility to FMD with increasing numbers of cattle and sheep kept (Tildesley and Keeling, 2009; Tildesley et al., 2008). Whether premises biosecurity is indirectly related to this term in some way would be useful to know to better understand the mechanisms of spread underlying the model. If increasing numbers of stock were associated with decreasing biosecurity risk, then the true relationship between the number of stock and susceptibility may be being underestimated. Conversely, if increasing numbers of stock relates to increasing biosecurity risk, this would suggest that at least some of the relationship observed between susceptibility and stock numbers was actually due to biosecurity risk.

Furthermore, if certain types of premises at higher risk from lack of implementation of biosecurity measures could be identified in advance of any outbreak, biosecurity promotion and education could be targeted towards such premises to encourage greater adherence to protective practices, and therefore help limit spread in the event of a subsequent outbreak. Also, in the very early stages of the outbreak when it has only just been confirmed, being able to predict the most vulnerable premises/areas around IPs would enable targeted surveillance and testing.

This chapter is concerned with whether differences in biosecurity levels among farms of different production types exist, as reported in the literature, among cattle and sheep farmers in Scotland. Whether any relationship between biosecurity and premises size translates into a relationship with FMD susceptibility, as a function of the number of cattle and sheep present on a premises (Tildesley and Keeling, 2009; Tildesley et al., 2008), is also of interest. This would indicate that the associated biosecurity risk of premises to FMD is already indirectly captured by the models. Thus, one hypothesis is that biosecurity risk scores are not equal between production types, and another that they are not equal between premises of different sizes. The composite biosecurity risk score used to examine these relationships was the same as that used in Chapter 5. It was composed of the following 12 dimensions relating to fomite transmission routes (Ellis-Iversen et al., 2011):

1. No main gate is present, or kept open some/all of the time;
2. There is no physical separation between public access areas and livestock areas;
3. There are gates onto public land, or some/all gates onto public land are not locked;
4. There is no sign prohibiting entry at the entrance to the farm;
5. Car parking is not away from the areas that livestock access;
6. A boot dip is not used at the entrance to the farm;
7. Farm-specific boots are not provided for all staff and family;
8. Farm-specific overalls are not provided for all staff and family;
9. There is no clothes-changing area available;
10. There is a farm shop or other enterprise on the premises;
11. Dogs are free-roaming and/or accompany staff around the farm premises;
12. 'Unusual events' occurred in the 'risk period' (in 2007 this ranged between 14 and 33 days).

In addition to this, production type and size were examined in relation to whether or not premises make regular movements of livestock down public roads, tracks or bridleways. It is hypothesised that dairy farms undertake such movements more commonly than other production type premises, due to moving between fields/barns and the milking parlour. This could be another important risk relating to biosecurity during the silent spread phase of an FMD outbreak, before a movement ban has been put in place.

## 6.2 Methods

For details regarding data collection by questionnaires see Chapter 5, section 5.2.1. Analyses were conducted in R (R Core Team, 2013). Descriptive analysis of reported movement-related risks were conducted using data collected in Section D of the questionnaire (see Appendix 4). Two outcomes were considered for further analysis: FMD biosecurity risk and whether or not premises undertook 'risky' movements. The composite biosecurity risk score as described above and in Chapter 5 was used as the FMD biosecurity risk outcome: this was on a scale of 0 (excellent biosecurity) to 11 (poor biosecurity) (ascertained from Section B of the questionnaire - see Appendix 4). The "'risky' movements" outcome was defined as monthly or more regular movements that were most commonly made by herding livestock down roads/tracks/bridleways (ascertained from Section D of the questionnaire). In Aberdeenshire this outcome also included premises which had stated that their stock regularly directly cross roads - a question that was included in the questionnaire after having observed this occurrence in Ayrshire.

The two outcomes were studied in relation to three exposure variables. These were:

- **Production type**. This was classified on the basis of answers to the question regarding the main production types the farmer considered were present on the premises. Farmers could give up to three main production types. Production type groups used for analysis were: beef and sheep/sheep only, beef only, and any dairy (where any of the potential three production types were dairy). There was no dairy production among the premises surveyed in Aberdeenshire. In Ayrshire, production type was also examined in terms of a two-level category: any dairy production versus beef and/or sheep production. In Ayrshire, one premises classified as 'any dairy' had reported their main production type as 'dairy breeding' and did not produce milk.

Another premises in Aberdeenshire had reported their main production type only as poultry (eggs), but kept sheep, and was hence grouped into the category 'beef and sheep/sheep only' for the purposes of analysis.

- **Holding size**. This was classified from the June census 2011. The median value of sheep and cattle on premises with $>0$ of the species, respectively, was used to divide farms into "larger" and "smaller" premises. The two sample areas were considered together in making this calculation. Among premises which kept any cattle, the median number kept was 210, and among premises keeping any sheep the median number kept was 342. Thus the two categories of premises considered were "large": $\geq$210 cattle and/or $\geq$342 sheep, and "small": $<$210 cattle and $<$342 sheep.
- **FMD susceptibility**. This was the premises-level susceptibility to FMD as defined by the FMD model using Scotland-specific parameters identified by Tildesley and colleagues (Tildesley and Keeling, 2009; Tildesley et al., 2008). The equation of susceptibility for each premises $i$ was:

$$S_i = s_{cow} N_{cow,i}^{p_c} + s_{sheep} N_{sheep,i}^{p_s}$$

  with the Scotland-specific parameters being: $s_{cow}$= 10.771, $s_{sheep}$= 1, $p_c$= 0.227, and $p_s$= 0.326.

The mean, median and range of biosecurity risk scores were calculated for subcategories within the three exposure variables described above. The proportion of premises undertaking the different dimensions of the biosecurity risk score, as well as undertaking 'risky' movements, were examined using radar plots to compare the different categories of premises.

Statistical models for each of the two sample areas were then constructed to examine the associations between the two outcomes: biosecurity risk score and 'risky' movements, and the three exposure variables: production type, premises size, and FMD susceptibility. A Gaussian Generalised Linear Model (GLM) was used to model the biosecurity risk score outcome (which was approximately Normally distributed in both areas), and a Binomial GLM was used to model 'risky' movements. The association between the exposure and outcome was assessed using a Likelihood Ratio Test of the model including the exposure variable against a model with no predictor variables. If the model incorporating the exposure variable was a significant improvement on the model with no predictor variables (at $p<0.05$), bivariate models were studied incorporating potential confounding variables into the model. If the coefficient of the confounding variable was significant ($p<0.05$), and the more complex model was a significant improvement on the simpler model (with the exposure of interest as the only predictor), with an LRT $p<0.05$, they were taken forwards. The correlation between the selected confounding variables and the exposure variable was calculated, with the confounding variable being excluded if correlation was $\geq 0.8$, since this is likely to have indicated collinearity in the model including both variables. Multivariable models were then developed in a forward step-wise procedure, including confounding variables in order of the strength of association with the outcome. A LRT was performed to test whether the more complex model was an improvement on the simpler model with the addition of each variable. The Akaike Information Criterion (AIC) was also examined when comparing models. The AIC allows models constructed on the exact same dataset to be compared, with a smaller AIC indicating a better-fitting model. It is calculated as: $AIC = -2 \times l + 2(p+1)$, where $l$ is the log likelihood and $p$ is the number of parameters (Crawley, 2007).

## 6.3 Results

### 6.3.1 Biosecurity risk score outcome

#### Production type

In Aberdeenshire, beef and sheep/sheep only premises had a higher mean and median biosecurity risk score than beef only premises, while the reverse was true in Ayrshire (Table 6.1). Holdings reporting to have any dairy production as a main production type had similar average risk scores to that of beef only premises in Ayrshire. Neither area provided any strong statistical evidence for an association between main production type and biosecurity risk score: the univariate model LRT for Aberdeenshire was p=0.155, and for Ayrshire was p=0.735 for the three-category production type, and p=0.969 for the two-category production type (Tables 6.2 and 6.3).

The only dimension of the biosecurity risk score that was considerably different between premises production types in Aberdeenshire was having free-roaming dogs (Figure 6.1): beef and sheep/sheep only premises had a higher percentage of premises with free-roaming dogs (n=38, 86.4%) compared to beef only premises (n=14, 45.2 %; Appendix 7, Table 14.1). This difference was not found in Ayrshire. In Ayrshire, a higher percentage of beef and sheep/sheep only premises had no changing area (n=9, 69.2%), compared to beef only premises (n=16, 43.2%) and premises with any dairy production (n=35, 46.7%; Figure 6.2 and Appendix 7, Table 14.2). A higher percentage of beef only premises did not provide farm-specific boots for staff and family (n=17, 45.9%), compared to premises with any dairy production (n=20, 26.7%) and beef and sheep/sheep only premises (n=3, 23.1%; Figure 6.2 and Appendix 7, Table 14.2).

### Holding size and FMD susceptibility

Smaller premises (with <342 sheep and <210 cattle) had lower mean and median biosecurity risk scores than larger premises in Aberdeenshire, while the reverse pattern was observed in Ayrshire (Table 6.1). There did not appear to be any particular pattern in the mean and median biosecurity risk scores (Table 6.1), or in the dimensions of biosecurity risk undertaken between the quantiles of susceptibility in either area (Appendix 7, Figures 14.1 and 14.2).

In Aberdeenshire, larger premises had a higher percentage than smaller premises undertaking the majority of biosecurity risk dimensions: there is no physical separation between public access areas and livestock areas, there are gates onto public land which are not locked, farm-specific boots and clothing are not provided for all staff and family, there is no clothes-changing area available, there is a farm shop/other enterprise on the premises, and dogs are free-roaming on the farm/accompany staff around the farm premises (Figure 6.3, Appendix 7, Table 14.3). In Ayrshire, larger premises had a higher percentage undertaking fewer of the biosecurity risk dimensions: there is no gate/the gate is open at the main farm entrance, there are gates onto public land which are not locked, and there is no car parking away from livestock areas (Figure 6.4, Appendix 7, Table 14.4).

The univariate GLM of biosecurity risk score outcome found premises size to be significant in Aberdeenshire ($p=0.018$, Table 6.2), but not in Ayrshire ($p=0.105$, Table 6.3). The final multivariable GLM for Aberdeenshire found that after controlling for the effects of being part of a multi-premises farm business and education level of the farmer surveyed, larger premises had a higher biosecurity risk score (Table 6.4). Controlling for premises size and education level showed that premises that were part of a multi-premises farm business had a lower biosecurity risk score; controlling for premises size and being part of a multi-premises farm business showed that premises where the farmer had college or university education had a higher biosecurity risk score (Table 6.4). Addition of the two variables (being part of a multi-premises farm business and education level) improved the model, with a drop in AIC from 254.0 in the univariate model to 246.9 in the multivariable model, and a rise in adjusted $R^2$ from 0.06 to 0.17.

The univariate GLM of FMD susceptibility was non-significant for both areas (Aberdeenshire p=0.124, Ayrshire p=0.549, Tables 6.2 and 6.3). Although not statistically significant, the directions of effect of each premises size and FMD susceptibility in Ayrshire were opposite to those observed in Aberdeenshire.

| | Aberdeenshire | | | | Ayrshire | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Range | n | Mean | Median | Range | n |
| **Main production type** | | | | | | | | |
| Any dairy | - | - | - | 0 | 6.0 | 6.0 | 3.0 - 8.5 | 75 |
| Beef only | 6.6 | 6.5 | 5.0 - 9.5 | 31 | 6.1 | 6.0 | 3.0 - 9.0 | 37 |
| Beef and sheep/sheep only | 7.1 | 7.0 | 4.0 - 10.0 | 44 | 5.7 | 5.0 | 4.0 -9.0 | 13 |
| **Holding size** | | | | | | | | |
| <342 sheep and <210 cattle | 6.5 | 6.0 | 4.0 - 9.5 | 34 | 6.2 | 6.0 | 4.0 - 9.0 | 52 |
| ≥342 sheep and/or ≥210 cattle | 7.2 | 7.0 | 4.0 - 10.0 | 41 | 5.8 | 6.0 | 3.0 -9.0 | 73 |
| **Susceptibility** | | | | | | | | |
| Quantile 1 | 6.4 | 6.0 | 4.0 - 9.0 | 27 | 5.9 | 6.0 | 4.0 - 9.0 | 23 |
| Quantile 2 | 7.3 | 7.0 | 6.0 - 9.5 | 13 | 6.4 | 6.0 | 4.0 -9.0 | 37 |
| Quantile 3 | 6.8 | 7.0 | 5.0 - 8.0 | 12 | 5.7 | 5.5 | 3.0 - 8.0 | 37 |
| Quantile 4 | 7.3 | 7.0 | 4.0 - 10.0 | 23 | 5.8 | 5.75 | 3.0 - 8.0 | 28 |

Table 6.1: Table showing mean, median and range of biosecurity risk scores by main production type, premises size and susceptibility, in each sample area. Where susceptibility was calculated as that defined by the FMD model using Scotland-specific parameters identified by Tildesley and colleagues (Tildesley and Keeling, 2009; Tildesley et al., 2008). The equation of susceptibility for each premises $i$ was:

$$S_i = s_{cow} N_{cow,i}^{p_c} + s_{sheep} N_{sheep,i}^{p_s}$$

with the Scotland-specific parameters being: $s_{cow}$= 10.771, $s_{sheep}$= 1, $p_c$= 0.227, and $p_s$= 0.326. Quantiles shown in this table are: quantile 1, $<$31.8; quantile 2, $<$37.8; quantile 3, $<$43.1; quantile 4, $\geq$ 43.1.

| Variable | Coefficient estimate | Standard error | Wald p-value | LRT p-value | Adjusted $R^2$ |
|---|---|---|---|---|---|
| **Production type** (baseline: beef and sheep/sheep only) | | | | 0.155 | 0.013 |
| Beef only | -0.43 | 0.308 | 0.162 | | |
| **Holding size** (baseline: <342 sheep and <210 cattle) | | | | 0.018 | 0.059 |
| ≥342 sheep and/or ≥210 cattle | 0.70 | 0.297 | 0.020 | | |
| **Susceptibility** | 0.02 | 0.012 | 0.131 | 0.124 | 0.018 |

Table 6.2: Univariate model results of association of variables with biosecurity risk score, Aberdeenshire.

| Variable | Coefficient estimate | Standard error | Wald p-value | LRT p-value | Adjusted $R^2$ |
|---|---|---|---|---|---|
| **Production type** (baseline: beef and sheep/sheep only) | | | | 0.735 | -0.011 |
| Beef only | 0.35 | 0.452 | 0.439 | | |
| Any dairy | 0.25 | 0.421 | 0.555 | | |
| **Holding size** (baseline: <342 sheep and <210 cattle) | | | | 0.105 | 0.013 |
| ≥342 sheep and/or ≥210 cattle | -0.41 | 0.251 | 0.108 | | |
| **Susceptibility** | -0.01 | 0.012 | 0.553 | 0.549 | -0.005 |

Table 6.3: Univariate model results of association of variables with biosecurity risk score, Ayrshire.

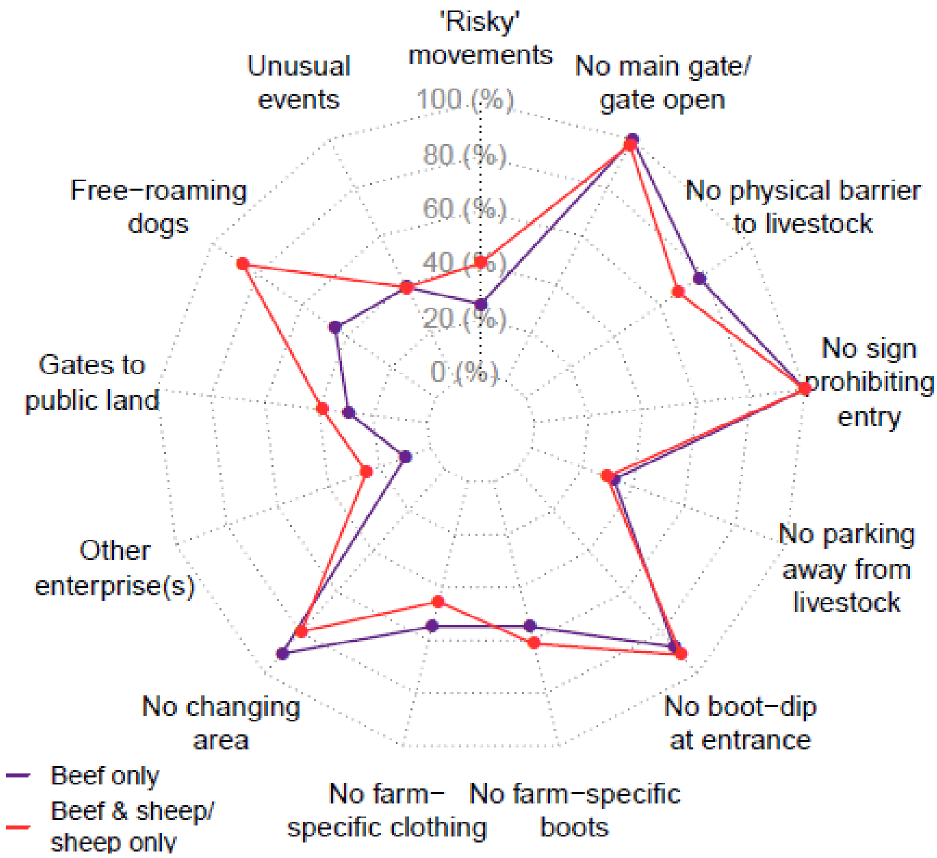



Figure 6.1: Radar chart showing proportion of premises undertaking each biosecurity risk component in Aberdeenshire, by main production type.

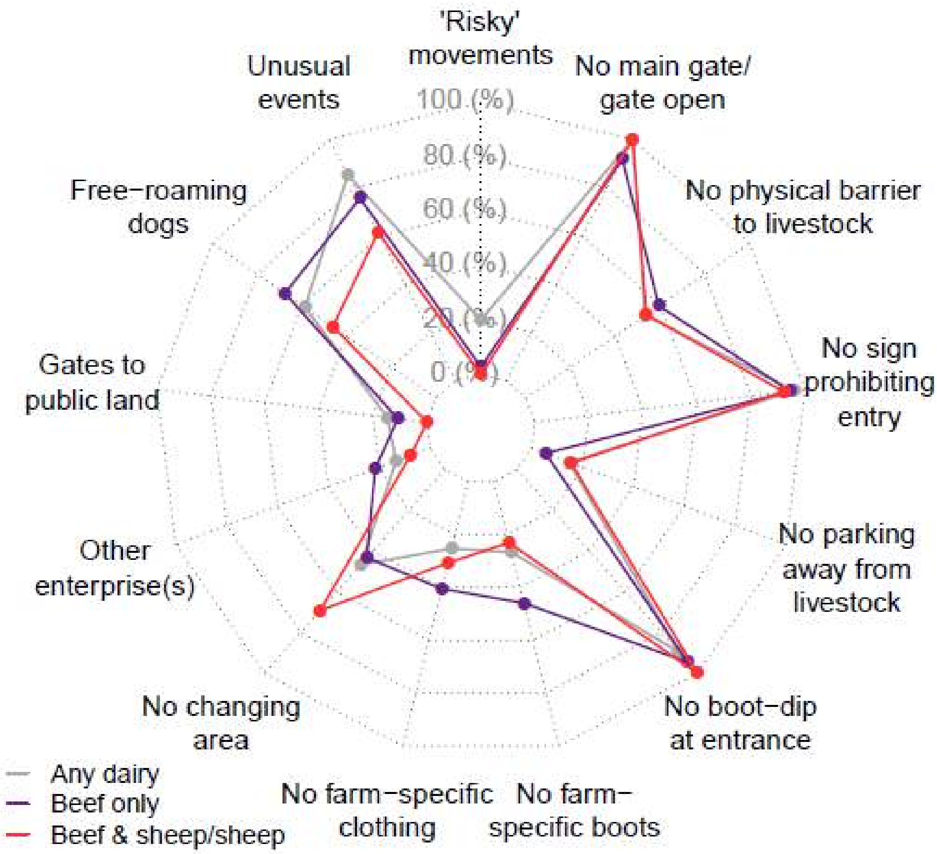



Figure 6.2: Radar chart showing proportion of premises undertaking each biosecurity risk component in Ayrshire, by main production type.

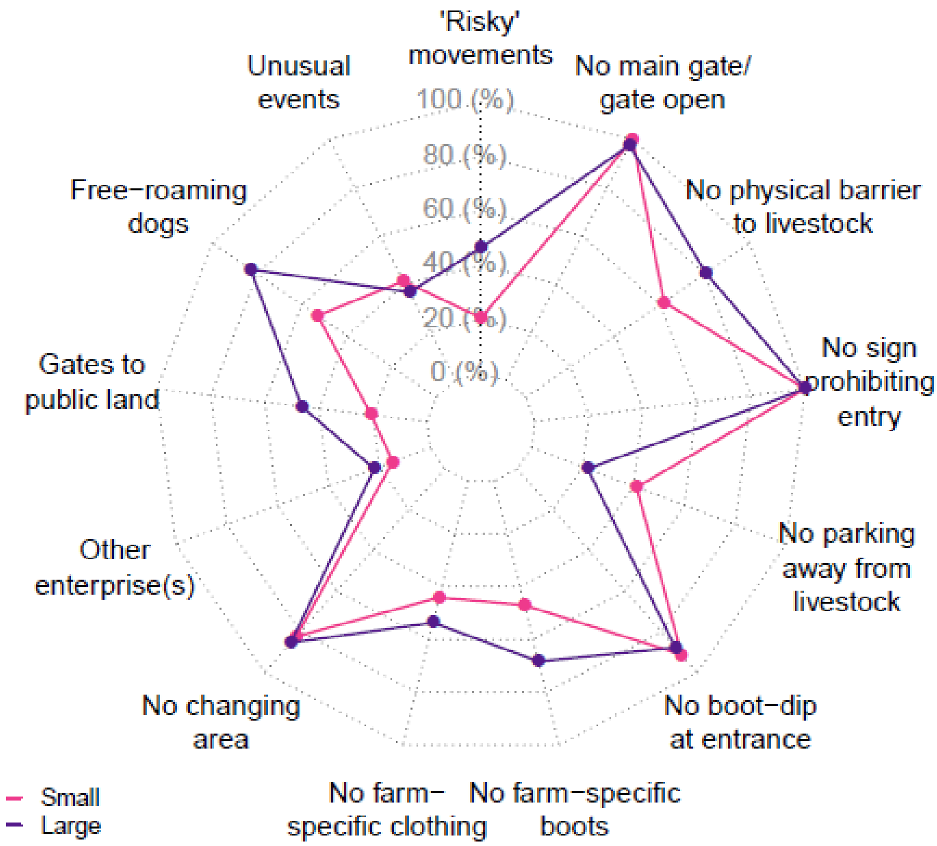



Figure 6.3: Radar chart showing proportion of premises undertaking each biosecurity risk component in Aberdeenshire, by premises size.

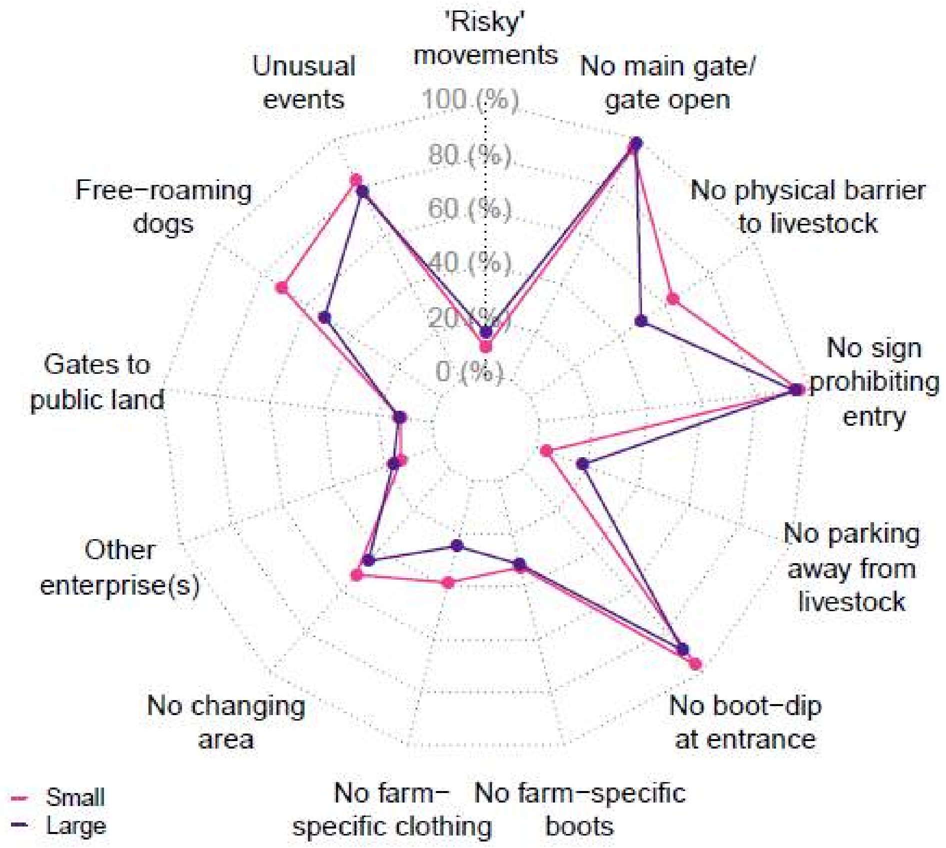



Figure 6.4: Radar chart showing proportion of premises undertaking each biosecurity risk component in Ayrshire, by premises size.

| Variable | Coefficient estimate | Standard error | Wald p-value |
|---|---|---|---|
| **Holding size** (baseline: <342 sheep and <210 cattle) | | | |
| ≥342 sheep and/or ≥210 cattle | 0.70 | 0.282 | 0.016 |
| **Part of a multi-holding farm business** (baseline : No) | | | |
| Yes | -1.03 | 0.395 | 0.011 |
| **Education level** (baseline: School) | | | |
| College or university | 0.60 | 0.282 | 0.037 |

Table 6.4: Multivariable model for biosecurity risk score outcome, Aberdeenshire.

### 6.3.2 'Risky' movements outcome

#### Description of reported movement-related risks

In Ayrshire, 26 (20.8%) and 29 (23.2%) holdings reported having a footpath running through and around the outside perimeter of a livestock field, respectively. One and three holdings reported having a footpath through and around the outside perimeter of a field which never has livestock in, respectively. In Aberdeenshire, 29 (38.7%) and 25 (33.3%) holdings reported having a footpath running through and around the outside perimeter of a livestock field, respectively, while three holdings reported having a footpath running around the outside perimeter of a field which never has livestock in. There is no 'private property' in Scotland, so this is not necessarily indicative of public access: anecdotally, holdings close to towns/villages seemed to say they had more public passing through their fields than did holdings further from towns/villages.

Given the dominance of dairy production, it was unsurprising that the majority of farms in Ayrshire reported that livestock moved between their field and the main farm buildings several times daily (n=69; 55.2%); 21 (16.8%) and 20 (16.0%) moved between their field and the main farm building less than monthly and seasonally, respectively (Table 6.5). Of the holdings that reported keeping cattle (n=69) in Aberdeenshire, only one holding reported daily movement of cattle between their field and the main farm building; the majority moved seasonally (n=31; 44.9%) or less than once a month (n=29; 42.0%), 2 holdings never moved cattle to the buildings. Of the 51 holdings that reported keeping sheep in Aberdeenshire, 19 (37.3%) holdings moved them between their field and the main farm buildings on average less than once a month, 11 (21.6%) seasonally, and 10 (19.6%) monthly (Table 6.6).

The majority of between-field movements reported in both areas were monthly or less often than monthly, although Aberdeenshire had a higher proportion of such movements (n=118/141, 83.7%) compared to Ayrshire (n=172/253, 68.0%)(Tables 6.7 and 6.8). The reported most frequent method of livestock movement between different fields was very similar between the two areas: 86.6% and 86.5% of movements were through their own premises' land or by vehicle, and 13.4% and 13.5% were by track/bridleway or herding along a road, in Ayrshire and Aberdeenshire, respectively. The breakdown of method of movement between fields in different land parcel types can be seen in Tables 6.7 and 6.8. No premises reported moving their livestock between fields mostly via another premises' land. In Aberdeenshire, responses to the extra question regarding regular crossing of roads found that 33 premises reported that their stock regularly crossed roads or were herded down roads equally often as being moved through their land; 2 further premises reported that their stock regularly crossed roads, but were usually moved by vehicle or down a track/bridleway.

In Ayrshire, the majority of daily movements between fields were via the premises' own land (n=23, 56.1%), and all of the premises reported that these movements were between fields <100m apart as part of the same CPH, except one which was to a rented premises (Table 6.9). Thirteen premises reported daily movements between fields <100m apart as part of the same CPH, that were along a track/bridleway or herding along a road. Of 101 movements reported as happening monthly or more frequently, 19 (18.8%) were between fields belonging to different premises (linked or rented) (Table 6.9).

Only 3 premises reported daily movements in Aberdeenshire, which were all through their own land (Table 6.10), and no premises reported movements between fields occurring several times a week. Thirty-five premises reported movements between fields occurring several times a month or monthly, 9 (25.7%) of which were via a track/bridleway or by herding along a road (Table 6.10). All movements monthly or more frequent were between fields belonging to the same premises.

From discussion with farmers, it was clear that the type and number of animals being moved between locations influenced the method of movement. It is easier to herd a larger number of animals than just a few, and easier to herd sheep than cattle. The distance between locations is also an influencing factor, as is the level of traffic on roads that could be used for herding. Overall, in Aberdeenshire 26 (34.7%) premises were classified as making ‘risky’ movements, while in Ayrshire 16 (12.8%) premises made such movements.

| | Number | % |
|---|---|---|
| **Several times daily** | 69 | 55.2 |
| **Several times a week** | 1 | 0.8 |
| **Weekly** | 4 | 3.2 |
| **Several times a month** | 4 | 3.2 |
| **Monthly** | 6 | 4.8 |
| **Less than once a month** | 21 | 16.8 |
| **Seasonally** | 20 | 16.0 |
| **TOTAL** | **125** | 100.0 |

Table 6.5: Frequency of movement (on average through the year) of livestock between their fields and the main farm buildings, Ayrshire.

| | Cattle | | Sheep | | TOTAL | |
|---|---|---|---|---|---|---|
| | Number | % | Number | % | Number | % |
| **Daily** | 1 | 1.3 | 0 | 0.0 | **1** | 0.7 |
| **Several times a week** | 0 | 0.0 | 1 | 1.3 | **1** | 0.7 |
| **Weekly** | 1 | 1.3 | 1 | 1.3 | **2** | 1.3 |
| **Several times a month** | 2 | 2.7 | 5 | 6.7 | **7** | 4.7 |
| **Monthly** | 3 | 4.0 | 10 | 13.3 | **13** | 8.7 |
| **Less than once a month** | 29 | 38.7 | 19 | 25.3 | **48** | 32.0 |
| **Seasonally** | 31 | 41.3 | 11 | 14.7 | **42** | 28.0 |
| **Never** | 2 | 2.7 | 4 | 5.3 | **6** | 4.0 |
| **NA** | 6 | 8.0 | 24 | 32.0 | **30** | 20.0 |
| **TOTAL** | **75** | 100.0 | **75** | 100.0 | **150** | 100.0 |

Table 6.6: Frequency of movement (on average through the year) of livestock between their fields and the main farm buildings, Aberdeenshire.

| Movement type | Same CPH <100m | | Same CPH >100m | | Different but linked premises (same MLC and/or CTS Linked) | | Rented premises | | TOTAL | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number | % | Number | % | Number | % | Number | % | Number | % |
| **FREQUENCY** | | | | | | | | | | |
| **Daily** | 36 | 28.8 | 1 | 0.8 | 3 | 2.4 | 1 | 0.8 | **41** | **8.2** |
| **Several times a week** | 11 | 8.8 | 1 | 0.8 | 1 | 0.8 | 0 | 0.0 | **13** | **2.6** |
| **Several times a month** | 16 | 12.8 | 1 | 0.8 | 7 | 5.6 | 3 | 2.4 | **27** | **5.4** |
| **Monthly** | 11 | 8.8 | 5 | 4.0 | 3 | 2.4 | 1 | 0.8 | **20** | **4.0** |
| **Less than once a month** | 22 | 17.6 | 5 | 4.0 | 5 | 4.0 | 4 | 3.2 | **36** | **7.2** |
| **Seasonally** | 28 | 22.4 | 24 | 19.2 | 34 | 27.2 | 30 | 24.0 | **116** | **23.2** |
| **NA** | 1 | 0.8 | 88 | 70.4 | 72 | 57.6 | 86 | 68.8 | **247** | **49.4** |
| **TOTAL** | **125** | **100.0** | **125** | **100.0** | **125** | **100.0** | **125** | **100.0** | **500** | **100.0** |
| | | | | | | | | | | |
| **METHOD** | | | | | | | | | | |
| **Premises' land** | 97 | 78.2 | 3 | 8.1 | 5 | 9.4 | 8 | 20.5 | **113** | **44.7** |
| **Vehicle** | 4 | 3.2 | 30 | 81.1 | 45 | 84.9 | 27 | 69.2 | **106** | **41.9** |
| **Track/bridleway** | 10 | 8.1 | 0 | 0.0 | 0 | 0.0 | 1 | 2.6 | **11** | **4.3** |
| **Walking/herding along road** | 13 | 10.5 | 4 | 10.8 | 3 | 5.7 | 3 | 7.7 | **23** | **9.1** |
| **TOTAL** | **124** | **100.0** | **37** | **100.0** | **53** | **100.0** | **39** | **100.0** | **253** | **100.0** |

Table 6.7: Frequency and method of movement of livestock between fields belonging to different parcel types, Ayrshire.

| Movement type | Same CPH <100m | | Same CPH >100m | | Different but linked premises (same MLC and/or CTS Linked) | | Rented premises | | TOTAL | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number | % | Number | % | Number | % | Number | % | Number | % |
| **FREQUENCY** | | | | | | | | | | |
| **Daily** | 3 | 4.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | **3** | **1.0** |
| **Several times a week** | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | **0** | **0.0** |
| **Several times a month** | 20 | 26.7 | 0 | 0.0 | 0 | 0.0 | 0 | 0.0 | **20** | **6.7** |
| **Monthly** | 14 | 18.7 | 1 | 1.3 | 0 | 0.0 | 0 | 0.0 | **15** | **5.0** |
| **Less than once a month** | 26 | 34.7 | 1 | 1.3 | 4 | 5.3 | 0 | 0.0 | **31** | **10.3** |
| **Seasonally** | 11 | 14.7 | 22 | 29.3 | 34 | 45.3 | 5 | 6.7 | **72** | **24.0** |
| **Never** | 0 | 0.0 | 3 | 4.0 | 3 | 4.0 | 0 | 0.0 | **6** | **2.0** |
| **NA** | 1 | 1.3 | 48 | 64.0 | 34 | 45.3 | 70 | 93.3 | **153** | **51.0** |
| **TOTAL** | **75** | **100.0** | **75** | **100.0** | **75** | **100.0** | **75** | **100.0** | **300** | **100.0** |
| | | | | | | | | | | |
| **METHOD** | | | | | | | | | | |
| **Premises' land** | 60 | 81.1 | 2 | 8.3 | 5 | 13.2 | 0 | 0.0 | **67** | **47.5** |
| **Vehicle** | 2 | 2.7 | 16 | 66.7 | 33 | 86.8 | 4 | 75.0 | **55** | **39.0** |
| **Track/bridleway** | 6 | 8.1 | 2 | 8.3 | 0 | 0.0 | 0 | 0.0 | **8** | **5.7** |
| **Walking/herding along road** | 6 | 8.1 | 4 | 16.7 | 0 | 0.0 | 1 | 25.0 | **11** | **7.8** |
| **TOTAL** | **74** | **100.0** | **24** | **100.0** | **38** | **100.0** | **5** | **100.0** | **141** | **100.0** |

Table 6.8: Frequency and method of movement of livestock between fields belonging to different parcel types, Aberdeenshire.

| Frequency / Method of movement | Same CPH <100m | Same CPH >100m | Different but linked premises (same MLC and/or CTS Linked) | Rented premises | TOTAL | % |
|---|---|---|---|---|---|---|
| **DAILY** | | | | | | |
| Premises' land | 22 | 0 | 0 | 1 | **23** | **56.1** |
| Vehicle | 1 | 1 | 3 | 0 | **5** | **12.2** |
| Track/bridleway | 6 | 0 | 0 | 0 | **6** | **14.6** |
| Walking/herding along road | 7 | 0 | 0 | 0 | **7** | **17.1** |
| **TOTAL** | **36** | **1** | **3** | **1** | **41** | **100.0** |
| **SEVERAL TIMES A WEEK** | | | | | | |
| Premises' land | 10 | 1 | 0 | 0 | **11** | **84.6** |
| Vehicle | 0 | 0 | 1 | 0 | **1** | **7.7** |
| Track/bridleway | 0 | 0 | 0 | 0 | **0** | **0.0** |
| Walking/herding along road | 1 | 0 | 0 | 0 | **1** | **7.7** |
| **TOTAL** | **11** | **1** | **1** | **0** | **13** | **100.0** |
| **SEVERAL TIMES A MONTH** | | | | | | |
| Premises' land | 16 | 0 | 1 | 2 | **19** | **70.4** |
| Vehicle | 0 | 1 | 6 | 0 | **7** | **25.9** |
| Track/bridleway | 0 | 0 | 0 | 0 | **0** | **0.0** |
| Walking/herding along road | 0 | 0 | 0 | 1 | **1** | **3.7** |
| **TOTAL** | **16** | **1** | **7** | **3** | **27** | **100.0** |
| **MONTHLY** | | | | | | |
| Premises' land | 10 | 1 | 0 | 0 | **11** | **55.0** |
| Vehicle | 0 | 2 | 3 | 0 | **5** | **25.0** |
| Track/bridleway | 0 | 0 | 0 | 0 | **0** | **0.0** |
| Walking/herding along road | 1 | 2 | 0 | 1 | **4** | **20.0** |
| **TOTAL** | **11** | **5** | **3** | **1** | **20** | **100.0** |
| | | | | | | |
| **LESS THAN ONCE A MONTH** | | | | | | |
| Premises' land | 17 | 0 | 0 | 1 | **18** | **50.0** |
| Vehicle | 1 | 4 | 5 | 3 | **13** | **36.1** |
| Track/bridleway | 3 | 0 | 0 | 0 | **3** | **8.3** |
| Walking/herding along road | 1 | 1 | 0 | 0 | **2** | **5.6** |
| **TOTAL** | **22** | **5** | **5** | **4** | **36** | **100.0** |
| | | | | | | |
| **SEASONALLY** | | | | | | |
| Premises' land | 22 | 1 | 4 | 4 | **31** | **26.7** |
| Vehicle | 2 | 22 | 27 | 24 | **75** | **64.7** |
| Track/bridleway | 1 | 0 | 0 | 1 | **2** | **1.7** |
| Walking/herding along road | 3 | 1 | 3 | 1 | **8** | **6.9** |
| **TOTAL** | **28** | **24** | **34** | **30** | **116** | **100.0** |

Table 6.9: Breakdown of method of movement of livestock between fields belonging to different parcel types by frequency of movement, Ayrshire.

| Frequency / Method of movement | Same CPH <100m | Same CPH >100m | Different but linked premises (same MLC and/or CTS Linked) | Rented premises | TOTAL | % |
|---|---|---|---|---|---|---|
| **DAILY** | | | | | | |
| Premises' land | 3 | 0 | 0 | 0 | **3** | **100.0** |
| Vehicle | 0 | 0 | 0 | 0 | **0** | **0.0** |
| Track/bridleway | 0 | 0 | 0 | 0 | **0** | **0.0** |
| Walking/herding along road | 0 | 0 | 0 | 0 | **0** | **0.0** |
| **TOTAL** | **3** | **0** | **0** | **0** | **3** | **100.0** |
| | | | | | | |
| **SEVERAL TIMES A MONTH** | | | | | | |
| Premises' land | 16 | 0 | 0 | 0 | **16** | **80.0** |
| Vehicle | 0 | 0 | 0 | 0 | **0** | **0.0** |
| Track/bridleway | 1 | 0 | 0 | 0 | **1** | **5.0** |
| Walking/herding along road | 3 | 0 | 0 | 0 | **3** | **15.0** |
| **TOTAL** | **20** | **0** | **0** | **0** | **20** | **100.0** |
| | | | | | | |
| **MONTHLY** | | | | | | |
| Premises' land | 10 | 0 | 0 | 0 | **10** | **66.7** |
| Vehicle | 0 | 0 | 0 | 0 | **0** | **0.0** |
| Track/bridleway | 3 | 0 | 0 | 0 | **3** | **20.0** |
| Walking/herding along road | 1 | 1 | 0 | 0 | **2** | **13.3** |
| **TOTAL** | **14** | **1** | **0** | **0** | **15** | **100.0** |
| | | | | | | |
| **LESS THAN ONCE A MONTH** | | | | | | |
| Premises' land | 20 | 0 | 1 | 0 | **21** | **67.7** |
| Vehicle | 2 | 1 | 3 | 0 | **6** | **19.4** |
| Track/bridleway | 2 | 0 | 0 | 0 | **2** | **6.5** |
| Walking/herding along road | 2 | 0 | 0 | 0 | **2** | **6.5** |
| **TOTAL** | **26** | **1** | **4** | **0** | **31** | **100.0** |
| | | | | | | |
| **SEASONALLY** | | | | | | |
| Premises' land | 11 | 2 | 4 | 0 | **17** | **23.6** |
| Vehicle | 0 | 15 | 30 | 4 | **49** | **68.1** |
| Track/bridleway | 0 | 2 | 0 | 0 | **2** | **2.8** |
| Walking/herding along road | 0 | 3 | 0 | 1 | **4** | **5.6** |
| **TOTAL** | **11** | **22** | **34** | **5** | **72** | **100.0** |

Table 6.10: Breakdown of method of movement of livestock between fields belonging to different parcel types by frequency of movement, Aberdeenshire.

#### Production type

A higher percentage of beef and sheep/sheep only premises made 'risky' movements (n=18, 40.9%) compared to beef only (n=8, 25.8%) premises in Aberdeenshire (Figure 6.1; Appendix 7, Table 14.1). However, production type was non-significant (p=0.172) in the univariate model for the 'risky' movement outcome (Table 6.11).

In Ayrshire however, no beef and sheep/sheep only premises and only one beef only (2.7%) premises made 'risky' movements, while 15 (20.0%) dairy premises did (Figure 6.2; Appendix 7, Table 14.2). For the two-category production type exposure variable, the univariate model for the 'risky' movements outcome found premises with any dairy production to be 12.25 times the odds of making such movements. While the 95% confidence interval for this was extremely large (2.35-225.39), the model was a significant improvement on the null model with no predictor variables (p=0.001, Table 6.12). After controlling for the number of sheep kept on contiguous premises (CPs) (a measure of sheep density in the local area), the odds ratio for premises with any dairy production increased to 13.93 (95% CI 2.57-260.51, p=0.001) compared to premises with beef and/or sheep production (Table 6.13). After controlling for the effects of production type, having $\geq$392 sheep on CPs increased the odds of premises making 'risky' movements ($\geq$392 but $<$1215 sheep on CPs: OR=5.37, 95% CI 1.59-19.34; $\geq$1215 sheep on CPs: OR=2.22, 95% CI 0.29-12.02) compared to baseline ($<$392 sheep on CPs) (Table 6.13). The AIC of the multivariable model including the term for number of sheep on CPs was 85.6 compared to 88.9 for the univariate model with only production type.

### Holding size and FMD susceptibility

In Aberdeenshire, a higher percentage of larger premises undertook 'risky' movements (n=19, 46.3%) compared to smaller premises (n=7, 20.6%; Figure 6.3 and Appendix 7, Table 14.3). The univariate GLM was found to be significant (p=0.018): larger premises had 3.33 times the odds (95% CI 1.22-9.88) of making 'risky' movements compared to smaller premises (Table 6.11). No potential confounding variables were found to be significant. The observed relationship with premises size did not however translate into a significant relationship between premises FMD susceptibility and 'risky' movements. The lowest quantile of susceptibility had a smaller percentage undertaking 'risky' movements than the highest quantile (Appendix 7, Figure 14.1), but the relationship between the two variables was not significant in the univariate GLM (p=0.127; Table 6.11).

There was little difference in the percentage of smaller (n=5, 9.6%) and larger (n=11, 15.1%) premises undertaking 'risky' movements in Ayrshire (Figure 6.4 and Appendix 7, Table 14.4). The univariate GLM for the outcome 'risky' movements found the relationship with premises size to be non-significant (p=0.362; Table 6.12). This carried through to the relationship with FMD susceptibility (p=0.107; Table 6.12). Nonetheless, the direction of effect of both exposure variables was the same as identified in Aberdeenshire.

| Variable | Odds Ratio | 95% CI | LRT p-value | Coefficient estimate | Standard error | Wald p-value |
|---|---|---|---|---|---|---|
| **Production type** (baseline: beef and sheep/sheep only) | | | 0.172 | | | |
| Beef only | 0.50 | (0.18-1.34) | | -0.69 | 0.512 | 0.179 |
| **Holding size** (baseline: <342 sheep and <210 cattle) | | | 0.018 | | | |
| ≥342 sheep and/or ≥210 cattle | 3.33 | (1.22 - 9.88) | | 1.20 | 0.527 | 0.022 |
| **Susceptibility** | 1.03 | (0.99 - 1.08) | 0.127 | 0.03 | 0.021 | 0.142 |

Table 6.11: Univariate model results of association of variables with ‘risky’ movements, Aberdeenshire.

| Variable | Odds Ratio | 95% CI | LRT p-value | Coefficient estimate | Standard error | Wald p-value |
|---|---|---|---|---|---|---|
| **Production type** (baseline: beef and/or sheep) | | | 0.001 | | | |
| Any dairy | 12.25 | (2.35 - 225.39) | | 2.51 | 1.051 | 0.017 |
| **Holding size** (baseline: <342 sheep and <210 cattle) | | | 0.362 | | | |
| ≥342 sheep and/or ≥210 cattle | 1.67 | (0.57 - 5.59) | | 0.51 | 0.573 | 0.372 |
| **Susceptibility** | 1.05 | (0.99 - 1.13) | 0.107 | 0.05 | 0.034 | 0.139 |

Table 6.12: Univariate model results of association of variables with ‘risky’ movements, Ayrshire.

| Variable | Odds Ratio | 95% CI | LRT p-value | Coefficient estimate | Standard error | Wald p-value |
|---|---|---|---|---|---|---|
| **Production type** (baseline: beef and/or sheep) | | | 0.001 | | | |
| Any dairy | 13.93 | (2.57 - 260.51) | | 1.07 | 2.471 | 0.013 |
| **Number of sheep on contiguous premises** (baseline: <392) | | | 0.026 | | | |
| <1215 sheep | 5.37 | (1.59 - 19.34) | | 0.63 | 2.671 | 0.008 |
| ≥1215 sheep | 2.22 | (0.29 - 12.02) | | 0.91 | 0.879 | 0.379 |

Table 6.13: Multivariable model for ‘risky’ movements outcome, Ayrshire.

### 6.3.3 Risky movements in relation to biosecurity risk score

Undertaking ‘risky’ movements appeared to be associated with having a higher biosecurity risk score in both areas, with higher mean and median scores among premises that undertake ‘risky’ movements in both areas (Table 6.14). In Aberdeenshire, premises making ‘risky’ movements also had a larger percentage undertaking each biosecurity risk dimension compared to premises that did not make ‘risky’ movements, except for not having a boot-dip at the farm entrance (Figure 6.5 and Appendix 7, Table 14.3). In Ayrshire, premises making ‘risky’ movements had a higher percentage undertaking the majority of the biosecurity risk dimensions, except for the dimensions: no parking away from livestock areas, farm specific boots are not provided for all staff and family, there is no clothes changing area available, and there is a farm shop/other enterprise on the premises. The largest differences found between premises making ‘risky’ movements and premises not making such movements were for dimensions: free-roaming dogs and ‘unusual events’ in the three weeks prior to survey, both of which had a higher proportion undertaking the risks among premises making ‘risky’ movements (Figure 6.6 and Appendix 7, Table 14.4).

| | Aberdeenshire | | | | Ayrshire | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Range | n | Mean | Median | Range | n |
| **'Risky' movements** | | | | | | | | |
| Yes | 7.4 | 7.3 | 4.0 - 10.0 | 26 | 6.3 | 6.3 | 4.0 - 8.0 | 16 |
| No | 6.6 | 6.5 | 4.0 - 9.5 | 49 | 5.9 | 6.0 | 3.0 - 9.0 | 109 |

Table 6.14: Table showing mean, median and range of biosecurity risk scores by whether or not premises undertake ‘risky’ movements.

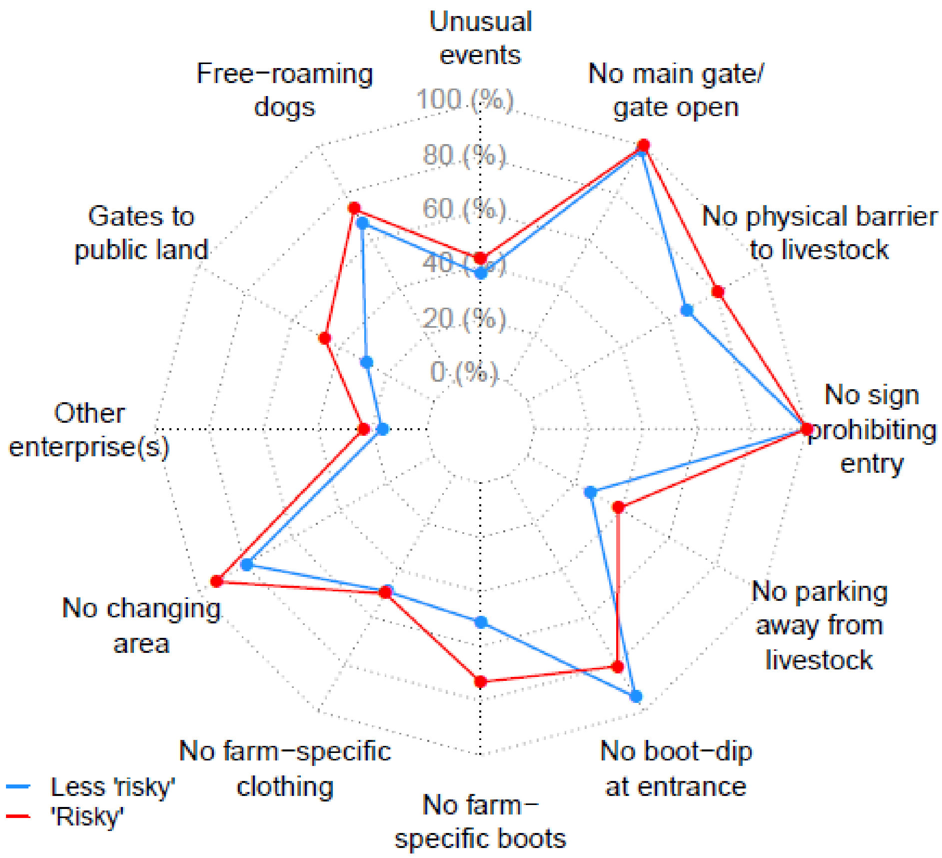



Figure 6.5: Radar chart showing proportion of premises undertaking each biosecurity risk component in Aberdeenshire, by whether or not they undertake 'risky' movements.

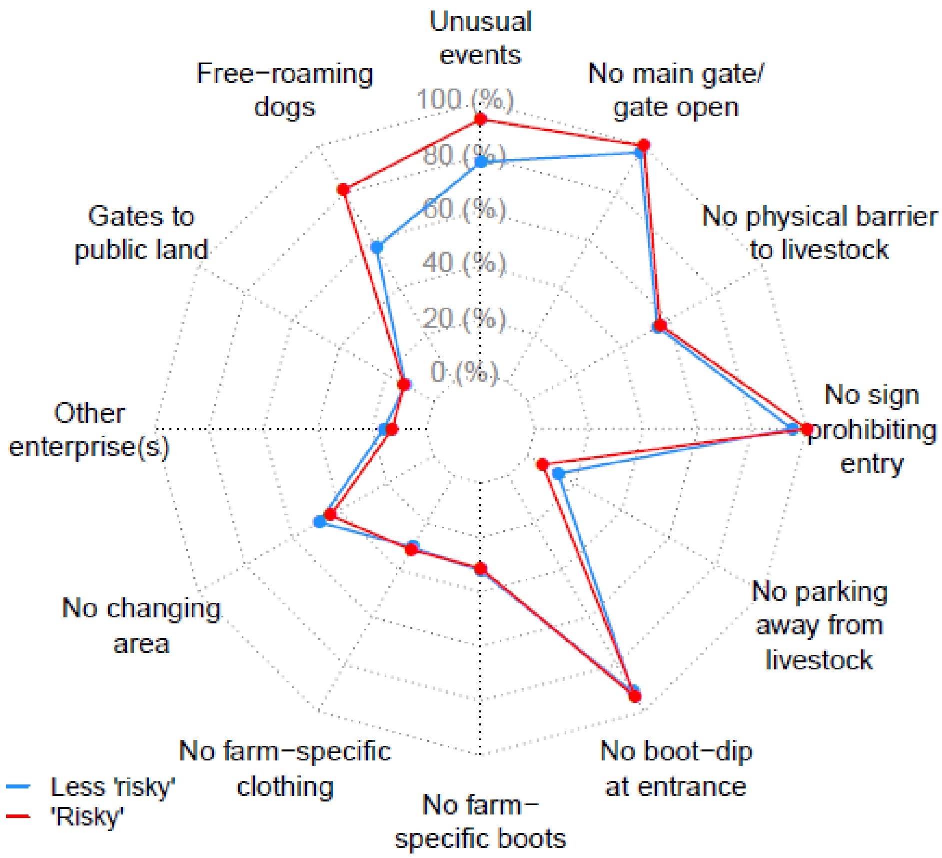



Figure 6.6: Radar chart showing proportion of premises undertaking each biosecurity risk component in Ayrshire, by whether or not they undertake 'risky' movements.

## 6.4 Discussion

This study did not find any clear association between premises size and biosecurity risk in Ayrshire. However, in Aberdeenshire, larger premises (in terms of number of animals) were found to be associated with a higher biosecurity risk score, meaning a poorer level of biosecurity compared to smaller premises. This is in agreement with Ortiz-Pelaez and Pfeiffer (2008) suggestion that increased odds of larger farm premises in having one of several diseases reflected poorer biosecurity among Welsh cattle premises. However, it contrasts to the findings of other studies reported in the literature which have indicated that larger farms tend to have better biosecurity (Can and Altug, 2014; Ellis-Iversen et al., 2010; Laanen et al., 2013). These disagreements could possibly be explained by additional inclusion of the variable 'part of a multi-premises farm business' in the final multivariable model presented here. This indicates that being part of a multi-farm business is associated with a reduction in biosecurity risk, and that this is of greater magnitude than the increase associated with larger premises size. It is clear from Ortiz-Pelaez and Pfeiffer (2008) that the premises level is equivalent to that used in this analysis, but unclear in the other studies if this was the case. Thus it is possible that if the studies were at the 'farm business' level the relationship of better biosecurity with larger size could have been observed and be in line with the results found here.

Education level was also in the final multivariable model of biosecurity risk score for Aberdeenshire, with farmers with college or university level education tending to have higher biosecurity risk than those educated only to school level. This, too, is in disagreement with other studies finding higher levels of education to be associated with improved biosecurity practices (Can and Altug, 2014; Laanen et al., 2013; Racicot et al., 2012), or in interest in biosecurity (Garforth et al., 2013). From observation, it seemed that those with higher education in Aberdeenshire tended to farm supplementary to another (main-income) job, and that their higher education subject was less likely to be in agriculture (which had seemed the most common subject studied among farmers in Ayrshire with higher education). This may result in those with degrees in other subject areas' knowledge of, and commitment to, biosecurity practices being less than those with higher education in agriculture. Collecting this further detail on the subject of study would in retrospect have been extremely useful, and may have highlighted a relationship more in keeping with other studies' findings.

While this study found no clear association between a premises' production type and biosecurity risk score in either of the areas surveyed, having any dairy production was found to be strongly associated with an increased odds of making 'risky' movements - monthly or more regular movements by road/track/bridleway - in Ayrshire (OR=13.93, 95% CI 2.57-260.51). In addition to production type, increasing sheep density around premises was also found to significantly increase the odds of making 'risky' movements. A higher local sheep density might indicate that premises are situated in more remote areas with quieter roads surrounding them, making it more likely that farmers would choose to walk the animals by road as was mentioned by several farmers surveyed. Future analysis of volume of traffic down roads adjacent to premises would help to assess whether this is the case.

The findings from this study suggest that during the silent phase of an FMD outbreak, dairy premises may be at increased risk of becoming infected as a result of 'risky' movements and of transmitting by this route if they became infected. However, if local sheep density is related to remoteness of location and traffic volume, it may be that there is a lower risk of fomite contamination of the roads that these livestock are herded down.

In the absence of any dairy production among the premises surveyed in Aberdeenshire, there did not appear to be a difference in 'risky' movements between beef and sheep/sheep only premises and beef only premises. However, larger premises with more animals were associated with significant increase in odds of making 'risky' movements compared to smaller premises in Aberdeenshire (OR=3.33, 95% CI 1.22-9.88). This may be due to both the fact that having a larger number of animals requires a larger land area and hence potential distance between fields, and that several farmers mentioned in conversation that herding animals on foot was easier when more animals needed to be moved. While the association between premises size and 'risky' movements showed the same direction of association in Ayrshire, this was not statistically significant.

Many premises have fields located on either side of a road. Premises field layout in relation to the network of roads is not something that can be easily changed, and therefore movement of livestock across/down intervening roads cannot be helped if that is the given geography of the premises. It seems unlikely therefore that 'risky' movements could feasibly be avoided by those premises that currently make them, especially when in relation to direct crossing of roads or short-distance movements. It would be logistically highly impractical to load up a large number of animals into vehicles for transporting a short distance down, or even across, the road when they could instead be herded down a road or track. Using vehicles for such transport would not only increase the time taken to move stock, but also may cause the animals undue stress.

Neither the observed association between premises size and biosecurity risk score or premises size and 'risky' movements in Aberdeenshire translated into a statistically significant association of FMD susceptibility and either outcome. However, the data suggested a positive (but statistically non-significant) association between susceptibility and making 'risky' movements in both areas (Aberdeenshire p=0.127, Ayrshire p=0.107). It may be that a larger sample size is required to provide greater power for support of this association. Nonetheless, the results of this study suggest that premises biosecurity is not being indirectly captured by the FMD model of Tildesley and colleagues (Tildesley and Keeling, 2009; Tildesley et al., 2008). Therefore it seems that increased susceptibility of larger premises does relate to number of livestock (as described by the model) rather than an associated increase in biosecurity risk with larger numbers of stock. Furthermore, the model was parameterised from data on transmission following the introduction of the movement ban, when biosecurity would likely have been elevated and practices more homogeneously applied between premises than was observed in this 'peace-time' study. Thus, any association between susceptibility and biosecurity risk would likely be dampened rather than strengthened in the event of a known outbreak.

The higher percentage of premises in Aberdeenshire undertaking 'risky' movements compared to in Ayrshire (26/75=34.7% compared to 16/125=12.8%), will in large part be due to the inclusion of the extra question regarding regular direct crossing of roads in the Aberdeenshire questionnaire. Since this phenomenon was regularly observed in Ayrshire - particularly of dairy cattle crossing roads to get from field to milking parlour - it is expected that the number of premises making 'risky' movements in Ayrshire to be higher than that reported here. It is likely that this would only have served to strengthen the association between having any dairy production and making 'risky' movements in Ayrshire. It might also have strengthened the association between premises size and 'risky' movements.

Making regular movements of livestock by herding down roads/tracks/bridleways may be an important exposure factor to consider for premises that become infected during the silent spread phase of an FMD outbreak. Indeed, it may even continue to occur once the outbreak has been detected and a movement ban put in place, as Bates et al (2003) found that experts believed some movements continue despite such bans (although it is likely such movements would mostly be by vehicle). 'Risky' movements could therefore be considered as another dimension of biosecurity risk and may be worth incorporating into the AHVLA's existing biosecurity risk score, particularly if premises biosecurity during the silent phase or 'peace time' is of interest. However, given that premises making 'risky' movements also appeared to have higher biosecurity risk scores in both areas surveyed, it is possible that its addition would be superfluous.

In conclusion, this study found some evidence for larger premises having worse biosecurity and for undertaking 'risky' movements more often than smaller premises, and for premises with any dairy production to be more likely to make 'risky' movements compared to premises with only beef and/or sheep production. While larger premises could be targeted for biosecurity awareness for the dimensions relating to the risk score as found to be associated with FMD infection by Ellis-Iversen et al. (2011), it seems unlikely that 'risky' movements could logistically feasibly be avoided by those premises that currently make them. However, given that premises making 'risky' movements appeared to have higher biosecurity risk scores, targeting biosecurity promotion at larger premises that tend to have higher risk scores may prove a more feasible intervention, and therefore may be more likely to actually be taken into effect. That no association between premises FMD susceptibility and biosecurity risk score or 'risky' movements were detected suggests that the susceptibility of premises described by the FMD models does indeed relate to numbers of livestock rather than to any associated increase in biosecurity risk with larger number of animals.

# 7 General discussion

This thesis has considered the local epidemiology of FMD in relation to the farming landscape, investigating the assumptions of the transmission and susceptibility parameters of the Keeling et al. (2001) model. In the main, it has focussed on the representation of farm premises' locations within the model, and examined the use of fine-scale maps in place of the original transmission kernel between premises' point locations. Results call into question the relative contributions of farm geography and demography to FMD spread. It has also explored local spatial patterns in FMD biosecurity risk, as well as the relationship between FMD biosecurity risk and farm demography in order to consider whether model parameters might be indirectly affected by patterns in biosecurity. The main findings are summarised below, and their implications and limitations discussed.

Mathematical models for predicting FMD spread have previously incorporated spatial spread by using a transmission kernel. Such transmission kernels as were used for modelling the 2001 outbreak in the UK (see General Introduction, Figures 1.1 and 1.2), represent farm premises locations as points in space. However, transmission of FMD in 2001 was thought to be largely as a result of locally aerosolised virus passing between animals on CPs, contaminated material passing between IPs and proximal premises, and contaminated fomites carried by people or vehicles (Gibbens et al., 2001). As a result, CPs were at elevated risk of becoming infected (Anderson, 2002). CPs were initially determined by on the ground inspection, and later - at least in Dumfries and Galloway - by cartographic inspection, where they were identified as having a land border touching that of an IP, or as being separated from an IP by only a country road, river, railway or woodland belt <20m in width (Thrusfield et al., 2005). Chapter 2 used maps of IACS data showing the locations of farm premises' fields, to ascertain which premises were contiguous to one another in two areas of Scotland - within Aberdeenshire and Ayrshire - using several definitions of contiguity, similar to that used by Thrusfield et al. (2005). The choice of <15m distance to classify premises as map-based CPs was arbitrary, but informed by such on-the-ground inspection. Further work to investigate the sensitivity of this thesis' results to different distances between field edges would be useful - particularly larger distances, since having a shared boundary (i.e. 0m separation) proved to have results in-keeping with those based on <15m. Some of the definitions of map-based contiguity took into account various landscape features that may act as barriers to transmission, such as was found for rivers and railways in the 2001 outbreak (Bessell et al., 2008). Distances between the point locations were found to be inaccurate at discriminating between contiguous and non-contiguous premises according to map-based contiguity definitions. This may account for some of the low level predictive ability of the Keeling et al. (2001) model for identifying IPs during the 2001 outbreak (as was found by Tildesley et al. (2008)). Identification of map-based CPs as done within this thesis provides an improved method of studying premises contiguity as compared to Tildesley et al. (2009), and would enable a greater level confidence to be achieved in an analysis such as that by Bessell et al. (2008)'s study of the effect of rivers and railways on FMD transmission, were it to be repeated.

Based on this, the updated version of the Keeling et al. (2001) model, as described in Tildesley et al. (2008) and Tildesley and Keeling (2009), was adapted to examine simulated spatial spread in Chapter 3 by Thibaud Porphyre. In this adapted model, the transmission kernel was replaced by a heightened level of possible transmission between map-based CPs, alongside a longer-distance low level of possible background transmission. The results showed that spatial predictions did indeed differ between the two models, particularly when the simulated outbreaks took-off. Under such circumstances, it appeared that outbreaks were predicted to be more geographically widespread using the contiguity model than compared to using the distance model. While these findings were based on an example simulation (of identical size) from each model, the contiguity model did have a different distribution of outbreak sizes compared to the distance model - with more smaller outbreaks, and larger outbreaks when they took-off. A possible explanation for this is that transmission between map-based CPs in the contiguity model allows transmission between premises that may, when represented as points, be geographically distant, if the premises involved are large in area, or are fragmented across the landscape. If they are geographically distant when represented as point locations, then within the distance model they will have a low transmission rate according to the kernel, and consequently transmission between them will be unlikely. This will result in large outbreaks being less widespread across the landscape. This apparent reduction in transmission probability for larger premises may be another contributing factor to the inaccuracy of the distance model described by Tildesley et al. (2008). Which model predicts spatial spread of FMD most accurately can, however, only be determined by validation against epidemiological data in the event of a disease incursion in future.

In 2001, the effect of CP culling was examined within the Keeling et al. (2001) model by using area weighted tessellation to identify CPs. Chapter 2's analysis also demonstrated that area weighted tessellation does not accurately distinguish between map-based CPs and non-CPs. The contiguity based models in this thesis did not incorporate CP culling (instead using the original model's method for Dangerous Contact (DC) culling). Future work ought to update this such that CP culling is investigated within the contiguity model, and based on the same map-based CP identification as for transmission. To do this would be a major undertaking, but would enable a more complete comparison between the two models (distance and contiguity), and their spatial predictions of DCs as well as IPs. It may be that incorporating map-based CP culling into the contiguity model reduces the difference observed in geographic extent over which large outbreaks appeared to cover. Whether it also results in more comparable distributions of simulated outbreak sizes between the two models would be useful to know, as well as if, as a consequence, the distributions of number of times individual premises become IPs become more different.

Should there be another outbreak in future, the recommendation is that both the original distance based model and the new contiguity based model (developed by Thibaud Porphyre) should be used in parallel. This is of crucial importance given that the contiguity based model is yet to be validated using real outbreak data. Both models should be re-parameterised to the new outbreak data to account for any differences in transmissibility of the particular outbreak virus strain to that of 2001. The differences between the models' predictions would be important to examine, and these predictions would need to be compared to what plays out in reality to be able to make a full assessment of which model performs best in terms of accuracy of predicted spread.

Chapter 4 involved creating networks out of farm premises (the nodes) in the landscape, where they were linked (by edges) if they were contiguous according to map data, for a large area in southern Scotland. A major development as part of this work was that an accurate automated procedure for the detection of landscape features between map-based CPs was created. This enabled different definitions of contiguity - including and excluding landscape features - to be examined over a much larger area than in Chapter 2. Analysis of the map-based contiguity network found that the farming landscape was extremely connected via contiguity, with the vast majority of premises within the network's GC. This means that within the studied area there is substantial potential for FMD spread by local transmission mechanisms alone. Identifying and removing premises in order of their betweenness centrality in the network, resulted in a huge reduction in the GC size. This was taken forwards into simulations of the contiguity model, which showed that excluding these premises considerably reduced the mean predicted outbreak size. This suggests that ensuring that these key premises do not become infected in the event of an outbreak will be likely to help reduce the number of IPs. Implementation of enhanced biosecurity measures on these premises as soon as FMD is detected in Great Britain would be the recommended way to ensure this. Increased surveillance on such premises would also be important to allow control measures to be implemented rapidly in the event that one became an IP. A limitation of this analysis is that only an area of southern Scotland was used. It is paramount in the event of an outbreak that the farming landscape is studied as a whole and that Scotland is not considered as an island. Looking at Great Britain's farming landscape in its entirety may well alter which premises are identified as occupying key positions in connecting it.

The automated procedure for detecting landscape features between map-based CPs may prove useful for future studies investigating the role of landscape features in modifying the transmission rate of FMD (or other locally-spread diseases) between CPs. However, as with the identification of map-based CPs in terms of field edges <15m apart, such a measure of contiguity will be more applicable to some areas than others. For map-based contiguity to be used to examine local disease transmission between farm premises requires that individual premises are clearly defined and self-contained. This assumption is likely to hold and be applicable for use in areas such as Devon, but may break down for areas classified as Less Favoured Areas (LFA) such as the Scottish Highlands and the English Lake District where farmers frequently co-graze their stock with those of other farmers on common grazing land (Harvey and Scott, 2015; Holland et al., 2011). Additionally, the method may be variably applicable to different production types since the likely transmission routes between premises that keep all stock housed, as is the case for some intensive pig farms and some dairy farms, would not relate to map-based CPs as defined within this body of work.

Over a two-month period I conducted surveys on biosecurity practices with 200 farmers in Aberdeenshire and Ayrshire. This is the largest of its kind known to have been conducted in the UK to date. Following analysis of this survey data, in Chapter 5 I found that neighbours on CPs did not appear to have more similar FMD biosecurity risk compared to those who were non-CPs. Thus there did not seem to be an imitation effect between farmers on CPs that resulted in similar implementation of biosecurity practices related to FMD on CPs within the study population. Additionally, Chapter 5's findings highlight the large amount of variation in FMD biosecurity risk between premises. When taken with the findings of Ellis-Iversen et al. (2011), these suggest that some premises, with high FMD biosecurity risk, have considerably increased odds of becoming an IP in the event that there is an FMD compared to premises with lower biosecurity risk. Thus, areas containing such premises may be considerably more susceptible to secondary FMD transmission, should an outbreak occur. This will be particularly applicable during the silent spread phase, since once the disease has been detected farmers are likely to alter their biosecurity practices which may result in more homogeneous levels of FMD biosecurity risk between farm premises. Whether biosecurity risk is more similar between premises in certain areas at a broader scale than that studied here, or across different social networks than were studied, would be useful to ascertain by further research. This would, however, require further extensive data collection. Such research could help to identify areas or social networks that could be usefully tapped to disseminate ideas among high risk areas. Given farmers often take advice on biosecurity from their vet (Brennan and Christley, 2013; Ellis-Iversen et al., 2010; Heffernan et al., 2008), there may be such an effect operating within the 'social network' of vet practice membership.

Further analysis of the survey data was undertaken in Chapter 6. This showed that in the areas studied there did not appear to be a relationship between FMD biosecurity risk score and the susceptibility term of the Keeling et al. (2001) model. Therefore it appears that the susceptibility term does indeed relate to the number of sheep and cattle kept on the premises rather than indirectly capturing an association between biosecurity risk and premises size. However, it remains possible that it could in part be capturing the effect of another element of premises size, since having larger numbers of cattle and sheep was found to be correlated with having more CPs and larger area in Chapter 4. Indeed, in a statistical FMD susceptibility model which correctly predicted 45% IPs following the livestock movement ban in the 2001 outbreak, premises area (but not number of CPs) was incorporated in the final multivariable model, showing that larger premises had increased susceptibility (Bessell et al., 2010).

Chapter 6 also found that dairy premises in Ayrshire were more likely than other production types to make ‘risky’ movements, defined as monthly or more regular movements that were most commonly made by herding livestock down roads/tracks/bridleways. Additionally, it was observed that dairy cattle regularly directly crossed roads to get to the milking parlour. Thus, dairy premises may be more at risk of coming into contact with contaminated material in the event of an FMD incursion into an area, due to their greater frequency of ‘risky’ movements. They may also pose a greater risk to transmission, since they may be more likely to deposit FMD virus particles onto roads in the event they become infected, prior to disease detection. Since milk tankers also pose a transmission risk, dairy premises should perhaps be targeted for promotion of biosecurity practices.

As emphasised by Enticott et al. (2012), it is important that biosecurity recommendations should be at the local level, assessing relative costs and benefits of different biosecurity practices at the local social and physical landscape level. Only by being realistic about what practices make sense for different farmers in different areas to undertake, will FMD-related biosecurity measures be increased during ‘peace-time’ and consequently during the silent spread phase in the event of a future incursion. Results from Bessell (2009) provide risk maps that indicate areas at high risk of FMD spread in the event of a future incursion into Great Britain, and Porphyre et al. (2013) provides maps of epidemic impact of FMD vaccination strategies in Scotland from which FMD risk can be inferred. Consideration of the risk of an area as a whole, as identified from these analyses, in addition to the production type of each premises in question may be used to target promotion of increased FMD-related biosecurity practices during ‘peace-time’. This may help to lower risk of disease spread in the event of an incursion. Additionally, premises that may play a key role in connecting the landscape in terms of FMD transmission - identified by such as the method used in Chapter 4’s analysis - may also be targeted for biosecurity promotion. This would have to be very tactfully and carefully undertaken via discussion with farm veterinarians, taking care to ensure such premises are not stigmatised simply for their location. At a national level, it would be useful to disseminate regular information regarding FMD signs in livestock through the farming community to help ensure rapidity in diagnosis and reporting in the event of an incursion.

Combining the results and findings of this thesis leads to new recommendations for FMD control strategies should there be a future outbreak in the UK. In the event of an outbreak, identification of map-based CPs should be done to create a network of contiguous farm premises throughout the UK (or at least for the areas across which it is applicable, as discussed above). From this network, premises occupying key positions in the farming landscape in terms of connecting otherwise disconnected sub-populations of map-based CPs should be identified using the network measure of betweenness centrality. Starting with the premises with the highest betweenness centrality (and working down the list to include as many high betweenness premises as is practical and possible), premises’ land parcels should be studied on a map to identify where possible fragmentation can be achieved. For example, it might be that simply not using one or two particular fields for grazing livestock may result in a premises no longer being contiguous to the premises that make it have high betweenness. Or it may even be possible just to bring back the fencelines to increase the distance between premises that would otherwise be classified as map-based CPs. An alternative may be to have elevated biosecurity practices in the dimensions found by Ellis-Iversen et al. (2011) to be associated with secondary FMD infections, or to offer free pre-emptive vaccination to the highest betweenness premises. The number of premises required to be targeted in these ways to have a considerable impact on potential FMD spread would be different to that identified in this thesis, given that most of the UK's premises would be included. The number of premises to be targetted would need to be re-assessed given the dataset and location of the initial outbreak.

It would be useful in the meantime to conduct a sensitivity analysis looking at the predicted spread of the disease using different map-based definitions of contiguity (e.g. varying the distance between field edges considered as being contiguous), to establish how much of an effect it has on predicted outbreak sizes and geographic extent. Building on this even further, it may also be useful to examine the outputs of an adapted contiguity model such that the CP transmission parameter is based on the distance between field edges and where this is reduced by a factor where a river/railway is present between CPs, given the finding of Bessell et al. (2008) that rivers and railways act as semi-permeable barriers to transmission. This may provide a more realistic representation of rivers and railways as semi-permeable barriers, than using the network of the map-based definition 'All <15m - river/railway' which assumes no contiguous transmission between premises separated by such features. To apply this to a large area would require using an automated process to identify rivers and railways. While the automated process developed here was found to have good discriminatory ability in determining presence/absence of landscape features, it was not perfect and there is room for improvement in its development. Conducting a sensitivity analysis would be useful to investigate how much of an effect different classification measures for identifying landscape features have on final results of predicted FMD spread and identification of key premises in the contiguity network. Such developments in this research would provide valuable information in the event of a future outbreak.

This work has been based on specific definitions of map-based contiguity that may not be the best representation of contiguity in terms of FMD transmission. This should be borne in mind in the event of a future disease incursion. Furthermore, the data used to determine map-based CPs in this body of work was related to individual premises. In reality however, premises may be part of a multi-premises farm business, or have Cattle Tracing System (CTS) Links (for cattle only), or Sole Occupancy Authorities (SOAs) to other premises (Orton et al., 2012), all of which enable livestock to be moved with fewer restrictions. New SOA connections can no longer be created (NFUS, 2014), however, those already in existence remain linked. It would be useful in future work to try to obtain data regarding all types of premises links so that connected premises can be considered as one entity in terms of potential disease spread. This may result in farms being hugely fragmented through the landscape and will likely considerably affect the contact structures of the networks. How this affects the results found in this thesis, especially in relation to Chapter 4's network analysis identification of key premises that connect the farming landscape, would be useful to ascertain. Certainly in the event of an outbreak, premises links should be taken into account within analyses.

There are several potential consequences for the farming landscape arising from the Common Agricultural Policy (CAP) reform 2015 that may be relevant to the findings of this thesis. The grants provided for crofts and small farms will encourage these small enterprises to remain (The Scottish Government, 2015b), with the result that there will be a reduced conversion to a smaller number of bigger farms in any particular area than there otherwise might be, as fewer small premises sell their land to surrounding premises. This may actually have the effect of making the farming landscape more complex to fragment than were there fewer farms in the contiguity network, which may result in increased complexity in the use of fragmentation based on contiguity network betweenness in the event of a outbreak. Additionally, farm payments will now be composed of a basic payment plus a 'greening payment' (The Scottish Government, 2015a). This greening payment is made up of requirements relating to maintenance of permanent grassland, crop diversification and development of Ecological Focus Areas (EFAs). These EFAs include measures such as use of field margin areas and buffer strips around water bodies (The Scottish Government, 2015a). Such measures would be invaluable to contribute to the fragmentation of the livestock farming landscape by increasing the distance between neighbouring premises, and in so doing making them no longer CPs where once they would have been classified as such. However, EFA measures are targeted largely at cropping land rather than grassland used to graze livestock. Thus, this may have a limited effect on the fragmentation of the livestock farming landscape.

This thesis has sought to incorporate a more realistic representation of farm contiguity as relating to likely FMD transmission routes, by moving away from representing farm premises as point locations to considering them as areas based on their field locations. Ultimately, however, it is where the animals are located in the landscape - and the locations of the fields or buildings they are in - that should be considered when looking to incorporate contiguity information into analysis of livestock disease spread between premises. To incorporate this level of detail would require creating a method whereby such data could be collected, such as a combination of high resolution aerial photography and an automated process that identifies animals from the resulting photographs. However, the frequency with which livestock are moved between pastures may hinder such an exercise. My fieldwork found that 7.7% (23/300) and 16.2% (81/500) of reported movements between fields in Aberdeenshire and Ayrshire, respectively, were more than monthly (Appendix 7, Tables 6.8 and 6.7).

Furthermore, this body of work has been concerned with the FMD model developed for the 2001 outbreak. Airborne transmission by virus plumes was found to not play a large role for this strain of virus during the 2001 outbreak (Donaldson et al., 2001; Gibbens et al., 2001; Thrusfield et al., 2005) and thus was not considered by the Keeling et al. (2001) model. It is possible that should a different strain of virus cause an outbreak in the UK in future, windborne transmission may need to be considered in addition to the transmission routes considered in this thesis. This may be achieved by incorporating a windborne transmission kernel to capture this other transmission route in addition to local contiguous spread.

While this thesis has studied farm premises contiguity in relation to FMD, it may be useful as the basis for studying other diseases that have a significant local spread component, such as bovine tuberculosis (White et al., 2013), bovine viral diarrhoea (Gates et al., 2013), and rabies (Haydon et al., 2006). In particular, using the combination of map-based contiguity identification and network analysis as was used in Chapter 4 may help to identify effective targeted channels for disease control measures. This would of course require detailed consideration of transmission mechanisms and the effect of landscape features on these diseases' transmission potential, in order to decide upon the most applicable definition of contiguity for the disease in question.

In conclusion, this thesis' findings bring to light the question of the relative importance of farm premises fragmentation and size, as well as species composition and production type to FMD spread. These factors are likely to all be correlated with one another to a considerable extent. Untangling this complexity will be difficult to achieve. Nonetheless, map-based contiguity is likely to capture these different physical and demographic characteristics of premises by its very nature, since the size and fragmentation of a premises is taken into account simply by representing it as an area in relation to other premises areas. Whether this explains transmission of FMD effectively as described by the contiguity model, is however another matter, and will require investigation using detailed epidemiological data in the event of a future outbreak. Furthermore, this thesis has identified analysis of contiguity networks as a method which may enable extremely targeted control measures to be used to prevent FMD spread in the event of a future incursion, by effectively fragmenting the landscape using enhanced biosecurity measures on a small number of premises. Indeed, more generally, targeted promotion of biosecurity practices based on premises' position in the farming landscape as well as production type may help to reduce the potential for an outbreak to take-off in GB in the event of an FMD incursion in future. Using network analysis to study the connections between susceptible sub-populations in the landscape may provide a useful method for identifying how the landscape can be fragmented by using extremely targeted control measures, and disease spread consequently reduced for a variety of animal diseases where local transmission is considerable.

# 8 Appendix 1: To accompany Chapters 3 and 4

## 8.1 Methods for mathematical modelling simulations to accompany Chapters 3 and 4

### 8.1.1 The distance-based model

N.B. These methods were written by Thibaud Porphyre, as described in Porphyre et al. (2013).

Premises pass through four epidemiological states: susceptible, infected but not infectious, infectious, or reported infected and thereby culled. In line with previous versions of the model (Keeling et al., 2001, 2003; Tildesley et al., 2006), it is assumed that all farms are infected for 5 days before becoming infectious, and are infectious for 4 days before being reported with infection. As a baseline, the model considers that once an infected premises (IP) is reported, a national movement ban (NMB) would be enforced and culling measures would be implemented within 24 hours.

The model assumes that each $i^{th}$ premises would be infected with a daily probability depending on its own susceptibility $S_i$ and on the transmissibility $T_j$ of the surrounding $j$ premises. For the $n$ premises involved in the study population, each $i^{th}$ premises has a daily probability to be infected such as

$$M_i = 1 - exp\left[-S_i \sum_{j \neq i}^{n} T_j K(d_{ij})\right] \tag{8.1}$$

where $S_i$ and $T_j$ depend on the species (i.e. cattle and sheep) and on related herd size present on premises. The component $K(d_{ij})$ of equation (8.1) denotes the 'between-farm transmission kernel function' and determines how the relative risk of infection between a susceptible and infectious farm as a function of inter-farm distance $d_{ij}$.

Both the susceptibility $S_i$ of a given premises $i$, and the transmissibility $T_j$ of those that are surrounding it, are computed such as:

$$S_i = s_{cow} N_{cow,i}^{p_c} + s_{sheep} N_{sheep,i}^{p_s} \tag{8.2}$$

$$T_j = t_{cow} N_{cow,j}^{q_c} + t_{sheep} N_{sheep,j}^{q_s} \tag{8.3}$$

The parameters $s$ and $t$ in equations (8.2) and (8.3) correspond to the susceptibility and transmissibility of a farm per head of livestock recorded present on premises during the study period. Herd size and structure are given by the parameters $N_{cow,i}$ and $N_{sheep,i}$ for each premises $i$. In concordance with the modified version of the model (Tildesley and Keeling, 2009; Tildesley et al., 2008), but in contrast with the earlier implementation of the model (Keeling et al., 2001, 2003; Tildesley et al., 2006), we used the power law parameters $p_c$, $p_s$, $q_c$ and $q_s$ to account for the non-linear dependence of animal numbers upon susceptibility and transmissibility of a farm. In the UK-wide version of the model, the seven parameters $s_{cow}$, $t_{cow}$, $t_{sheep}$, $p_c$, $p_s$, $q_c$ and $q_s$ (with $s_{sheep}$ fixed to 1) were determined for five distinct regions (Cumbria, Devon, Scotland, Wales and the rest of GB) by fitting the model to the UK 2001 epidemics. Here, all parameters involved in the model are therefore the Scotland-specific parameters ($s_{cow}$= 10.771, $s_{sheep}$= 1, $t_{cow}$= 8.37e-07, $t_{sheep}$= 9.69e-07, $p_s$= 0.326, $p_c$= 0.227, $q_s$= 0.403 and

$q_c$= 0.202) as defined by Tildesley's work (Tildesley and Keeling, 2009; Tildesley et al., 2008).

In addition to the routine culling of IPs, premises where animals have been in direct contact with infected animals or have, in any way, become exposed to infection, known as dangerous contacts (DCs), are culled in an effort to control disease. Premises defined as DCs are determined stochastically based upon both prior infection by an IP and future risk of infection, which is partly determined by the component $K(d_{ij})$ (Tildesley et al., 2006). All farms defined as DCs in our model would be depopulated within 48 hours. Once animals at an IP are slaughtered, disinfection procedures are initiated and no transmission events to other premises may occur. For the purpose of this work, pre-emptive culling based on spatial proximity (i.e. 'contiguous premises' culling) was not considered.

In this distance-based model framework, we assume that the spatial extent of the transmissibility between farms $K(d_{ij})$ in Scotland is similar to that recorded during the 2001 UK FMD epidemic. Therefore, as a baseline, we used the shape of the transmission kernel function that was empirically derived from the contact tracing performed by DEFRA during the 2001 UK FMD epidemic once movement restrictions were implemented. This further assumes that contact tracing procedures carried out in the field identified all infected premises and correctly determined all source of infection. Therefore, this model considers that the function $K(d_{ij})$, derived from ground investigations, would be an accurate representation of the epidemiological processes. As such, procedures which model the disease spread are considered similar to those which model surveillance activities (i.e. procedures identifying DCs) during an epidemic.

### 8.1.2 The contiguity-based models

N.B. These methods were written by Thibaud Porphyre.

The contiguity-based models are a simple extension of the distance-based model. While the model assumes again that each $i^{th}$ premises would be infected with a daily probability depending on its own susceptibility $S_i$ and on the transmissibility $T_j$ of the surrounding $j$ premises, as defined in equations (8.2) and (8.3), the contiguity-based models do not consider the inter-farm distance $d_{ij}$ as influential in the rate of disease spread but rather consider that transmission between farms are directly related to their spatial contiguity. Equation (8.1) then becomes

$$M_i = 1 - exp\left[-S_i \sum_{j \neq i}^{n} T_j K(c_{ij})\right] \tag{8.4}$$

where the component $K(c_{ij})$ of equation (8.4) denotes the 'contiguity-based between-farm transmission kernel function' and determines the relative risk of infection between a susceptible and infectious farm as a function of their contiguity status $c_{ij}$. Here, $c_{ij}$ takes the value 1 if $i$ and $j$ are defined contiguous, and 0 otherwise. As such, the component $K(c_{ij})$ takes the form of

$$\begin{cases} K(c_{ij}) = \rho, & \text{if } c_{ij} = 1 \\ K(c_{ij}) = \delta, & \text{if } c_{ij} = 0 \end{cases} \tag{8.5}$$

The parameters of $\rho$ and $\delta$ in equation (8.5) represent the transmission parameter when farms $i$ and $j$ are contiguous and when they are not, respectively. The latter may provide information on the background transmission rate via other transmission routes, such as through shared equipment or movement of personnel. The best estimates of $\rho$ for each contiguity network studied can be seen in Table 8.1.

While the distance-based model framework considers that the transmission kernel function derived from contact tracing procedures carried out in the field would be an accurate representation of the epidemiological processes, the contiguity-based models depart from this assumption. In this model, what is known from the epidemics (i.e. the information generated from contact tracing procedures) and the disease spread process are considered separately. Therefore, although the transmission between farms occurs at a rate as defined by equations (8.4) and (8.5), the rate at which surveillance activities determine DCs remains determined based on $K(d_{ij})$ as in (Tildesley et al., 2006). However, it is assumed that the maximum spatial extent farms may infect another is similar to what was previously observed during contact tracing.

Given that there has not been a recent FMD epidemic in Scotland (for which we have IACS data), the contiguity-based model could not be parameterised using empirical data. Calibration was therefore achieved by identifying the transmission parameter that produced a similar simulated epidemic profile to that of the distance-based model. For details on how this was done, see details in the section below.

Table 8.1: Estimates of $\hat{\rho}$ for various values of $\delta$.

| **Contiguous classification** | $\delta = 0$ | $\delta = 2.8 \times 10^{-6}$ |
|---|---|---|
| All <15m | 0.1075 | 0.0776 |
| All <15m - river/railway | 0.1176 | - |
| Shared boundary | 0.2025 | - |
| Shared boundary - river/railway | 0.2225 | - |

### 8.1.3 Mathematical model fitting

N.B. These methods were written by Thibaud Porphyre.

Approximate Bayesian computation (ABC) methods can be used to evaluate posterior distributions of parameters without having to calculate likelihoods (Beaumont et al., 2002; Toni et al., 2009) when trying to capture a single observed epidemic trajectory. Here, parameters for the new stochastic model (8.5) needed to be inferred from another stochastic model (8.1), which had been parameterised using empirical data. To do this, ABC was used to identify which parameter values minimised the error between epidemic profiles generated by the two models.

In line with a previous study (Porphyre et al., 2013), the epidemic profile of the generated epidemics was defined by a set $D_k$ of $k$ summary statistics. For the purpose of this study, three summary statistics were considered: (1) the mean epidemic duration (in days), (2) the mean number of infected premises (IPs), and (3) the likelihood of severe epidemics (here, defined as the probability that epidemics have >100 IPs and last for >100 days). These enabled the shape of the potential epidemic distribution to be largely captured: with a low estimated mean duration and number of IPs, but with a relatively high probability of severe epidemics within the study period (Porphyre et al., 2013).

The prior parameter space was divided into numerous bins of equal width, with each bin representing the proposed parameter value $p*$. Given no prior knowledge on the transmission rate given contact, prior distributions for all tested parameters were approximated by a uniform distribution ranging from 0 to 1. Approximately 500 simulated epidemics were generated for each parameter space bin. The resulting epidemic profile for each bin of the parameter space $D_{k,p*}$ was computed and compared it to the epidemic profile of the distance-based model $D_{k,0}$.

The estimate was chosen based on identifying the best-fitting model that minimised the normalised sum of the squared errors, such as

$$min\left(\sum_k \left(\frac{D_{k,p*} - D_{k,0}}{max(D_{k,p*} - D_{k,0})}\right)^2\right) \tag{8.6}$$

where the error was normalised by the maximum to homogenise the weight of all measures.

## 8.2 Comparison of predicted geographical spread of predicted IPs in sample simulations from each model (To accompany chapter 4)

### 8.2.1 Methods

Outbreaks of identical size (in terms of number of IPs) were identified for each model, for both a medium size (around the mean values for the two models' simulations), and a large one. These were mapped to show the geographical distribution of the density of premises identified as IPs. Ripley's L-function was calculated and plotted using the 'spatstat' package (Baddeley et al., 2013) in R (R Core Team, 2013) to study the relative clustering of the IP point locations within the study area under the different sized outbreaks and models. The L-function is a transformation of the K-function which is calculated over a range of distance values, d, and is defined as

$$K(d) = \frac{a}{n} \times \frac{1}{n} \sum_{i=1}^{n} \#[S \in C(s_i, d)] \tag{8.7}$$

Where $S$ is a set of $n$ point locations $S = \{s_1, s_2, ...s_i, ...s_n\}$, $C(s_i, d)$ is a circle around point $s_i$ with radius $d$, and $a$ is the area of the bounding study area (O'Sullivan and Unwin, 2010). The L-function is then calculated from $K(d)$ as

$$L(d) = \sqrt{\frac{K(d)}{\pi}} - d. \tag{8.8}$$

$L(d)$ can then plotted against distance $d$ to compare the spatial pattern of points to 'complete spatial randomness' (CSR) which is at $L(d) = 0$ (O'Sullivan and Unwin, 2010). It is used in preference to the K-function since it provides easier visualisation. Thus, the further from zero the L-function, the more clustered it can be concluded the point pattern is.

### 8.2.2 Results

The density distribution of IPs in the selected large- (n=980, the largest of the distance model simulations) and medium- (n=446) sized outbreaks are shown in Figures 8.1 and 8.2. These density maps suggest that the contiguity model produced a more geographically widespread outbreak than the distance model for the large outbreak - since the greater number of contours on the density map for the distance model demonstrate a higher degree of clustering of IPs within the landscape (Figure 8.1). However, the two models appeared to produce similar levels of spread in the medium outbreak (Figure 8.2). This was confirmed by the L-function plots, with the distance model simulation's distribution showing a greater degree of clustering than the contiguity model for the large outbreak, since the observed L-function is further from the horizontal at most of the distances observed (Figure 8.3). This was not the case for the selected medium outbreak simulations, with the distance and contiguity models showing similar degrees of clustering of IPs up to around 20km (Figure 8.4).

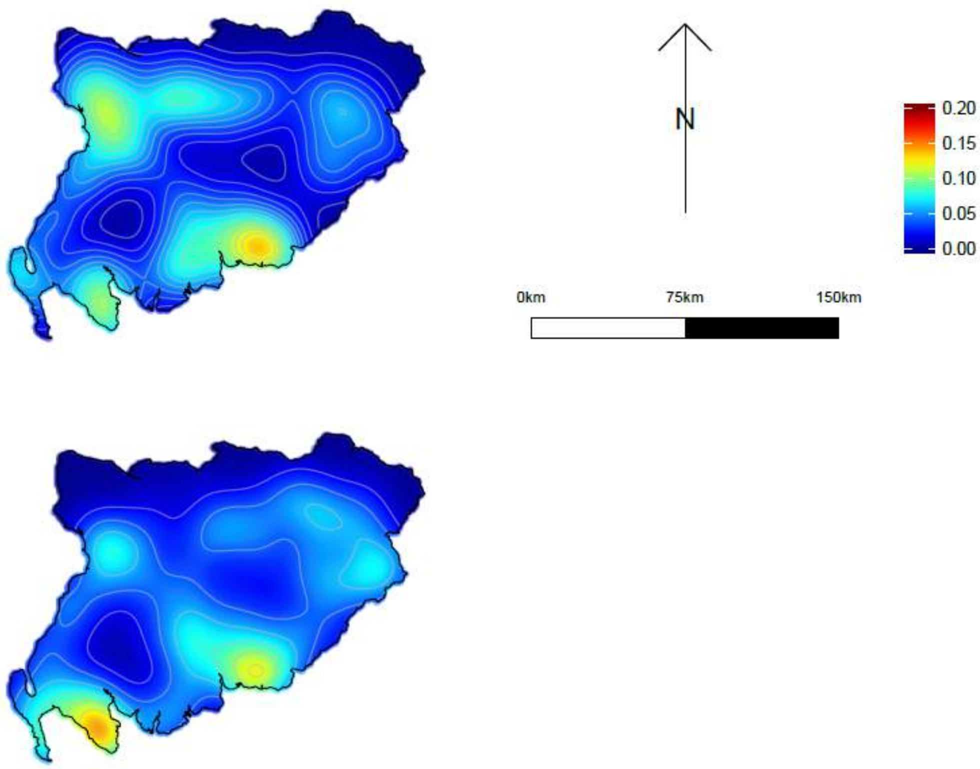



Figure 8.1: Maps showing the density of premises identified as IPs across the study area in one simulation resulting in n=980 IPs for (top) the distance model and (bottom) the contiguity model.

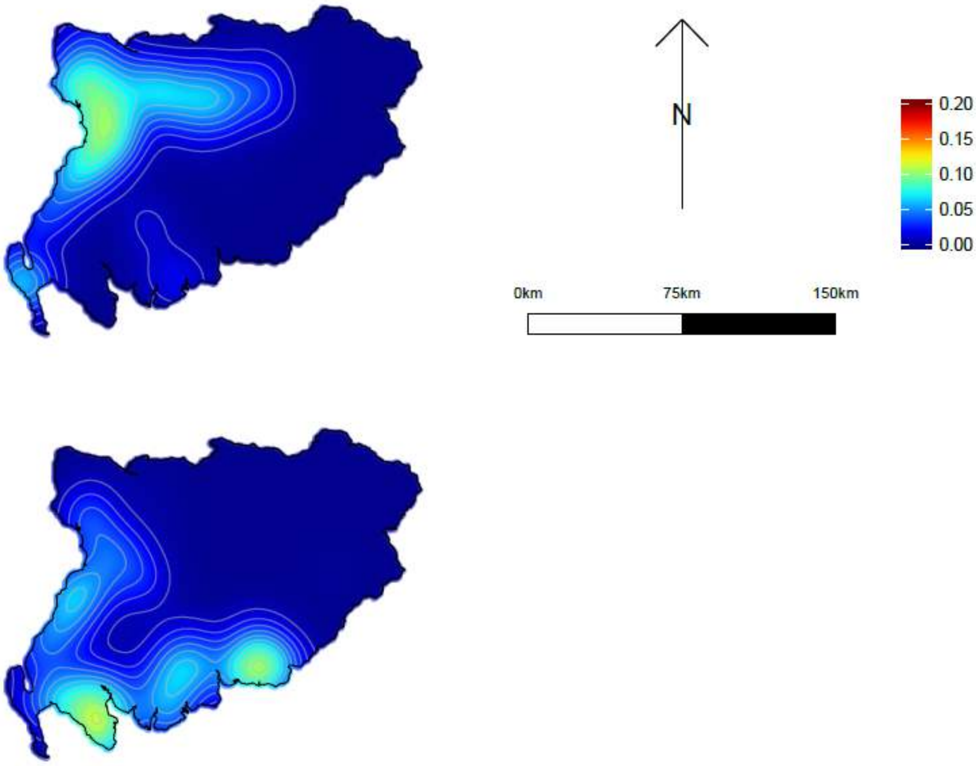



Figure 8.2: Maps showing the density of premises identified as IPs across the study area in one simulation resulting in n=446 IPs for (top) the distance model and (bottom) the contiguity model.

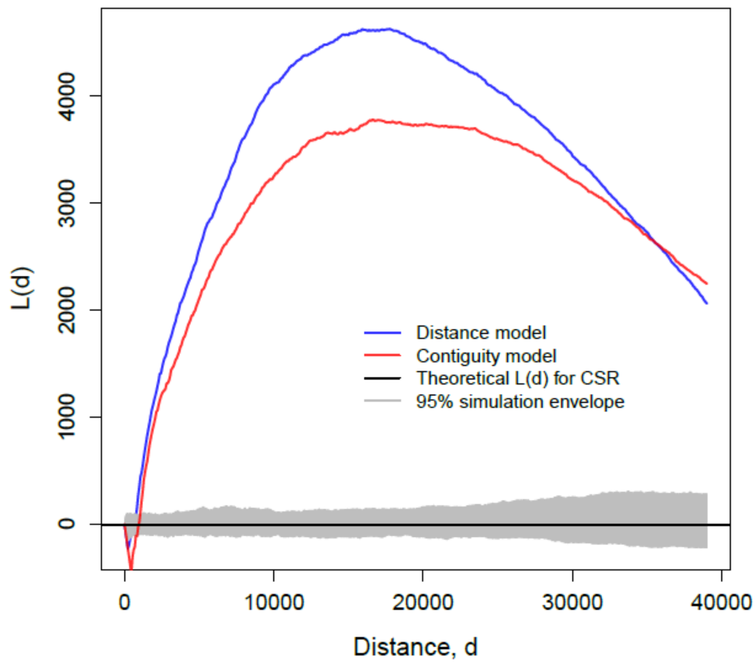



Figure 8.3: L-function plots for the point patterns of IPs observed in one simulation resulting in n=980 IPs for the distance model (blue) and the contiguity model (red). CSR = complete spatial randomness.

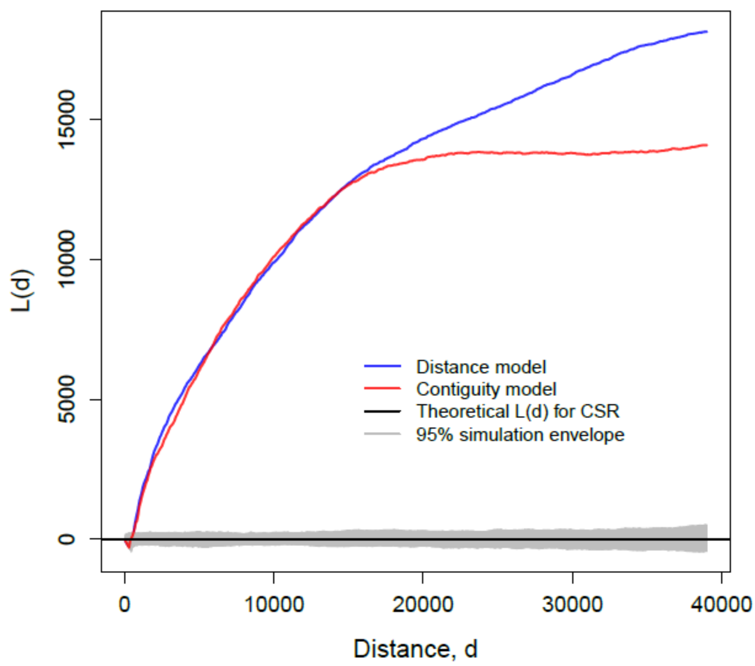



Figure 8.4: L-function plots for the point patterns of IPs observed in one simulation resulting in n=446 IPs for the distance model (blue) and the contiguity model (red). CSR = complete spatial randomness.

# 9 Appendix 2: To accompany Chapter 4's automated process

| **OS MasterMap Roads** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 50 | 0 | 50 |
| | Absent | 0 | 306 | 306 |
| | Total | 50 | 306 | 356 |

TSS = 1.000

| **OS MasterMap Rivers** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 27 | 3 | 30 |
| | Absent | 0 | 326 | 326 |
| | Total | 27 | 329 | 356 |

TSS = 0.991

| **OS MasterMap Ditches** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 28 | 22 | 50 |
| | Absent | 0 | 306 | 306 |
| | Total | 28 | 328 | 356 |

TSS = 0.933

| **OS Meridian2/MasterMap Railways** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 1 | 0 | 1 |
| | Absent | 0 | 355 | 355 |
| | Total | 1 | 355 | 356 |

TSS = 1.000

| **OS Meridian2 Roads** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 44 | 0 | 44 |
| | Absent | 6 | 306 | 312 |
| | Total | 50 | 306 | 356 |

TSS = 0.880

Table 9.1: Resulting classification of presence/absence of landscape features separating CP pairs, on visual inspection, and using the automated process, Ayrshire. TSS calculated where visual inspection is taken to be the gold standard, as TSS = (sensitivity + specificity - 1).

| **OS MasterMap Roads** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 21 | 0 | 21 |
| | Absent | 2 | 133 | 135 |
| | Total | 23 | 133 | 156 |

TSS = 0.913

| **OS MasterMap Rivers** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 9 | 3 | 12 |
| | Absent | 1 | 143 | 144 |
| | Total | 10 | 146 | 156 |

TSS = 0.879

| **OS MasterMap Ditches** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 13 | 18 | 31 |
| | Absent | 2 | 123 | 125 |
| | Total | 15 | 141 | 156 |

TSS = 0.739

| **OS Meridian2 Roads** | | **Visual inspection** Present | Absent | Total |
|---|---|---|---|---|
| **Automated process** | Present | 16 | 0 | 16 |
| | Absent | 7 | 133 | 140 |
| | Total | 23 | 133 | 156 |

TSS = 0.696

Table 9.2: Resulting classification of presence/absence of landscape features separating CP pairs, on visual inspection, and using the automated process, Aberdeenshire. TSS calculated where visual inspection is taken to be the gold standard, as TSS = (sensitivity + specificity - 1).

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | All <15m | 32.8 | 87.1 | 95.7 | 100.0 | 100.0 | 100.0 | 62.6 | 67.2 |
| | | 32.8 | 87.1 | 95.7 | 100.0 | 100.0 | 100.0 | 62.6 | 67.2 |
| | All <15m - river | 33.2 | 86.3 | 95.7 | 100.0 | 100.0 | 100.0 | 62.4 | 67.1 |
| | | 32.6 | 86.2 | 95.6 | 100.0 | 100.0 | 100.0 | 62.1 | 66.8 |
| | All <15m - road | 32.3 | 88.3 | 96.7 | 100.0 | 100.0 | 100.0 | 64.3 | 69.0 |
| | | 32.4 | 88.2 | 96.4 | 100.0 | 100.0 | 100.0 | 64.1 | 68.6 |
| | All <15m - river/road | 32.8 | 87.6 | 96.7 | 100.0 | 100.0 | 100.0 | 64.2 | 69.0 |
| | | 32.1 | 87.4 | 96.4 | 100.0 | 100.0 | 100.0 | 63.5 | 68.2 |
| | All <15m - river/road/ditch | 35.5 | 87.9 | 96.8 | 100.0 | 100.0 | 100.0 | 64.9 | 69.0 |
| | | 33.9 | 87.4 | 96.1 | 100.0 | 100.0 | 100.0 | 65.2 | 69.1 |
| | All <15m - river/ditch | 35.6 | 86.8 | 95.9 | 100.0 | 100.0 | 100.0 | 63.1 | 67.1 |
| | | 34.4 | 86.3 | 95.6 | 100.0 | 100.0 | 100.0 | 63.7 | 67.8 |
| | Shared fence | 32.9 | 87.6 | 96.5 | 100.0 | 100.0 | 100.0 | 62.5 | 67.5 |
| | | 32.9 | 87.6 | 96.5 | 100.0 | 100.0 | 100.0 | 62.5 | 67.5 |
| | Shared fence - river | 33.5 | 87.2 | 96.6 | 100.0 | 100.0 | 100.0 | 63.2 | 68.0 |
| | | 32.7 | 87.1 | 96.6 | 100.0 | 100.0 | 100.0 | 62.7 | 67.7 |
| | Shared fence - river/ditch | 36.0 | 87.6 | 96.7 | 100.0 | 100.0 | 100.0 | 64.0 | 68.2 |
| | | 34.4 | 87.2 | 96.3 | 100.0 | 100.0 | 100.0 | 64.7 | 68.8 |

Table 9.3: Sensitivity (%) of approximation methods versus map-based contiguity measures for sample area, Ayrshire. Red = landscape features identified by automated process, black = identified visually. Road data used was from OS Meridian™2.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | All <15m | 29.4 | 90.8 | 94.8 | 100.0 | 100.0 | 100.0 | 73.2 | 82.4 |
| | | 29.4 | 90.8 | 94.8 | 100.0 | 100.0 | 100.0 | 73.2 | 82.4 |
| | All <15m - river | 30.1 | 91.6 | 95.8 | 100.0 | 100.0 | 100.0 | 73.4 | 82.5 |
| | | 29.8 | 92.2 | 96.5 | 100.0 | 100.0 | 100.0 | 74.5 | 83.0 |
| | All <15m - road | 29.2 | 92.3 | 94.6 | 100.0 | 100.0 | 100.0 | 73.1 | 83.1 |
| | | 29.2 | 92.0 | 94.9 | 100.0 | 100.0 | 100.0 | 73.0 | 82.5 |
| | All <15m - river/road | 30.0 | 93.3 | 95.8 | 100.0 | 100.0 | 100.0 | 73.3 | 83.3 |
| | | 29.6 | 93.6 | 96.8 | 100.0 | 100.0 | 100.0 | 74.4 | 83.2 |
| | All <15m - river/road/ditch | 31.2 | 92.7 | 95.4 | 100.0 | 100.0 | 100.0 | 72.5 | 83.5 |
| | | 31.6 | 92.9 | 96.9 | 100.0 | 100.0 | 100.0 | 73.5 | 84.7 |
| | All <15m - river/ditch | 32.0 | 90.6 | 95.3 | 100.0 | 100.0 | 100.0 | 72.7 | 82.8 |
| | | 32.7 | 90.9 | 96.4 | 100.0 | 100.0 | 100.0 | 73.6 | 84.5 |
| | Shared fence | 29.5 | 92.6 | 95.9 | 100.0 | 100.0 | 100.0 | 75.4 | 84.4 |
| | | 29.5 | 92.6 | 95.9 | 100.0 | 100.0 | 100.0 | 75.4 | 84.4 |
| | Shared fence - river | 29.7 | 92.4 | 95.8 | 100.0 | 100.0 | 100.0 | 74.6 | 83.9 |
| | | 29.9 | 93.2 | 96.6 | 100.0 | 100.0 | 100.0 | 76.1 | 84.6 |
| | Shared fence - river/ditch | 31.5 | 91.7 | 95.4 | 100.0 | 100.0 | 100.0 | 74.1 | 84.3 |
| | | 31.9 | 92.3 | 96.7 | 100.0 | 100.0 | 100.0 | 74.7 | 85.7 |

Table 9.4: Sensitivity (%) of approximation methods versus map-based contiguity measures for sample area, Aberdeenshire. Red = landscape features identified by automated process, black = identified visually. Road data used was from OS Meridian™2.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | **All <15m** | 56.7 | 17.2 | 7.4 | 96.1 | 80.4 | 32.0 | 41.2 | 39.1 |
| | | 56.7 | 17.2 | 7.4 | 96.1 | 80.4 | 32.0 | 41.2 | 39.1 |
| | **All <15m - river** | 53.2 | 15.8 | 6.8 | 89.0 | 74.4 | 29.6 | 38.0 | 36.1 |
| | | 51.7 | 15.6 | 6.7 | 88.1 | 73.7 | 29.3 | 37.4 | 35.6 |
| | **All <15m - road** | 48.3 | 15.0 | 6.4 | 82.9 | 69.3 | 27.5 | 36.5 | 34.6 |
| | | 49.3 | 15.3 | 6.5 | 84.5 | 70.7 | 28.1 | 37.1 | 35.1 |
| | **All <15m - river/road** | 44.8 | 13.6 | 5.9 | 75.7 | 63.3 | 25.2 | 33.3 | 31.6 |
| | | 44.3 | 13.7 | 5.9 | 76.5 | 64.0 | 25.4 | 33.3 | 31.6 |
| | **All <15m - river/road/ditch** | 43.8 | 12.4 | 5.3 | 68.5 | 57.3 | 22.8 | 30.4 | 28.5 |
| | | 38.8 | 11.4 | 4.9 | 63.5 | 53.1 | 21.1 | 28.4 | 26.5 |
| | **All <15m - river/ditch** | 52.2 | 14.5 | 6.3 | 81.5 | 68.1 | 27.1 | 35.2 | 33.1 |
| | | 46.3 | 13.2 | 5.7 | 74.6 | 62.4 | 24.8 | 32.5 | 30.6 |
| | **Shared fence** | 46.3 | 14.1 | 6.0 | 78.2 | 65.4 | 26.0 | 33.5 | 31.9 |
| | | 46.3 | 14.1 | 6.0 | 78.2 | 65.4 | 26.0 | 33.5 | 31.9 |
| | **Shared fence - river** | 44.3 | 13.1 | 5.7 | 73.5 | 61.4 | 24.4 | 31.8 | 30.2 |
| | | 42.8 | 13.0 | 5.6 | 72.7 | 60.7 | 24.2 | 31.2 | 29.7 |
| | **Shared fence - river/ditch** | 43.3 | 12.0 | 5.2 | 66.9 | 55.9 | 22.2 | 29.3 | 27.5 |
| | | 37.3 | 10.8 | 4.6 | 60.2 | 50.3 | 20.0 | 26.7 | 25.0 |

Table 9.5: PPV (%) of approximation methods versus map-based contiguity measures for sample area, Ayrshire. Red = landscape features identified by automated process, black = identified visually. Road data used was from OS Meridian$^{\mathrm{TM}}$2.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | All <15m | 65.2 | 22.7 | 10.4 | 93.9 | 85.0 | 37.4 | 38.1 | 36.4 |
| | | 65.2 | 22.7 | 10.4 | 93.9 | 85.0 | 37.4 | 38.1 | 36.4 |
| | All <15m - river | 62.3 | 21.4 | 9.9 | 87.7 | 79.4 | 35.0 | 35.7 | 34.1 |
| | | 60.9 | 21.2 | 9.8 | 86.5 | 78.3 | 34.5 | 35.7 | 33.8 |
| | All <15m - road | 55.1 | 19.6 | 8.9 | 79.8 | 72.2 | 31.8 | 32.3 | 31.2 |
| | | 58.0 | 20.6 | 9.4 | 84.0 | 76.1 | 33.5 | 34.0 | 32.7 |
| | All <15m - river/road | 52.2 | 18.3 | 8.3 | 73.6 | 66.7 | 29.3 | 29.9 | 28.9 |
| | | 53.6 | 19.1 | 8.7 | 76.7 | 69.4 | 30.6 | 31.6 | 30.1 |
| | All <15m - river/road/ditch | 49.3 | 16.5 | 7.5 | 66.9 | 60.6 | 26.7 | 26.9 | 26.3 |
| | | 44.9 | 14.8 | 6.8 | 60.1 | 54.4 | 24.0 | 24.5 | 24.0 |
| | All <15m - river/ditch | 59.4 | 18.9 | 8.8 | 78.5 | 71.1 | 31.3 | 31.6 | 30.6 |
| | | 52.2 | 16.3 | 7.6 | 67.5 | 61.1 | 26.9 | 27.6 | 26.9 |
| | Shared fence | 52.2 | 18.4 | 8.4 | 74.8 | 67.8 | 29.8 | 31.3 | 29.8 |
| | | 52.2 | 18.4 | 8.4 | 74.8 | 67.8 | 29.8 | 31.3 | 29.8 |
| | Shared fence - river | 50.7 | 17.8 | 8.1 | 72.4 | 65.6 | 28.9 | 29.9 | 28.6 |
| | | 50.7 | 17.8 | 8.1 | 71.8 | 65.0 | 28.6 | 30.3 | 28.6 |
| | Shared fence - river/ditch | 49.3 | 16.2 | 7.4 | 66.3 | 60.0 | 26.4 | 27.2 | 26.3 |
| | | 42.0 | 13.7 | 6.3 | 55.8 | 50.6 | 22.2 | 23.1 | 22.5 |

Table 9.6: PPV (%) of approximation methods versus map-based contiguity measures for sample area, Aberdeenshire. Red = landscape features identified by automated process, black = identified visually. Road data used was from OS Meridian$^{TM}$2.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | **All <15m** | 0.316 | 0.672 | 0.386 | 0.998 | 0.988 | 0.899 | 0.584 | 0.623 |
| | | 0.316 | 0.672 | 0.386 | 0.998 | 0.988 | 0.899 | 0.584 | 0.623 |
| | **All <15m - river** | 0.320 | 0.662 | 0.385 | 0.995 | 0.985 | 0.896 | 0.580 | 0.619 |
| | | 0.313 | 0.660 | 0.384 | 0.994 | 0.985 | 0.896 | 0.576 | 0.615 |
| | **All <15m - road** | 0.309 | 0.680 | 0.394 | 0.992 | 0.982 | 0.893 | 0.598 | 0.637 |
| | | 0.310 | 0.680 | 0.392 | 0.992 | 0.983 | 0.894 | 0.595 | 0.634 |
| | **All <15m - river/road** | 0.314 | 0.670 | 0.393 | 0.988 | 0.979 | 0.890 | 0.595 | 0.635 |
| | | 0.306 | 0.668 | 0.390 | 0.989 | 0.979 | 0.891 | 0.588 | 0.627 |
| | **All <15m - river/road/ditch** | 0.340 | 0.671 | 0.392 | 0.985 | 0.975 | 0.887 | 0.600 | 0.632 |
| | | 0.323 | 0.664 | 0.384 | 0.982 | 0.973 | 0.885 | 0.601 | 0.632 |
| | **All <15m - river/ditch** | 0.343 | 0.664 | 0.386 | 0.991 | 0.981 | 0.893 | 0.584 | 0.617 |
| | | 0.330 | 0.657 | 0.381 | 0.988 | 0.978 | 0.890 | 0.589 | 0.622 |
| | **Shared fence** | 0.314 | 0.672 | 0.391 | 0.989 | 0.980 | 0.891 | 0.578 | 0.620 |
| | | 0.314 | 0.672 | 0.391 | 0.989 | 0.980 | 0.891 | 0.578 | 0.620 |
| | **Shared fence - river** | 0.320 | 0.666 | 0.392 | 0.987 | 0.978 | 0.889 | 0.583 | 0.624 |
| | | 0.312 | 0.664 | 0.391 | 0.987 | 0.977 | 0.889 | 0.578 | 0.620 |
| | **Shared fence - river/ditch** | 0.344 | 0.668 | 0.391 | 0.984 | 0.974 | 0.886 | 0.590 | 0.624 |
| | | 0.327 | 0.661 | 0.386 | 0.981 | 0.971 | 0.883 | 0.595 | 0.628 |

Table 9.7: TSS of approximation methods versus map-based contiguity measures for sample area, Ayrshire. Red = landscape features identified by automated process, black = identified visually. Road data used was from OS Meridian$^{TM}$2.

| | | Current method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | All premises <1km point distance | All premises <3km point distance | All premises <5km point distance | All premises <26m field distance | All premises <151m field distance | All premises <1km field distance | By Voronoi tessellation | By area weighted tessellation |
| Gold standard | All <15m | 0.283 | 0.696 | 0.391 | 0.996 | 0.988 | 0.885 | 0.651 | 0.725 |
| | | 0.283 | 0.696 | 0.391 | 0.996 | 0.988 | 0.885 | 0.651 | 0.725 |
| | All <15m - river | 0.289 | 0.701 | 0.400 | 0.991 | 0.984 | 0.881 | 0.650 | 0.724 |
| | | 0.286 | 0.707 | 0.407 | 0.990 | 0.983 | 0.881 | 0.660 | 0.728 |
| | All <15m - road | 0.279 | 0.705 | 0.385 | 0.985 | 0.978 | 0.876 | 0.643 | 0.725 |
| | | 0.279 | 0.703 | 0.390 | 0.988 | 0.981 | 0.879 | 0.644 | 0.721 |
| | All <15m - river/road | 0.285 | 0.712 | 0.397 | 0.981 | 0.974 | 0.872 | 0.642 | 0.725 |
| | | 0.282 | 0.717 | 0.408 | 0.983 | 0.976 | 0.874 | 0.655 | 0.725 |
| | All <15m - river/road/ditch | 0.297 | 0.702 | 0.390 | 0.976 | 0.969 | 0.868 | 0.630 | 0.723 |
| | | 0.300 | 0.700 | 0.404 | 0.972 | 0.964 | 0.864 | 0.638 | 0.732 |
| | All <15m - river/ditch | 0.308 | 0.686 | 0.392 | 0.984 | 0.977 | 0.876 | 0.638 | 0.722 |
| | | 0.313 | 0.684 | 0.400 | 0.977 | 0.969 | 0.869 | 0.643 | 0.734 |
| | Shared fence | 0.281 | 0.705 | 0.398 | 0.982 | 0.974 | 0.873 | 0.665 | 0.737 |
| | | 0.281 | 0.705 | 0.398 | 0.982 | 0.974 | 0.873 | 0.665 | 0.737 |
| | Shared fence - river | 0.282 | 0.702 | 0.395 | 0.980 | 0.973 | 0.872 | 0.655 | 0.730 |
| | | 0.284 | 0.709 | 0.404 | 0.980 | 0.972 | 0.871 | 0.670 | 0.737 |
| | Shared fence - river/ditch | 0.299 | 0.691 | 0.390 | 0.976 | 0.968 | 0.868 | 0.647 | 0.731 |
| | | 0.301 | 0.693 | 0.401 | 0.969 | 0.961 | 0.861 | 0.649 | 0.740 |

Table 9.8: TSS of approximation methods versus map-based contiguity measures for sample area, Aberdeenshire. Red = landscape features identified by automated process, black = identified visually. Road data used was from OS Meridian$^{TM}$2.

Figures 1-5: Box plots showing distribution of cut-offs of landscape feature buffers as a percentage of the farm-farm intersection areas, with presence/absence of the feature upon visual inspection.

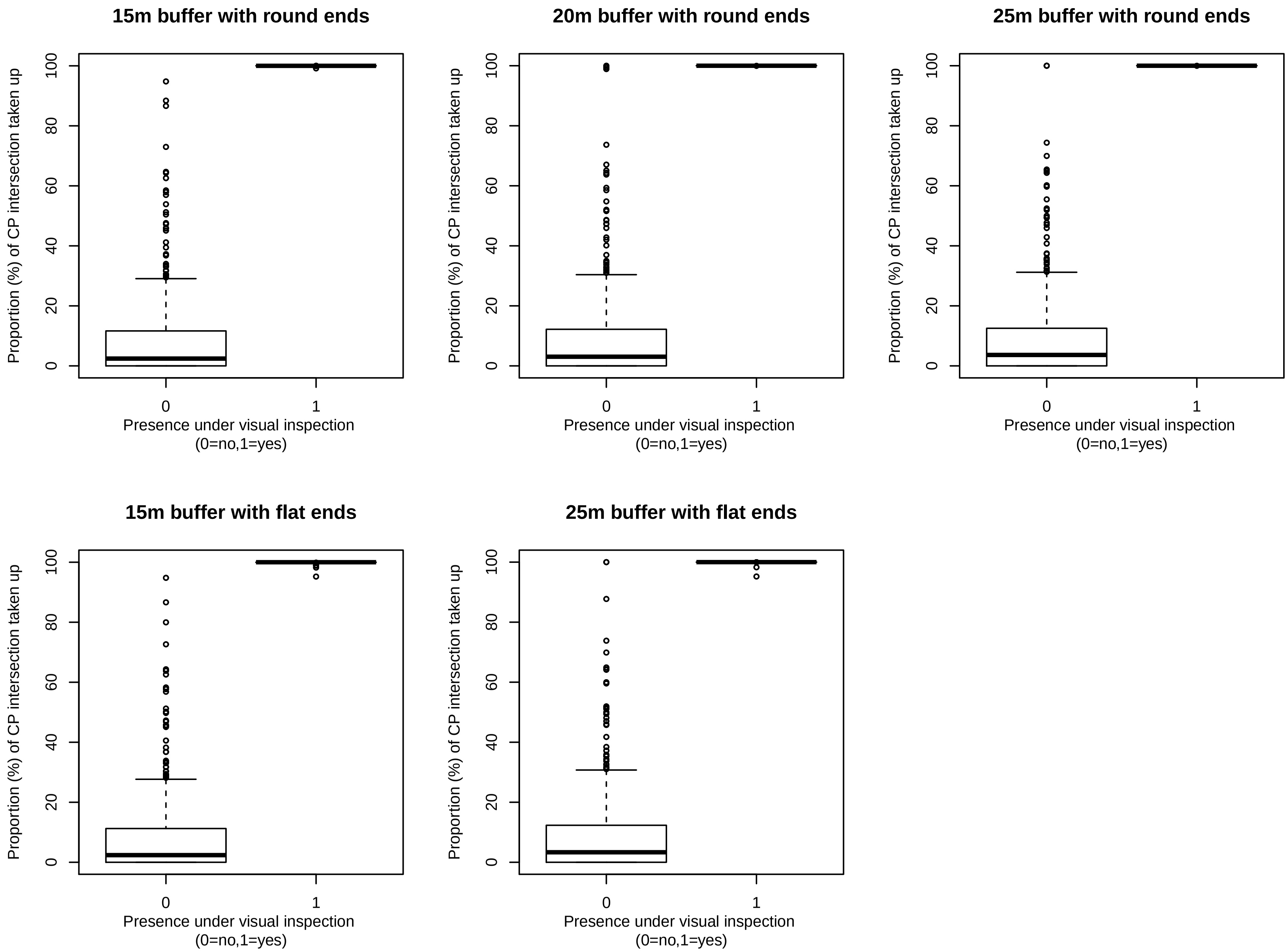



Figure 9.1: OS MasterMap® Roads

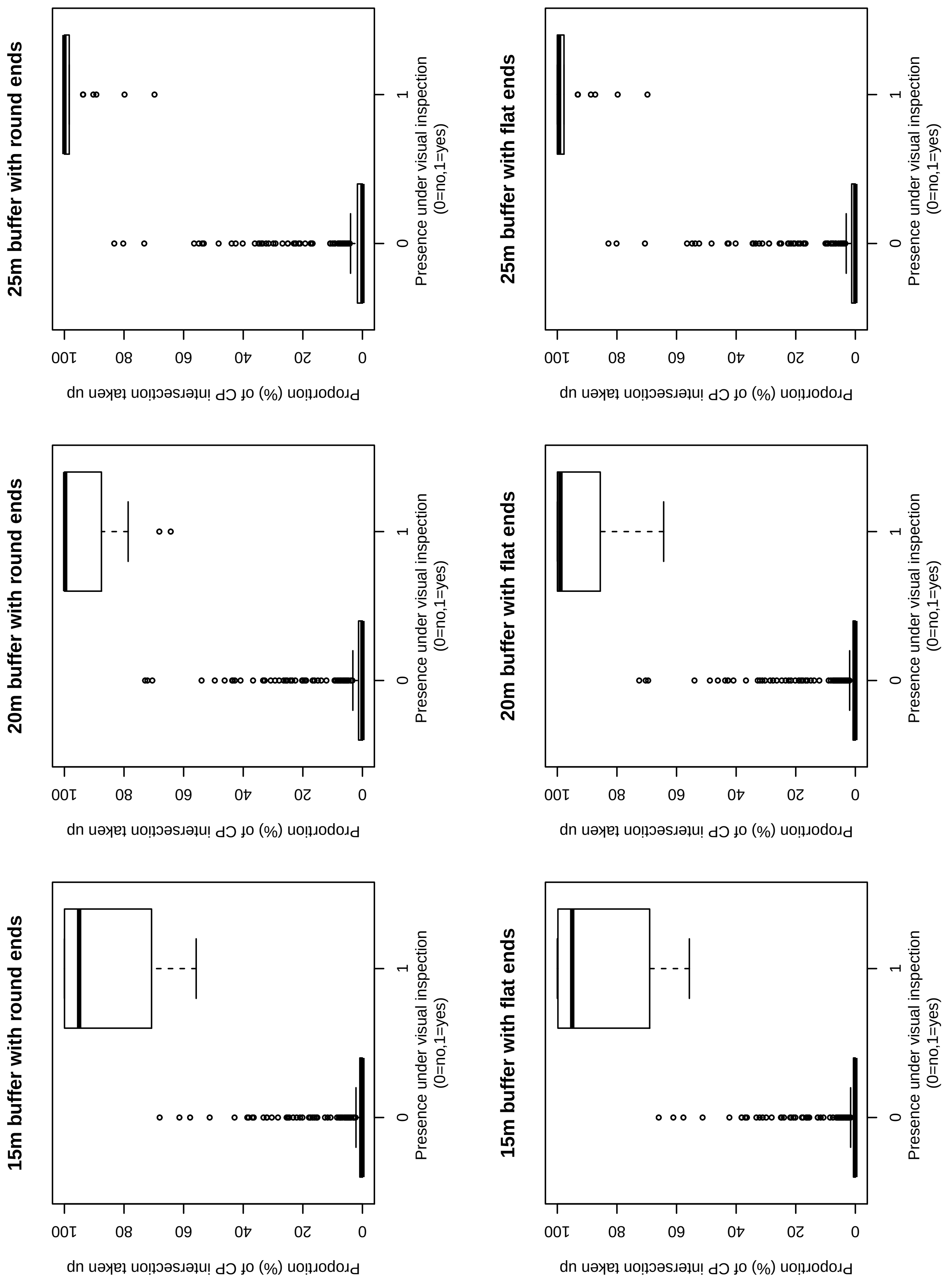



Figure 9.2: OS MasterMap® Rivers

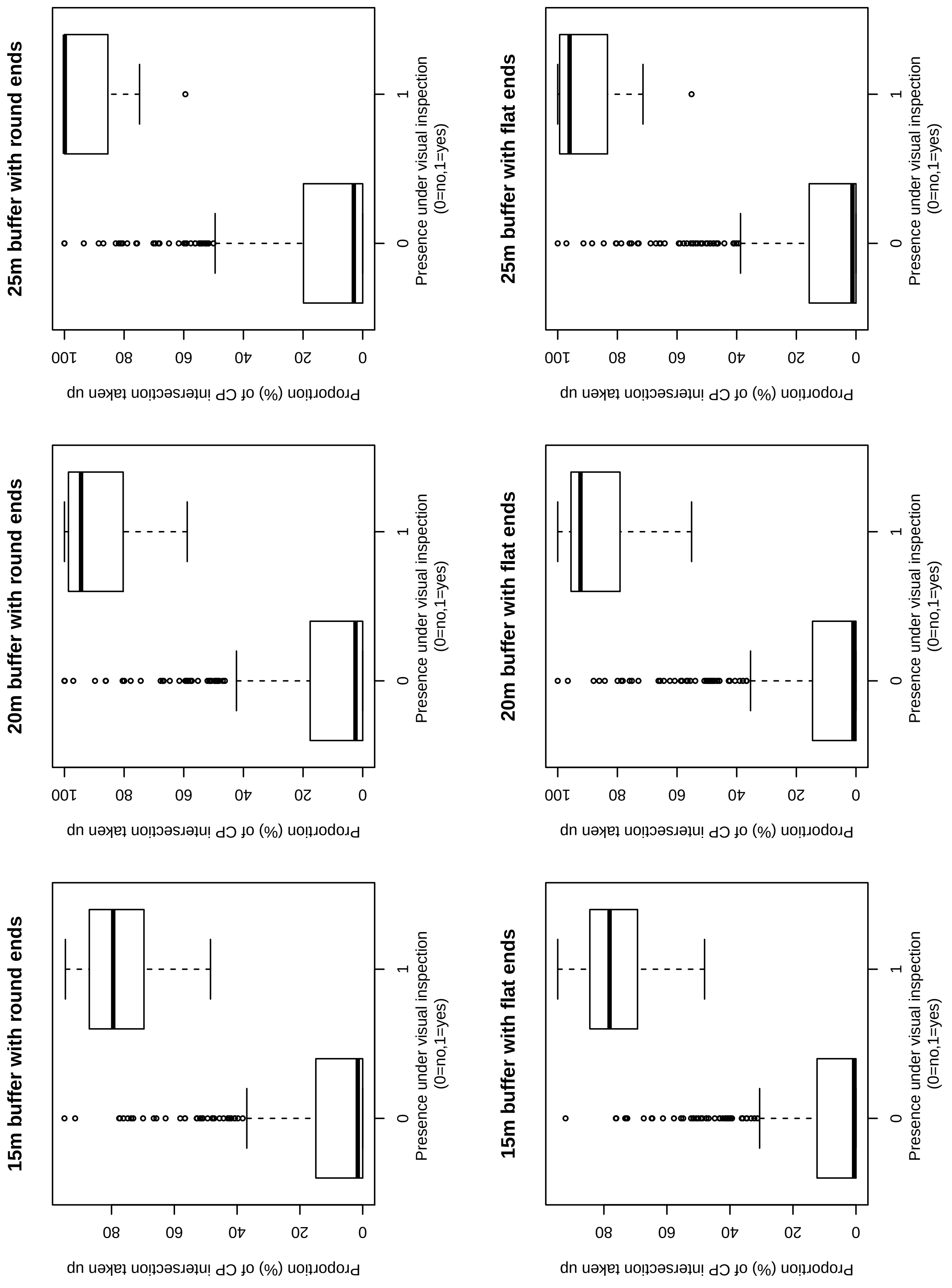



Figure 9.3: OS MasterMap® Ditches

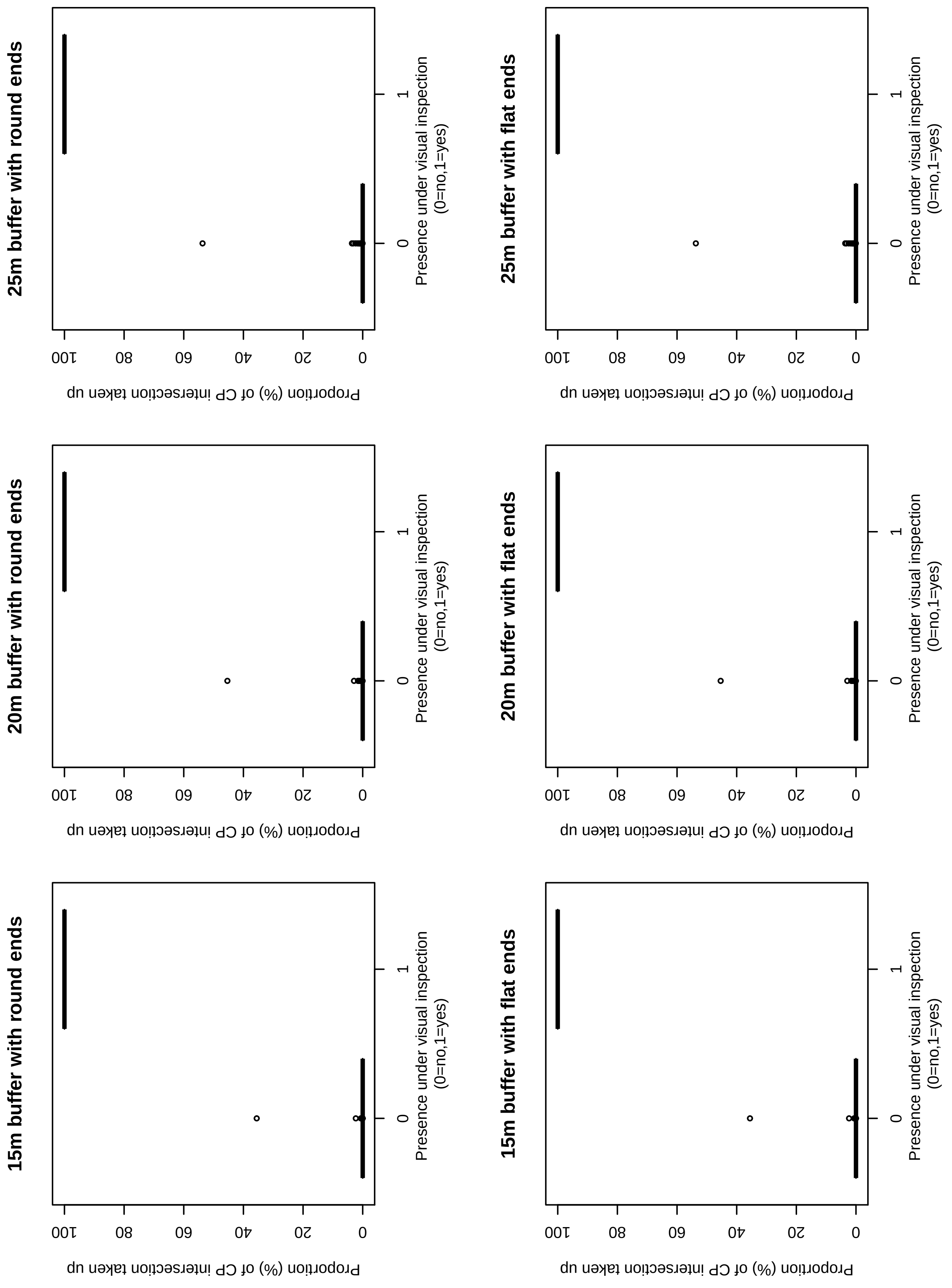



Figure 9.4: OS Meridian$^{\text{TM}}$2/MasterMap$^{\circledR}$ Railways

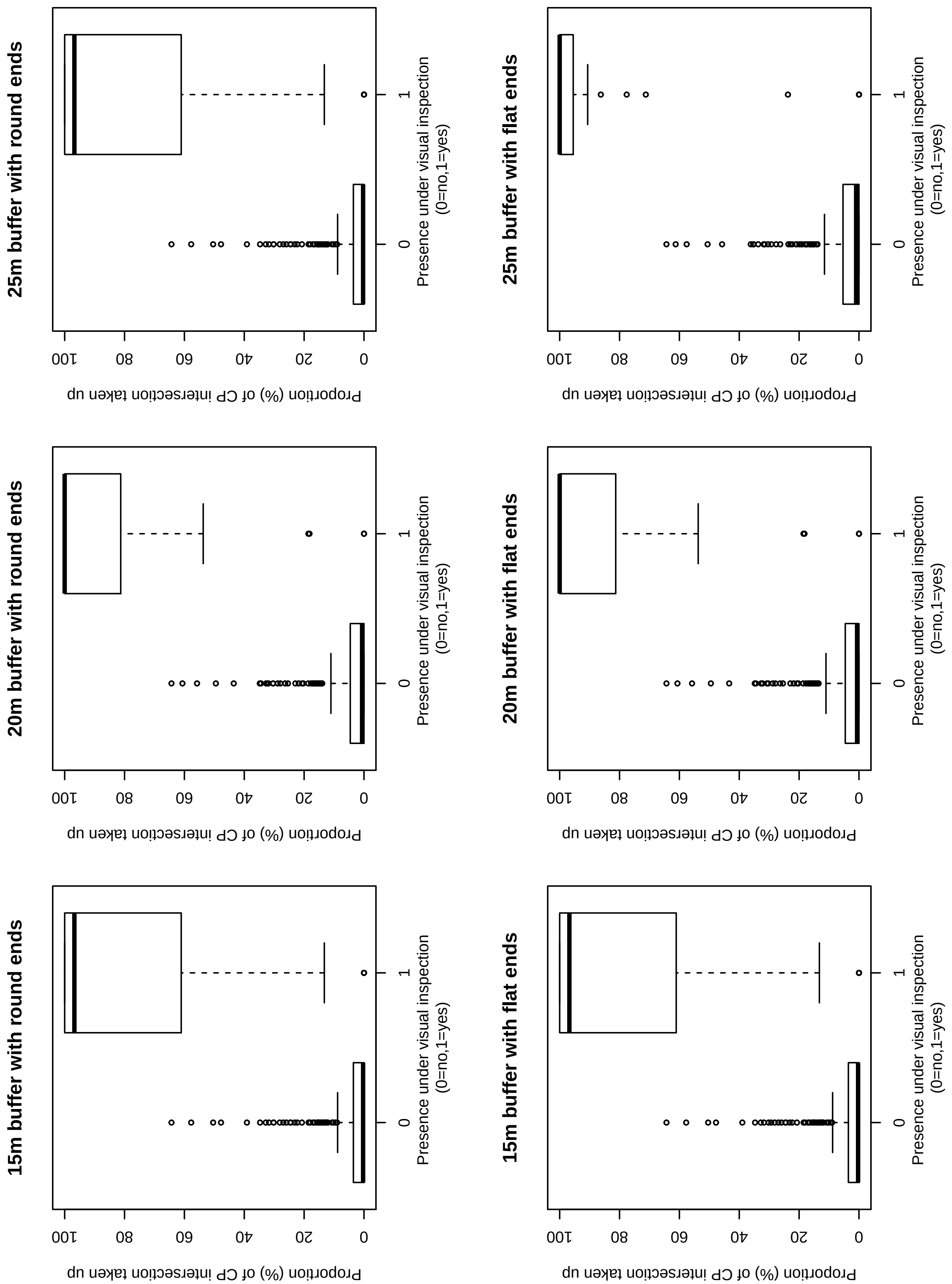



Figure 9.5: OS Meridian$^{TM}$2 Roads

# 10 Appendix 3: To accompany Chapter 4

## 10.1 Results: Network analysis

Table 10.1: Distribution of types of livestock kept on holdings in samples

| **Animals kept on holding** | **Number** | **%** |
|---|---|---|
| Cattle only | 1778 | 37.3 |
| Sheep only | 756 | 15.9 |
| Pigs only | 21 | 0.4 |
| Cattle/sheep | 2043 | 42.9 |
| Cattle/pigs | 33 | 0.7 |
| Sheep/pigs | 26 | 0.5 |
| Cattle/sheep/pigs | 102 | 2.1 |
| Deer/goats only | 8 | 0.2 |
| Total | 4767 | 100 |

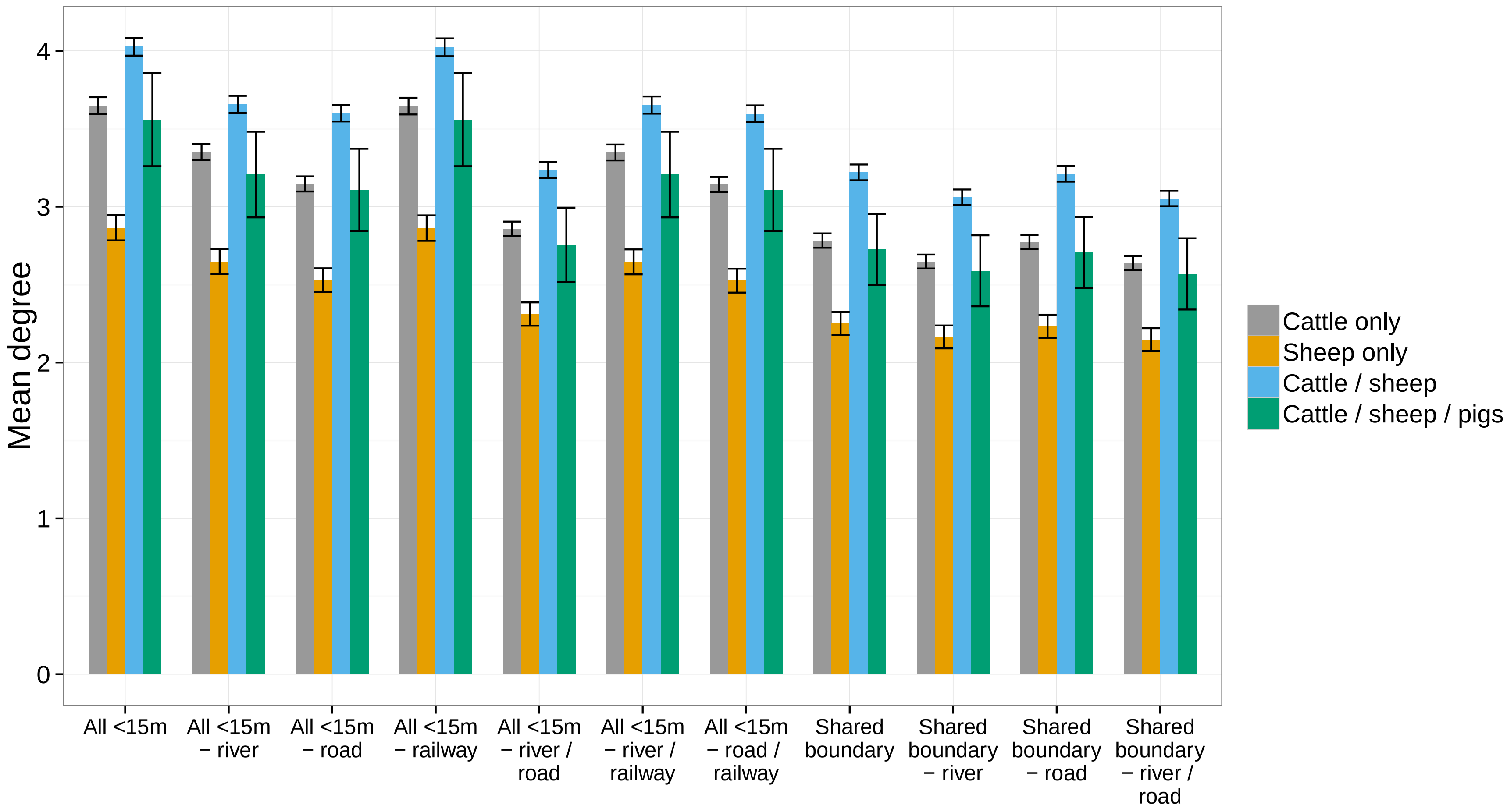



Figure 10.1: Bar graph of mean degree by species kept on premises, where CPs are considered to be premises within 15m. Error bars showing standard error of the mean.

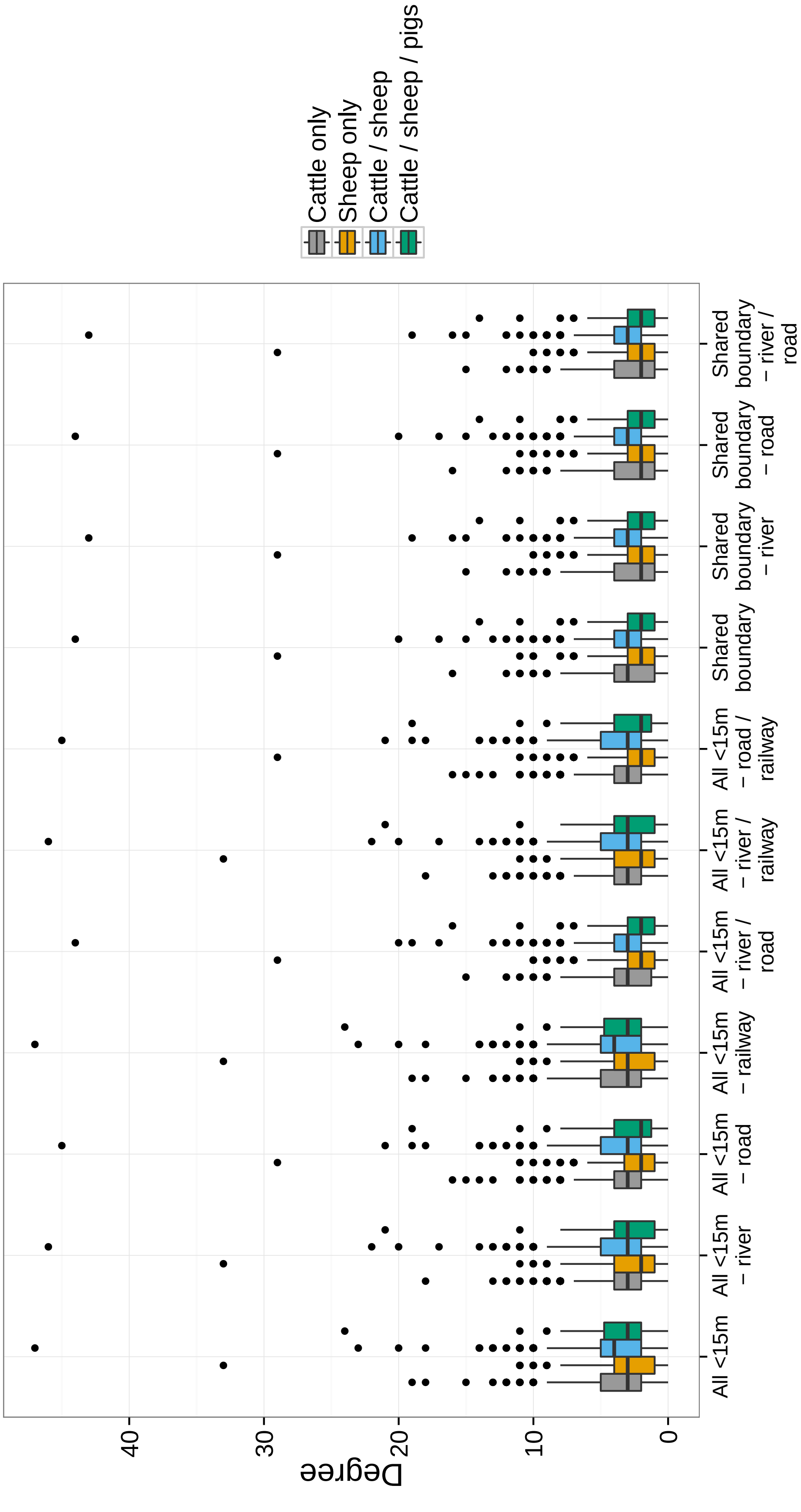



Figure 10.2: Box plots of degree distribution by species kept on premises, where CPs are considered to be premises within 15m.

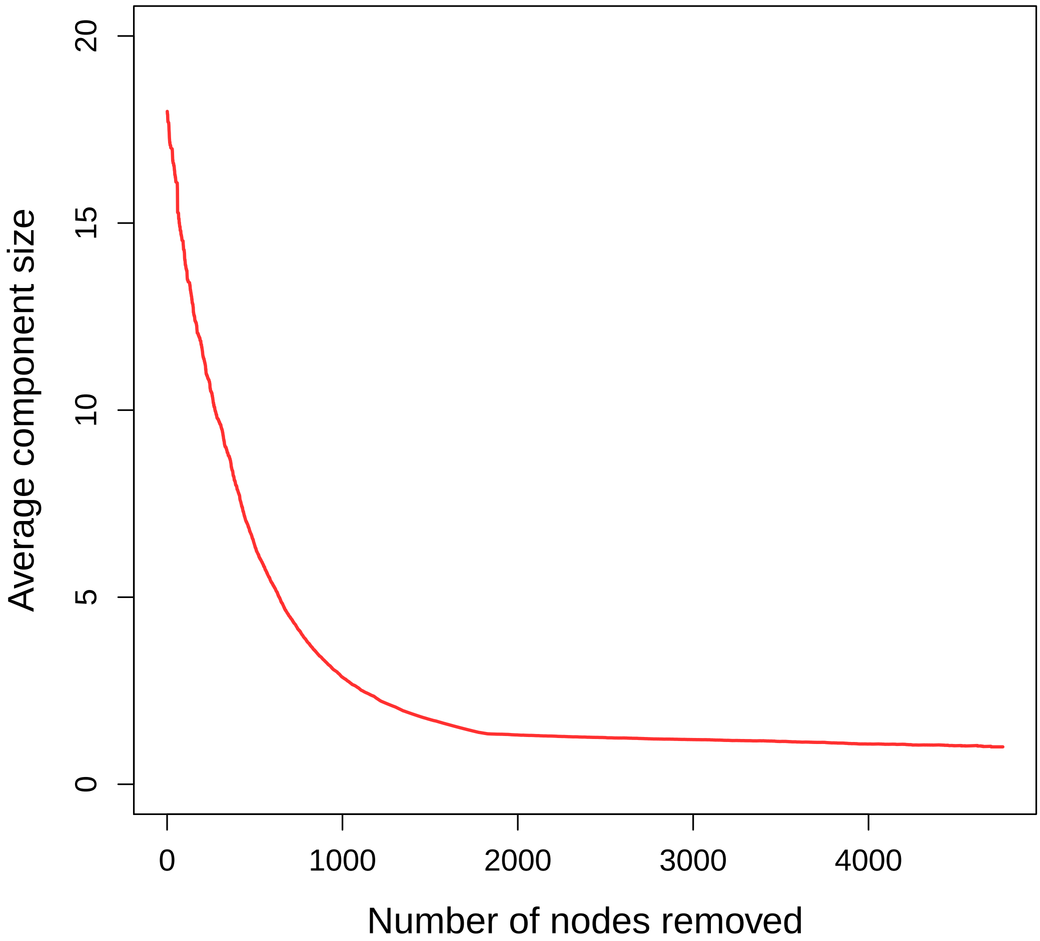



Figure 10.3: Graph showing decrease in average component size when holdings are removed in order of network betweenness centrality. Where CPs are defined as all holdings <15m apart at field edge.

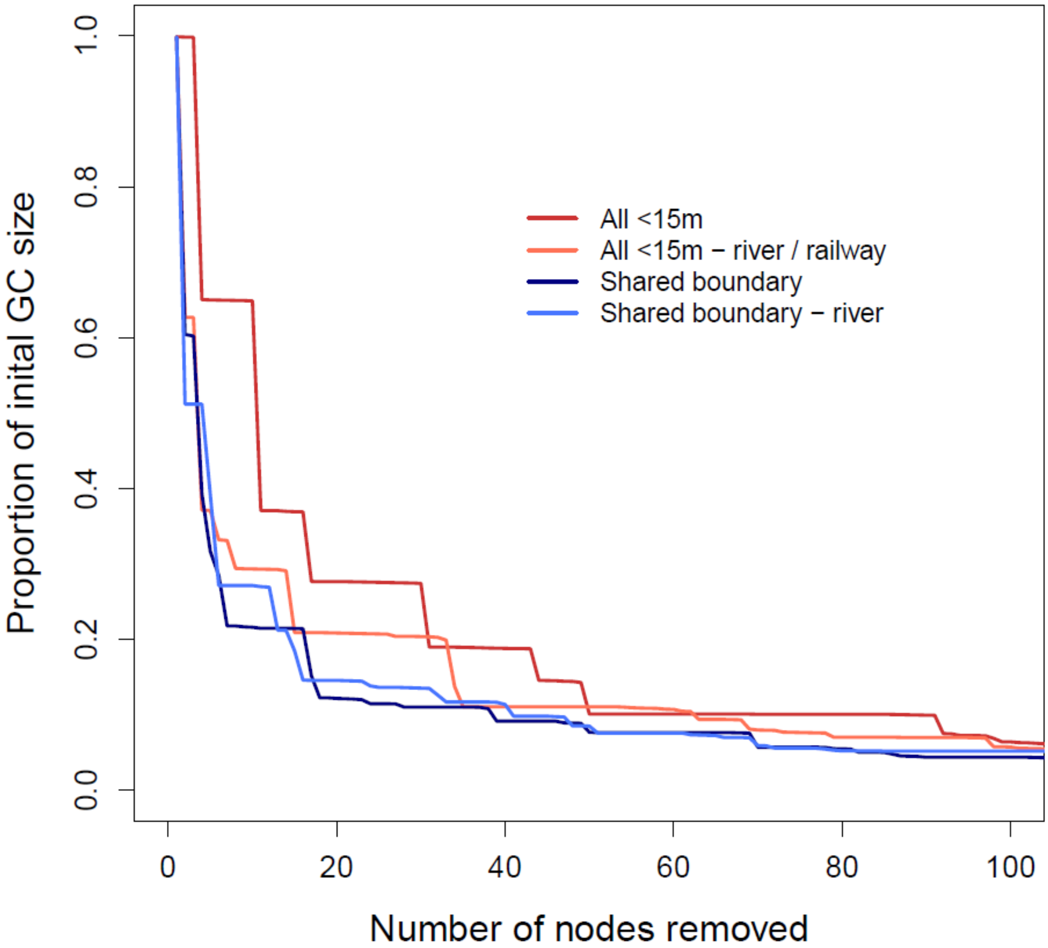



Figure 10.4: Proportion of initial giant component (GC) size of new GC on removal of holdings in order of betweenness, where networks are based on contiguity definitions with and without the inclusion of rivers and railways. Shown for removal of first 100 holdings.

| Contiguous classification | Density | Mean degree (standard deviation) with no buffers along edges | Mean degree (standard deviation) with buffer edge along north border |
|---|---|---|---|
| **All <15m** | 0.00077 | 3.65 (2.44) | 3.66 (2.45) |
| **All <15m - river** | 0.00070 | 3.34 (2.35) | 3.35 (2.35) |
| **All <15m - road** | 0.00067 | 3.22 (2.26) | 3.22 (2.27) |
| **All <15m - railway** | 0.00077 | 3.65 (2.44) | 3.66 (2.45) |
| **All <15m – river/road** | 0.00061 | 2.91 (2.15) | 2.92 (2.16) |
| **All <15m – river/railway** | 0.00070 | 3.34 (2.35) | 3.35 (2.35) |
| **All <15m – road/railway** | 0.00067 | 3.21 (2.26) | 3.22 (2.27) |
| **Shared field edge** | 0.00060 | 2.86 (2.14) | 2.87 (2.15) |
| **Shared field edge - river** | 0.00057 | 2.73 (2.09) | 2.73 (2.09) |
| **Shared field edge - road** | 0.00060 | 2.85 (2.14) | 2.86 (2.14) |
| **Shared field edge – river/road** | 0.00057 | 2.72 (2.09) | 2.72 (2.09) |

Table 10.2: Network properties according to different contiguity definitions, showing impact of including buffer edge for degree calculations on mean degree distribution.

# 11 Appendix 4: Fieldwork area reports and documents

## 11.1 Fieldwork area reports

### 11.1.1 Ayrshire

Driving between Ayrshire farms was quicker than expected at around 10-15 minutes. The majority of farms were dairy farms, and as a result, the farms were easily identifiable from the road since milk tankers need to be able to easily locate and access them. The greater proportion of telephone numbers found online meant that visits were generally pre-arranged at an agreed time and date. In the case of drop-bys, farmers were likely to be in or near to the farm house if they were running dairy farms, since dairy production is very labour intensive. However, we were frequently asked to come back at a more convenient time and/or day to go through the questionnaire, and several declined to participate altogether. One observation of this area was that there were several short stretches of muck on the public roads near to some dairy farms, since the milking cows are walked to and from their fields two or three times daily, and the fields tend therefore to be close by to the farm steading. We were several times delayed on our journeys by waiting for cattle to cross or walk down the road.

Table 11.1: Visits by day, Ayrshire

| Day | Mon | Tue | Wed | Thu | Total |
|---|---|---|---|---|---|
| Week 1 | 6 | 8 | 7 | 6 | 27 |
| Week 2 | 6 | 8 | 7 | 7 | 28 |
| Week 3 | 6 | 9 | 10 | 6 | 31 |
| Week 4 | 7 | 7 | 8 | 6 | 28 |
| Week 5 | NA | 6 | 5 | NA | 11 |
| Total | 25 | 38 | 37 | 25 | 125 |

### 11.1.2 Aberdeenshire

By road, farms were further apart than in Ayrshire, taking between 20-30 minutes to drive between them. The majority of farms were beef farms, and only around half were clearly signposted from the roads. Here drop-bys had less chance of finding the farmer to speak to, since beef production is considerably less labour intensive than dairy. If the farmer was in, however, they were more likely to agree to do the survey there and then, since presumably they had fewer time constraints.

Two holdings were excluded: one was attributed the wrong contact name and address, and another was rented out to different people each year, with the people living there having nothing to do with the farming.

Table 11.2: Visits by day, Aberdeenshire

| Day | Mon | Tue | Wed | Thu | Fri | Total |
|---|---|---|---|---|---|---|
| Week 1 | 6 | 11 | 8 | 5 | NA | 30 |
| Week 2 | 5 | 6 | 6 | 7 | 1 | 25 |
| Week 3 | 4 | 6 | 4 | 5 | 1 | 20 |
| Total | 15 | 23 | 18 | 17 | 2 | 75 |

## 11.2 Fieldwork documents used

Documents included in this appendix, in order, are:

1. Fieldwork survey approval form
2. Letter sent ahead of fieldwork visits
3. Fieldwork consent form
4. Fieldwork questionnaire - Ayrshire
5. Fieldwork questionnaire - Aberdeenshire

# RESAS RESEARCH APPROVALS PROFORMA

**MRP Contact Name: Jessica Flood**

**Organisation: University of Edinburgh**

**Email address: j.s.flood@sms.ed.ac.uk**

**Tel: 0131 650 5446**

**Date submitted to RESAS: 22/03/13**

**Date of Approval [RESAS to complete]: DD/MM/YY**

**Approved by [RESAS Science Adviser]:**

| | |
|---|---|
| **1** | **Title of Project** |
| | Investigating the role of neighbourhood and spatial proximity in farm biosecurity practices to improve model predictions of infectious diseases in livestock. |
| **2.** | **Key aims and objectives of the research elements** |
| | 1. To assess whether livestock farm biosecurity and management practices are more similar the smaller the separation distance between premises (i.e. whether there is spatial autocorrelation), in order to inform mathematical models.<br>2. To better understand within farm movement of livestock and land use in relation to livestock, in order to inform mathematical models.<br>3. To assess the accuracy of environmental data in locating livestock in the Scottish landscape given other data restrictions.<br>4. To assess the accuracy of Ordnance Survey MasterMap data in defining the presence of geographical features at premise boundaries. |
| **3.** | **Which Strategic Research Programme Theme(s), Centre of Expertise or Strategic Partnership is the research being conducted under?** |
| | **Centre of Expertise:** *Animal Disease Outbreaks* |
| **4.** | **What policy areas does the research relate to?** |
| | Rural and Environment |
| **5.** | **Please add in key dates below – Month/Year is sufficient** |

| | Fieldwork | When results will be available |
|---|---|---|
| | **Start** *06/13* **End** *08/13* | *09/14* |

| | | |
|---|---|---|
| **6.** | **Please give a brief description of the key methods to be used in the research in the box below.** | |
| | **Survey?**<br>YES | **Details**: *Method; sample size, information about participants; information covered in the questionnaire; time to complete questionnaire; geographical location of interviews.* |

| | | |
|---|---|---|
| | | *Method:* Letters informing farmers in the selected samples will be sent out in advance. The survey will then be conducted face-to-face.<br>*Sample size:* Approximately 100 in Aberdeenshire, approximately 170 in Ayrshire.<br>*Participants:* Livestock farmers with any cattle and/or sheep that are within selected areas.<br>*Geographical location:* There will be two areas over which the survey will be applied – both over approximately 225km$^2$, one in Ayrshire and one in Aberdeenshire. These sample areas will be used so that the key outcome, whether there is a neighbourhood/spatial proximity effect (spatial autocorrelation), can be best assessed.<br>*Information covered in questionnaire:* Specific biosecurity practices will be asked about in order to create the same composite score which was found to correlate with foot-and-mouth (FMD) disease during the 2007 outbreak in England by the AHVLA. Demographic information will be collected about the farm owner, as well as information on the farm (e.g. species type, main production type). Whether the farm has been affected by any infectious diseases in the past 5 years will be asked, as will the number of linked CPHs in the same IACS business and number of CTS Link CPHs the premise has. Information will be gathered on the use of different fields and parcels of land and movement of livestock between these and any CPHs in the same IACS business /CTS Links. Participants will be asked to verify presence of geographical features at the boundaries of their premise on a map. |
| | **Qualitative Interviews?**<br>NO | N/A |
| | **Focus groups?**<br>NO | N/A |
| **7.** | **Is the survey/interview/focus group work one-off or will it involve repeat contact with respondents?**<br>*If repeat contact is required, please give more information.* | |
| | One-off. | |
| **8.** | **Have you discussed the idea of the research, and the specific survey/focus groups/interviews, with the relevant Scottish Government policy teams?**<br>• *If yes, please give details in the box below, including names of people you have contacted and whether they support the research.* | |

| | |
|---|---|
| | • *if no, please specify reasons and/or note plans for contact.* |
| | The survey is to form part of a PhD thesis which has been funded by EPIC, the Scottish Government's Centre of Expertise on Animal Disease Outbreaks.<br>It has been discussed with Nia Ball, who is in the process of referring us to a contact within the relevant policy team(s). |
| **9.** | **Please set out the likely benefits of these research activities to the following:** |
| | A) The respondent/participant<br>Increased trust in recommendations for disease control in the event of future outbreaks of livestock diseases transmitted by contact.<br>Improvement of mathematical models is likely to lead to more effective control measures being recommended, therefore decreasing the burden on the farming community.<br><br>B) The wider research project<br>Understanding the role of neighbourhood influence on biosecurity practices and how land is used for within-farm operations will help inform and improve models of livestock disease spread.<br>The accuracy of unrestricted geographic data sources for use in research in this field will be assessed (Aim 3). This could potentially increase the number of research groups that could work on finding the optimal solutions in the event of future livestock disease outbreaks.<br>The accuracy of geographical/topographical datasets will be assessed, enabling sensitivity analyses of models incorporating this information to be performed.<br><br>C) The Scottish Government<br>This project will provide an evidence base for improvements to models of infectious livestock diseases spread by contact. Additionally, the assessment of the accuracy of unrestricted data sources may decrease the response time in which research groups are able to analyse the situation in the event of future outbreaks. It may also enable the number of groups working on the problem to be increased, and therefore provide the Government with a larger evidence base on which to make decisions. |
| **10.** | **Have these specific research elements been subject to a process of ethical approval?** *Please give further information on your answer, below.* |
| | No – no ethical implications are deemed to arise from the research. |
| **11.** | **Have other information sources been considered as an alternative to carrying out primary research? Please give details.** |

| | |
|---|---|
| | Background information from other data sources will be used to supplement the information collected by the survey (e.g. the Agricultural Census, Cattle Tracing System (CTS) movement database), but the information gathered in the survey will be unique. In particular, a composite biosecurity score is needed to undertake the proposed spatial analysis. Thus, a validated composite biosecurity score will be used which was developed by the AHVLA during the 2007 FMD outbreak in Surrey (showing an association with FMD on premises). This is based on a specific set of questions. Additionally, while CTS records between-premise movement the interest of this survey is on within-premise movement: in particular the use and movement of livestock between premises linked by CTS Link are of interest, for which movements are not recorded by CTS. |
| **12.** | **What steps are being taken to minimise the burden on respondents?** |
| | The questionnaire survey has been designed such that only questions deemed necessary to the research are included, and therefore the number of questions has been minimised.<br>The questionnaire is largely formed of closed questions.<br>The survey will be conducted over the summer months in order to avoid calving and lambing seasons. |
| **13.** | **Will you require access to any SG datasets in order to conduct the research? If YES, please give details.** |
| | Ideally SIACS land parcel data with addresses would be obtained for the sample areas in order to send a letter regarding the survey by post ahead of the survey itself. This would also enable the sample areas to be matched up to areas used for other related research projects. Alternatively, Agricultural Census data with farm premise addresses for the selected farms would be obtained. |

**Please return this form by e-mail or post to:**

Chris Rich
Scottish Government
Rural and Environment Science and Analytical Services Division (RESAS)
1-F (South)
Victoria Quay
Edinburgh EH6 6QQ

E-mail: chris.rich@scotland.gsi.gov.uk (if e-mailing please copy in scott.boyd@scotland.gsi.gov.uk )

SCHOOL of BIOLOGICAL SCIENCES
Institute of Evolutionary Biology

The University of Edinburgh
Ashworth Laboratories
The King's Buildings
West Mains Road
Edinburgh EH9 3JT

DATE 2013

Dear Livestock Farmer,

We would appreciate your input to help safeguard against future epidemic livestock disease outbreaks in Scotland.

We are interested in understanding attitudes and practices for farm biosecurity and management, and are going to be conducting a survey in your local area during July and August. The survey should take about 20-30 minutes to complete.

The survey is being undertaken as part of a wider research group, the Centre of Expertise in Animal Disease Outbreaks, details of which can be found by visiting http://www.sruc.ac.uk/epic/ online.

We appreciate that your time is valuable so we will try to telephone prior to arrival to arrange a convenient time for us to discuss this with you further.

Yours faithfully,

Jessica Flood

THE UNIVERSITY of EDINBURGH

# Livestock management survey 2013

## Information

This questionnaire will collect information on a small set of biosecurity practices, herd management, and land use in relation to livestock. We are particularly interested in looking at patterns of biosecurity practices between livestock farms. We would also like to investigate how environmental datasets could be used to predict where cattle and sheep are kept, in order to see if we can improve the quality of the data available for analyses in the event of future outbreaks of disease.

This questionnaire will allow us to improve the evidence base for recommendations for the control of any future outbreaks of epidemic disease in livestock. Your help will result in a better understanding of how disease spreads between farms and how this spread can be predicted. This information will be used to improve advice to farmers and the Scottish Government. We promise that:

- We will analyse and report data in a manner which protects your anonymity.
- Any information provided will be treated with care and discretion, within the terms of the Data Protection Act, 1998.
- We will keep personal details, such as name and address, separate from your questionnaire answers.
- Your personal details will not be used for any scientific or commercial purposes, although they will be retained for project administration.
- We will not make your personal details available to any third parties.
- We will ensure that no information about you or your business can be inferred from published results.

In return we ask that you answer all questions honestly, to the best of your knowledge.

If, in future, we are able to use your responses to help answer other scientific and practical questions, we will do so, subject to the safeguards listed above. During the interview, we will ask whether you are willing to be involved in future scientific studies. If you are able to help us in this way, we will retain your personal details, but can assure you that they will never be used as part of any commercial activities.

## Questionnaire structure

This survey is divided into the following three sections:

- Section A – 16 questions gathering background information on you and your farm premises.
- Section B – 12 questions regarding farm management and biosecurity.
- Section C – we will ask you to look at a map of your premises fields and identify where livestock are normally kept.
- Section D – 11 questions regarding herd management, and land/field use.

epic Centre of Expertise on Animal Disease Outbreaks

BioSS

## Consent form

**Project Name:** Livestock farm management survey 2013

**Name of project leader:** Jessica Flood

**Postal address:** 138, Ashworth 1, King's Buildings, University of Edinburgh, EH9 3JT, UK

**Telephone number:** 0131 650 5446

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I have read and understood the information provided about the project. I agree to take part in the study and understand that I can withdraw at any time, without having to give any reason, by contacting and informing the project leader. I consent to my personal data, as outlined at the visit, being used for the research project detailed above.

Name (print): …………………………………………………………………………………………………………………………….

Signed: ………………………………………………………………………………………………………………………………………

Date: ……………………………………………………………………………………………………………………………………..

Farm ID ______________

## Section A: Background information

**1.** Are you:
- ◯ Male
- ◯ Female

**2.** Which age group are you in?
- ◯ 18-35 years
- ◯ 36-50 years
- ◯ 51-65 years
- ◯ 66+ years

**3.** What is your educational level?
- ◯ School
- ◯ College
- ◯ University

**4.** How many years have you worked on a farm?

_______________years

**5.** Do you rent or own the main CPH site?
- ◯ Rent
- ◯ Own

**6.** For how long have you run this farm CPH?

_______________years

**7.** Did the premises belong to someone in your family before it belonged to you?
- ◯ Yes
- ◯ No

**8.** How many of your household members (**including yourself**) work on the farm:

Part-time _______________

Full-time _______________

**9.** How many workers do you have on the farm (**excluding yourself and your household members**) that are:

Part-time _______________

Full-time _______________

**10.** What is your main production type (**you may tick up to 2**)?
- ◯ Beef breeding
- ◯ Beef finishing
- ◯ Dairy herd
- ◯ Sheep breeding flock
- ◯ Purely hill bred flock
- ◯ Sheep breeder/finisher flock
- ◯ Lamb finishing flock

**11.** What species of large animal do you keep on this holding? Please tick all that apply.
- ◯ Cattle
- ◯ Sheep
- ◯ Pigs
- ◯ Goats
- ◯ Horses
- ◯ Other ______________________

**12.** In the last 5 years, have your livestock been diagnosed with and/or displayed clinical signs of any of the following diseases? Please tick all that apply.
- ◯ Bovine tuberculosis (bTB)
- ◯ Bovine Viral Diarrhoea (BVDV)
- ◯ Johne's Disease / paratuberculosis
- ◯ Liver fluke
- ◯ Schmallenberg
- ◯ Sheep scab

**13.** Have you taken up the AHWMP LMO (Animal Health and Welfare Management Programme, Land Managers Options)?
- ◯ Yes
- ◯ No

**14.** Are you certified organic?
- ◯ Yes
- ◯ No
- ◯ In the conversion period

**15.** Do you farm any rare breeds? If so please name.
- ◯ Yes ______________________
- ◯ No

**16.** Are you a member of the National Farmers Union Scotland?
- ◯ Yes
- ◯ No

## Section B: Farm management and biosecurity

**17.** Is there a gate at the main farm entrance?
- ◯ Yes
- ◯ No

If **yes**, is it:
- ◯ Kept closed throughout the day
- ◯ Closed evenings only
- ◯ Seldom closed
- ◯ Other (specify) ____________________________

**18.** For all fields with livestock in, are there any gates in the boundary that lead onto public land?
- ◯ Yes
- ◯ No

If **yes**, are the gates normally open/closed/ locked (**tick the one that most closely applies**)?
- ◯ All are locked
- ◯ Most are locked
- ◯ All are closed
- ◯ Most are closed
- ◯ Most are open
- ◯ All are open

**19.** If dogs are present (working or pet), do they accompany staff around the farm premises?
- ◯ Yes
- ◯ No

**20.** Do you operate a farm shop?
- ◯ Yes
- ◯ No

**21.** Is there any other enterprise on the farm premises that attracts members of the public? Tick all that apply.
- ◯ None
- ◯ Open farm
- ◯ School visits
- ◯ Campsite
- ◯ B&B
- ◯ Other ____________________

**22.** Which of the following biosecurity measures do you currently have in place?
- ◯ Physical separation between “public access areas” and “livestock areas” (eg. Gate)
- ◯ Changing area with/without hand washing facilities
- ◯ Car park outside animal area (i.e. outside areas to which animals have access)
- ◯ Notice or sign prohibiting entry at entrance
- ◯ Boot/foot dip at entrance to the farm
- ◯ ‘Farm’ specific boots/footwear provided for all staff and family?
- ◯ ‘Farm’ specific overcoats or overalls provided for all staff and family?

**23.** How frequently are the biosecurity measures used on the farm reviewed?

________________________

**24.** If livestock on your premises were to become infected with an infectious disease, how likely do you think it is that they would have come from:

| | **Very likely** | **Likely** | **Unlikely** | **Very unlikely** |
|---|---|---|---|---|
| Animals brought in | ◯ | ◯ | ◯ | ◯ |
| Neighbouring stock | ◯ | ◯ | ◯ | ◯ |
| Animals moved off and back on (e.g. to a show, to another premises) | ◯ | ◯ | ◯ | ◯ |
| Other (please state) ______________ | ◯ | ◯ | ◯ | ◯ |

**The following questions refer to the previous 3 weeks.**

**25.** In the specified period, did you notice any of the following unusual events / visits associated with your fields or with neighbouring land? (Tick all that apply.)

◯ Travellers camping
◯ Building work
◯ Agricultural contractors
◯ Road works
◯ Theft of equipment
◯ Fly tipping / rubbish
◯ Other ______________________________

**26.** In the specified period, did you notice any stock straying into your fields or into your immediate neighbours' fields?

◯ Yes
◯ No

If **yes**, which species of animal were seen?

◯ Cattle
◯ Sheep
◯ Goats
◯ Pigs
◯ Other

**27.** In the specified period, did you or your neighbouring community hold any events on your fields or on neighbouring land? (e.g. pony club or scout/guide camp, local fete or fair, agricultural show, sporting event, fishing (individuals or competitions), car boot sale, car parking for any reason etc.)

◯ Yes
◯ No

## Section C: Grazing land use

Please look at this CPH's field locations on the printed duplicate maps. One map is for cattle, and the other for sheep. For each species' map, please mark on the relevant fields:

__ **Which fields are permanent pasture** for the species (i.e. used every year) – indicate with a "P", or outline using green highlighter.
Please indicate in the space provided the months of the year this is usually grazed by this species e.g. "Apr-Sept".

__ **Which fields are temporary grazing** used for the species (please include all fields ever used for grazing for the species) – indicate with a "T", or outline using a yellow highlighter.
Please indicate in the space provided the months of the year these would usually be grazed by this species if in use.

__ Which **grazing field boundaries** have **neighbouring stock grazing adjacent** to them? Please indicate species most commonly grazing in the adjacent fields.

## Section D: Herd/flock management, within farm movement, and environment

**28.** Are there any public foot paths or bridle paths passing through any of this CPH premises' fields?

◯ Yes
◯ No

If **yes**, do any of these pass through any fields that livestock on this CPH premises are kept in?

◯ Yes
◯ No

**29.** Are there any public foot paths or bridle paths running beside (outside) the boundary of this CPH premises' fields?

◯ Yes
◯ No

If **yes**, do any of these run beside (outside) the boundary of any fields that livestock on this CPH premises are kept in?

◯ Yes
◯ No

**30.** How many CPHs are there in this IACS business (including this holding)? ________________

If **more than one**, are livestock grazed on land belonging to other CPHs that are part of the same IACS business?

- ◯ Yes
- ◯ No

If **yes**, how many separate parcels (i.e. where a land parcel = set of grouped fields) do they graze in? _____________________

**31.** Does this holding have any CTS Links? If so, what type (please refer to information sheet if needed), and how many (**excluding this CPH**)?

- ◯ No
- ◯ Yes – Shared Facility link ________________
- ◯ Yes – Additional Land link ________________

If **yes**, do you graze livestock on other CPHs that form a CTS Link with this holding?

- ◯ Yes
- ◯ No

If **yes**, how many separate parcels (i.e. grouped fields) do they graze in? _____________________

**32.** In addition to the fields outlined in section C, do you rent any land for grazing that does not form a CTS Link with this holding?

- ◯ Yes
- ◯ No

If **yes**, how many separate parcels (i.e. grouped fields) are there? _____________________

**33.** How many separately managed flocks and herds does this CPH have?

Cattle herds: _____________________

Sheep flocks: _____________________

**34.** What aspects of their management are separate? Please tick all that apply.

- ◯ Considered separate for management purposes
- ◯ Considered separate for book-keeping purposes
- ◯ No movement of animals between herds/flocks
- ◯ Cleaning/disinfecting facilities between herds/flocks coming into buildings
- ◯ Use of separate buildings/facilities for each herd/flock
- ◯ Cleaning/disinfecting vehicles, footwear and clothing between contacting each herd/flock
- ◯ Different staff and vehicles used for each herd/flock

**35.** How frequently do livestock from this holding move between the following types of grazing land (**please choose ONE**):

**a)** Fields within the same CPH, separated by ≤100m?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

**b)** Fields within the same CPH, separated by >100m?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

**c)** Fields belonging to a different CPH as part of the same IACS business?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

**d)** Fields belonging to a different CPH which forms a CTS Link with this holding?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

**e)** Rented fields belonging to a different CPH which do not form a CTS Link?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

**36.** When moving livestock from this holding between separate grazing fields, how are they most often moved between the following (**please choose ONE**):

**a)** Fields within the same CPH separated by ≤100m?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**b)** Fields within the same CPH separated by >100m?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**c)** Fields belonging to a different CPH as part of the same IACS business?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**d)** Fields belonging to a different CPH which forms a CTS Link with this holding?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**e)** Rented fields belonging to a different CPH which do not form a CTS Link?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**37.** How frequently do livestock from this CPH premises move between their field and the main farm buildings (**please choose ONE**)?

- ◯ Several times daily
- ◯ Once daily
- ◯ Several times weekly
- ◯ Once weekly
- ◯ Several times a month (< weekly)
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

Farm ID _______________

## Section A: Background information

**1.** Are you:
- ◯ Male
- ◯ Female

**2.** Which age group are you in?
- ◯ 18-35 years
- ◯ 36-50 years
- ◯ 51-65 years
- ◯ 66+ years

**3.** What is your educational level?
- ◯ School
- ◯ College
- ◯ University

**4.** How many years have you worked on a farm?

________________years

**5.** Do you rent or own the main CPH site?
- ◯ Rent
- ◯ Own

**6.** For how long have you run this farm CPH?

________________years

**7.** Did the premises belong to someone in your family before it belonged to you?
- ◯ Yes
- ◯ No

**8.** How many of your household members (**including yourself**) work on the farm:

Part-time ________________

Full-time ________________

**9.** How many workers do you have on the farm (**excluding yourself and your household members**) that are:

Part-time ________________

Full-time ________________

**10.** What is your **main** production type (**you may tick up to 3**)?
- ◯ Beef breeding
- ◯ Beef finishing
- ◯ Dairy herd
- ◯ Sheep breeding flock
- ◯ Purely hill bred flock
- ◯ Sheep breeder/finisher flock
- ◯ Lamb finishing flock

**11.** What species of large animal do you keep on this holding? Please tick all that apply.
- ◯ Cattle
- ◯ Sheep
- ◯ Pigs
- ◯ Goats
- ◯ Horses
- ◯ Other ________________________

**12.** In the last 5 years, have your livestock been diagnosed with and/or displayed clinical signs of any of the following diseases? Please tick all that apply.
- ◯ Bovine tuberculosis (bTB)
- ◯ Bovine Viral Diarrhoea (BVDV)
- ◯ Johne's Disease / paratuberculosis
- ◯ Liver fluke
- ◯ Schmallenberg
- ◯ Sheep scab

**13.** Do you use the AHWMP LMO (Animal Health and Welfare Management Programme, Land Managers Options)?
- ◯ Yes
- ◯ No

**14.** Are you certified organic?
- ◯ Yes
- ◯ No
- ◯ In the conversion period

**15.** Do you farm any rare breeds? If so please name.
- ◯ Yes ________________________
- ◯ No

**16.** Are you a member of the National Farmers Union Scotland?
- ◯ Yes
- ◯ No

## Section B: Farm management and biosecurity

**17.** Is there a gate at the main farm entrance?
- ◯ Yes
- ◯ No

If **yes**, is it:
- ◯ Kept closed throughout the day
- ◯ Closed evenings only
- ◯ Seldom closed
- ◯ Other (specify) ______________________________

**18.** For all fields with livestock in, are there any gates in the boundary that lead onto public land?
- ◯ Yes
- ◯ No

If **yes**, are the gates normally open/closed/ locked (**tick the one that most closely applies**)?
- ◯ All are locked
- ◯ Most are locked
- ◯ All are closed
- ◯ Most are closed
- ◯ Most are open
- ◯ All are open

**19.** If dogs are present (working or pet), do they accompany staff around the farm premises?
- ◯ Yes
- ◯ No

**20.** Do you operate a farm shop?
- ◯ Yes
- ◯ No

**21.** Is there any other enterprise on the farm premises that attracts members of the public? Tick all that apply.
- ◯ None
- ◯ Open farm
- ◯ School visits
- ◯ Campsite
- ◯ B&B
- ◯ Other ______________________

**22.** Which of the following biosecurity measures do you currently have in place?
- ◯ Physical separation between “public access areas” and “livestock areas” (eg. Gate)
- ◯ Changing area with/without hand washing facilities
- ◯ Car park outside animal area (i.e. outside areas to which animals have access)
- ◯ Notice or sign prohibiting entry at entrance
- ◯ Boot/foot dip at entrance to the farm
- ◯ ‘Farm’ specific boots/footwear provided for all staff and family?
- ◯ ‘Farm’ specific overcoats or overalls provided for all staff and family?

**23.** How frequently are the biosecurity measures used on the farm reviewed?

- ◯ Ongoing
- ◯ Annually
- ◯ Outbreak

**24.** If livestock on your premises were to become infected with an infectious disease, how possible / likely do you think it is that it would have come from:

| | **Likely** | **Possible** | **Unlikely** | **Not possible** |
|---|---|---|---|---|
| Animals brought in | ◯ | ◯ | ◯ | ◯ |
| Neighbouring stock | ◯ | ◯ | ◯ | ◯ |
| Animals moved off and back on (e.g. to a show, to another premises) | ◯ | ◯ | ◯ | ◯ |
| Other (please state) ______________ | ◯ | ◯ | ◯ | ◯ |

**25.** Is double fencing used in fields with livestock (cattle or sheep) in?

- ◯ No, in none
- ◯ Yes, in a few
- ◯ Yes, most of them
- ◯ Yes, all of them
- ◯ Only on neighbour's side

**The following questions refer to the previous 3 weeks.**

**26.** In the specified period, did you notice any of the following unusual events / visits associated with your fields or with neighbouring land? (Tick all that apply.)

- ◯ Travellers camping
- ◯ Building work
- ◯ Agricultural contractors
- ◯ Road works
- ◯ Theft of equipment
- ◯ Fly tipping / rubbish
- ◯ Other ______________________________

**27.** In the specified period, did you notice any stock straying into your fields or into your immediate neighbours' fields?

- ◯ Yes
- ◯ No

If **yes**, which species of animal were seen?

- ◯ Cattle
- ◯ Sheep
- ◯ Goats
- ◯ Pigs
- ◯ Other

**28.** In the specified period, did you or your neighbouring community hold any events on your fields or on neighbouring land? (e.g. pony club or scout/guide camp, local fete or fair, agricultural show, sporting event, fishing (individuals or competitions), car boot sale, car parking for any reason etc.)

- ◯ Yes
- ◯ No

## Section C: Grazing land use

Please look at this CPH's field locations on the printed duplicate maps. One map is for cattle, and the other for sheep. Please mark on the relevant maps:

__ **Which fields are grazed between different months of the year (e.g. G= grazing May-Sept, S= silage then grazing from Aug-Sept):**

- For cattle
- For sheep

__ Which **grazing field boundaries** have **neighbouring stock grazing adjacent** to them where they could have **nose-nose** contact? Please indicate species most commonly grazing in the adjacent fields.

## Section D: Herd/flock management, within farm movement, and environment

**29.** Are there any public foot paths or bridle paths passing through any of this CPH premises' fields?

◯ Yes
◯ No

If **yes**, do any of these pass through any fields that livestock on this CPH premises are kept in?

◯ Yes
◯ No

**30.** Are there any public foot paths or bridle paths running beside (outside) the boundary of this CPH premises' fields?

◯ Yes
◯ No

If **yes**, do any of these run beside (outside) the boundary of any fields that livestock on this CPH premises are kept in?

◯ Yes
◯ No

**31.** **Including this holding**, how many different location code numbers (e.g. 123/4567) are there in this IACS business that are:

- **Permanent Land** (i.e. number of different location codes submitted on IACS(3) / Permanent Land form)? _______________
- **Seasonal Land** (i.e. number of different location codes submitted on IACS(4) / Seasonal Land form)? _______________

**If there are multiple location codes** in the IACS business, are livestock grazed on land belonging to other location codes that are:

**Permanent Land?**

- ◯ Yes: number of land parcels grazed _______________
- ◯ No

**Seasonal Land?**

- ◯ Yes: number of land parcels grazed _______________
- ◯ No

**32.** Does this holding have any CTS Links (done through the British Cattle Movement Service (BCMS), allowing no reporting of movements between CPHs)? If so, what type (please refer to information sheet if needed), and how many (**excluding this CPH**)?

- ◯ No
- ◯ Yes: Shared Facility links _______________
- ◯ Yes: Additional Land links _______________

If **yes**, how many separate land parcels (i.e. groups of fields) do they graze in? _______________

- How many are adjoining / adjacent to the main holding? _______________
- How many adjoin each other? _______________

**33.** Do you rent any land **for grazing** that is not on your IACS form or does not form a CTS Link with this holding?

- ◯ Yes: number of land parcels grazed _______________(# adjoining main holding: _____)
- ◯ No

**34.** How many separately managed herds and flocks does this CPH have?

Cattle herds: ____________________

Sheep flocks: ____________________

**35.** What aspects of their management are separate? Please tick all that apply.

- ◯ Considered separate for management purposes
- ◯ Considered separate for book-keeping purposes
- ◯ No movement of animals between herds/flocks
- ◯ Cleaning/disinfecting facilities between herds/flocks coming into buildings
- ◯ Use of separate buildings/facilities for each herd/flock
- ◯ Cleaning/disinfecting vehicles, footwear and clothing between contacting each herd/flock
- ◯ Different staff and vehicles used for each herd/flock

**36.** How frequently do livestock from this holding move between the following types of grazing land (**please choose ONE**):

**a)** Fields within the same CPH, separated by ≤100m?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally
- ◯ Never (eg. move straight to buildings)

**b)** Fields within the same CPH, separated by >100m?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally
- ◯ Never (eg. move straight to buildings)

**c)** Fields belonging to a different CPH as part of the same IACS business?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally
- ◯ Never (eg. move straight to buildings)

**d)** Fields belonging to a different CPH which forms a CTS Link with this holding?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally
- ◯ Never (eg. move straight to buildings)

**e)** Rented fields belonging to a different CPH which do not form a CTS Link?

- ◯ N/A
- ◯ Daily
- ◯ Several times a week
- ◯ Several times a month
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally
- ◯ Never (eg. move straight to buildings)

**37.** When moving livestock from this holding between separate grazing fields, how are they most often moved between the following (**please choose ONE**):

**a)** Fields within the same CPH separated by ≤100m?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**b)** Fields within the same CPH separated by >100m?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**c)** Fields belonging to a different CPH as part of the same IACS business?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**d)** Fields belonging to a different CPH which forms a CTS Link with this holding?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**e)** Rented fields belonging to a different CPH which do not form a CTS Link?

- ◯ N/A
- ◯ Through your premises' land
- ◯ By vehicle
- ◯ Walking/herding along road
- ◯ By track/bridleway
- ◯ Through another premises' land

**38.** If movements are most often through your premises' land, do livestock have to directly cross any roads?

- ◯ Yes
- ◯ No

**39.** On average through the year, how frequently do livestock from this CPH premises move between their field and the main farm buildings (**please choose ONE for each**)?

**Cattle:**

- ◯ Several times daily
- ◯ Once daily
- ◯ Several times weekly
- ◯ Once weekly
- ◯ Several times a month (< weekly)
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

**Sheep:**

- ◯ Several times daily
- ◯ Once daily
- ◯ Several times weekly
- ◯ Once weekly
- ◯ Several times a month (< weekly)
- ◯ Monthly
- ◯ < Once a month, but more often than seasonally
- ◯ Seasonally

# 12 Appendix 5: To accompany Chapter 5

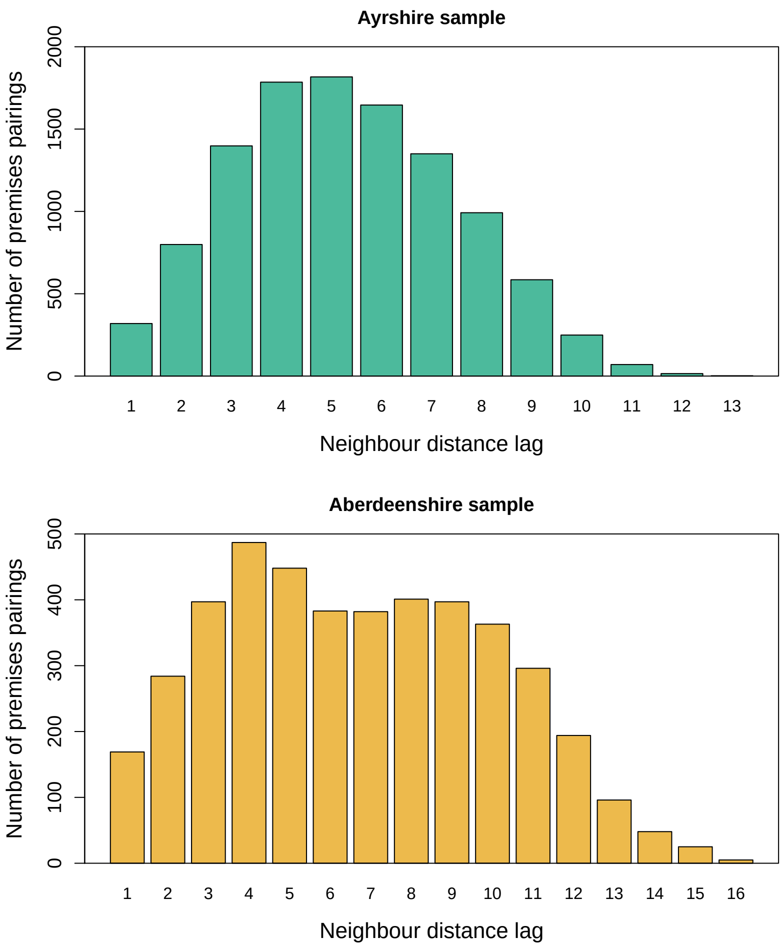


Figure 12.1: The number of premises pairings within each neighbour lag distance, for Ayrshire and Aberdeenshire.

# 13 Appendix 6: To accompany Chapters 5 and 6

## 13.1 Description of questionnaire findings

**Main production types.** A breakdown of the main production types reported can be seen in Table 13.1. In Ayrshire, of the 61 premises who reported beef production as one of their main production types, 14 (23.0%) both bred and finished beef cattle, 23 (37.7%) bred but did not finish beef cattle, and 24 (39.3%) finished but did not breed beef cattle. In Aberdeenshire, one premises' main production type was eggs. Of the 69 premises that reported beef production as one of their main production types, 29 (42.0%) both bred and finished beef cattle, 29 (42.0%) bred but did not finish beef cattle, and 11 (15.9%) finished but did not breed beef cattle.

**Species composition.** In Ayrshire, while 121 surveyed holdings reported keeping cattle in the questionnaire, 15 (12.4%) of those were not recorded as having cattle in the June Census, and one holding was reported to have cattle in the Census but not in the questionnaire. Forty-six holdings reported keeping sheep in the questionnaire, 12 (26.1%) of which were not recorded as having them in the Census; two holdings did not report keeping sheep in the questionnaire but did in the Census. Four holdings reported keeping pigs, none of which were recorded

Table 13.1: Breakdown of production types (N.B. holdings could report >1 production types)

| Production type | Ayrshire | Aberdeenshire |
|---|---|---|
| Dairy | 74 | 0 |
| Dairy breeding | 3 | 0 |
| Beef breeding | 37 | 58 |
| Beef finishing | 38 | 40 |
| Sheep breeding and finishing | 10 | 31 |
| Lamb finishing | 5 | 3 |
| Sheep breeding | 4 | 10 |
| Arable | 7 | 11 |

as being present for the Census.

In Aberdeenshire, 69 surveyed holdings reported keeping cattle in the questionnaire, 5 (7.2%) of which were not reported to have cattle in the Census. Fifty-one holdings reported keeping sheep in the questionnaire, 5 (9.8%) of which were not recorded as having sheep in the Census; one holding did not report keeping sheep in the questionnaire but did in the Census. One holding reported keeping pigs in the questionnaire which was not recorded in the Census, while 4 other holdings did not report keeping pigs in the questionnaire but had done in the Census. Eight and fourteen holdings kept horses in Aberdeenshire and Ayrshire, respectively.

| Sex | Aberdeenshire | Ayrshire |
|---|---|---|
| Female | 6 | 14 |
| Male | 69 | 111 |

| | Aberdeenshire | | Ayrshire | |
|---|---|---|---|---|
| Age (years) | Number | % | Number | % |
| 18-35 | 3 | 4.0 | 9 | 7.2 |
| 36-50 | 27 | 36.0 | 55 | 44.0 |
| 51-65 | 23 | 30.7 | 46 | 36.8 |
| 66+ | 22 | 29.3 | 15 | 12.0 |
| Total | 75 | 100 | 125 | 100 |

| Education level | Aberdeenshire | Ayrshire |
|---|---|---|
| School | 42 | 60 |
| College | 24 | 52 |
| University | 9 | 13 |

| Holding owned or rented | Aberdeenshire | Ayrshire |
|---|---|---|
| Owned | 40 | 114 |
| Rented | 35 | 11 |

| Previously run by family member | Aberdeenshire | Ayrshire |
|---|---|---|
| Yes | 46 | 93 |
| No | 29 | 32 |

| NFUS member | Aberdeenshire | Ayrshire |
|---|---|---|
| Yes | 45 | 80 |
| No | 29 | 45 |
| NK | 1 | 0 |

| Stray stock in/from their fields in preceding 3 weeks | Aberdeenshire | Ayrshire |
|---|---|---|
| Yes | 11 | 31 |
| No | 64 | 94 |

**Composition of farm workers.** In Aberdeenshire, 60 holdings had full-time workers from the household (including themselves), 29 of which also had part-time workers from the household. Fourteen further holdings had only part-time workers from the household, leaving one holding on which no-one from the household worked. Thirteen holdings employed full- and part-time workers, while 7 employed only part-time workers. In Ayrshire, 109 holdings had full-time workers from the household (including themselves), 68 of which also had part-time workers from the household. Sixteen further holdings had only part-time workers from the household. Thirty-four holdings employed full- and part-time workers (25 full-time only, 9 full and part-time), while 24 employed only part-time workers.

| Farm workers | Aberdeenshire | Ayrshire |
|---|---|---|
| From household only | 55 | 67 |
| From household and employed | 19 | 58 |
| Employed only | 1 | 0 |

**Stray livestock.** In Aberdeenshire, 11 (14.7%) holdings reported having had stray livestock in/from their fields in the preceding three weeks (6 involved cattle, 5 involved sheep), while in Ayrshire 31 (24.8%) holdings reported having had strays (26 involved cattle, 2 involved sheep, 3 involved cattle and sheep).

**Events.** In each Aberdeenshire and Ayrshire, 4 and 6 premises, respectively, had either themselves held an event on their land, or their neighbours had held an event adjacent to their land in the 3 weeks preceding the survey, respectively.

**Organic certification.** No surveyed holdings in Ayrshire were organic, but two holdings in Aberdeenshire were. One holding in Ayrshire and two holdings in Aberdeenshire (non-organic) kept a rare breed (all Border-Leicester sheep).

**Frequency of biosecurity review.** Farmers surveyed were asked about the frequency with which they reviewed the biosecurity practices they use on the holding.

In Ayrshire, 5 (4.0%) holdings reported that they would only review them in the event of an outbreak, whereas in Aberdeenshire, 25 (33.3%) reported this. However, in Ayrshire, 12 (9.6%) farmers declined to answer the question, and only one (1.3%) declined to answer in Aberdeenshire. For the remainder in Ayrshire, 11 (8.8%) said they reviewed them less than annually but more often than if there was an outbreak, 91 (72.8%) said practices were reviewed annually/biannually, and 6 (4.8%) said biosecurity reviews were ongoing. For the remainder in Aberdeenshire, 23 (30.7%) said practices were reviewed annually/biannually, and 26 (34.7%) said biosecurity reviews were ongoing.

# 14 Appendix 7: To accompany Chapter 6

## 14.1 Demographic factors in relation to biosecurity risk

| | Beef and sheep/sheep only | | Beef only | |
|---|---|---|---|---|
| | Number | Percentage | Number | Percentage |
| No/open gate at main entrance to farm | 43 | 97.7% | 31 | 100.0% |
| No physical separation between public access areas and livestock areas | 30 | 68.2% | 24 | 77.4% |
| There are gates onto public land which are not locked | 17 | 38.6% | 9 | 29.0% |
| There is no sign prohibiting entry at entrance to farm | 44 | 100.0% | 31 | 100.0% |
| There is no car parking away from livestock areas | 13 | 29.5% | 10 | 32.3% |
| There is no boot dip used at the entrance to the farm (for visitors that come into contact with animals) | 40 | 90.9% | 27 | 87.1% |
| Farm-specific boots are not provided for all staff and family | 27 | 61.4% | 17 | 54.8% |
| Farm-specific clothing are not provided for all staff and family | 20 | 45.5% | 17 | 54.8% |
| There is no clothes-changing area available | 35 | 79.5% | 28 | 90.3% |
| There is a farm shop/other enterprise on the premises | 11 | 25.0% | 3 | 9.7% |
| Dogs are free-roaming on the farm/accompany staff around the farm premises | 38 | 86.4% | 14 | 45.2% |
| 'Unusual events' occurred in the 3 weeks preceding survey | 17 | 38.6% | 12 | 38.7% |
| 'Risky' movements | 18 | 40.9% | 8 | 25.8% |

Table 14.1: Table showing breakdown of biosecurity risks on holdings by production type, Aberdeenshire.

| | Beef and sheep/ sheep only | | Beef only | | Any dairy | |
|---|---|---|---|---|---|---|
| | Number | Percentage | Number | Percentage | Number | Percentage |
| **No/open gate at main entrance to farm** | 13 | 100.0% | 34 | 91.9% | 75 | 100.0% |
| **No physical separation between public access areas and livestock areas** | 7 | 53.8% | 22 | 59.5% | 40 | 53.3% |
| **There are gates onto public land which are not locked** | 0 | 0.0% | 4 | 10.8% | 11 | 14.7% |
| **There is no sign prohibiting entry at entrance to farm** | 12 | 92.3% | 35 | 94.6% | 72 | 96.0% |
| **There is no car parking away from livestock areas** | 2 | 15.4% | 2 | 5.4% | 11 | 14.7% |
| **There is no boot dip used at the entrance to the farm (for visitors that come into contact with animals)** | 13 | 100.0% | 35 | 94.6% | 67 | 89.3% |
| **Farm-specific boots are not provided for all staff and family** | 3 | 23.1% | 17 | 45.9% | 20 | 26.7% |
| **Farm-specific clothing are not provided for all staff and family** | 4 | 30.8% | 15 | 40.5% | 19 | 25.3% |
| **There is no clothes-changing area available** | 9 | 69.2% | 16 | 43.2% | 35 | 46.7% |
| **There is a farm shop/other enterprise on the premises** | 1 | 7.7% | 8 | 21.6% | 10 | 13.3% |
| **Dogs are free-roaming on the farm/accompany staff around the farm premises** | 6 | 46.2% | 25 | 67.6% | 44 | 58.7% |
| **'Unusual events' occurred in the 3 weeks preceding survey** | 8 | 61.5% | 28 | 75.7% | 64 | 85.3% |
| **'Risky' movements** | 0 | 0.0% | 1 | 2.7% | 15 | 20.0% |

Table 14.2: Table showing breakdown of biosecurity risks on holdings by production type, Ayrshire.

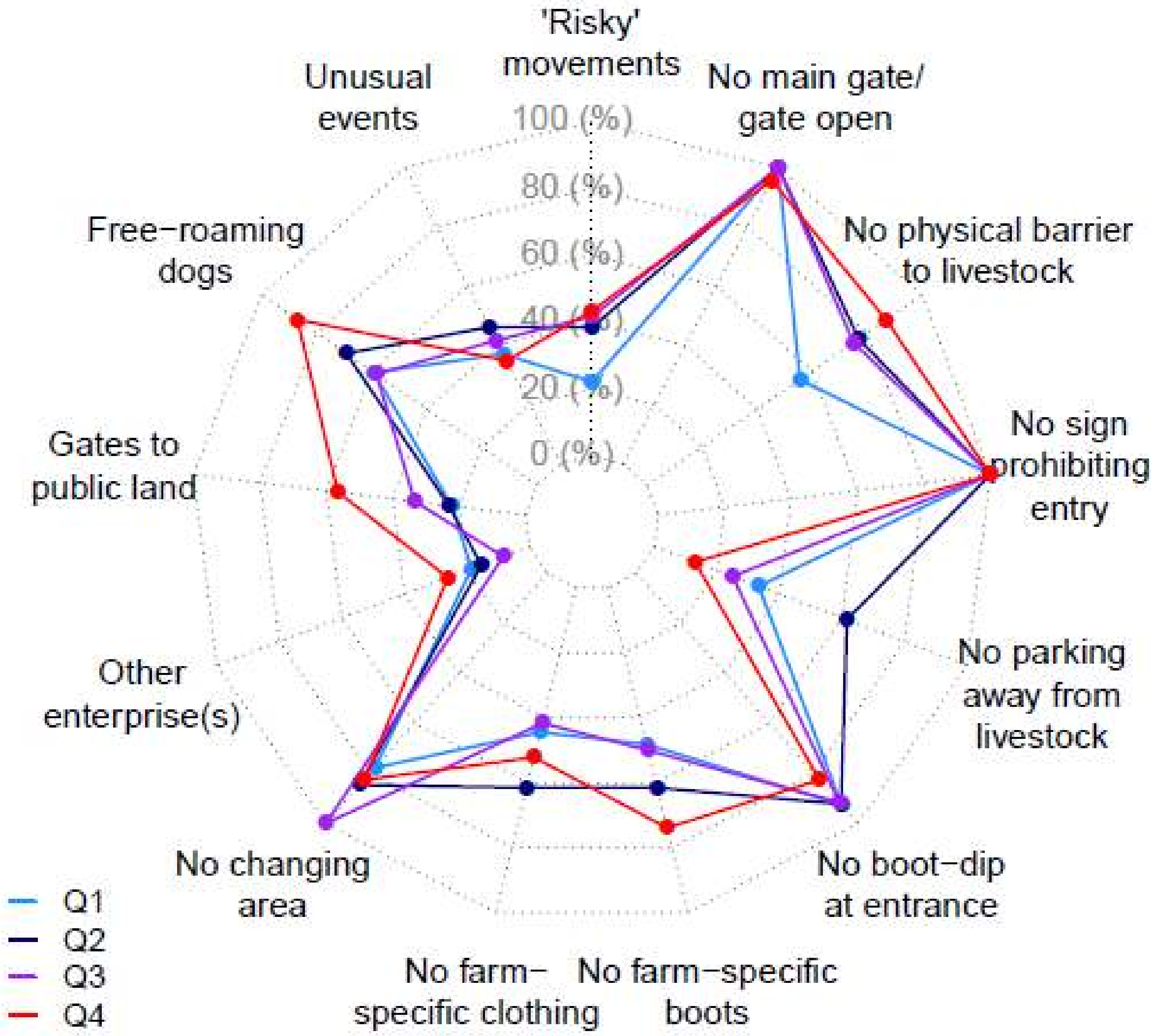


Figure 14.1: Radar chart showing proportion of holdings undertaking each biosecurity risk component in Aberdeenshire, by quantiles of FMD susceptibility (as defined in methods). Quantile 1 (Q1): <31.8, quantile 2 (Q2): <37.8, quantile 3 (Q3): <43.1, quantile 4 (Q4): ≥ 43.1.

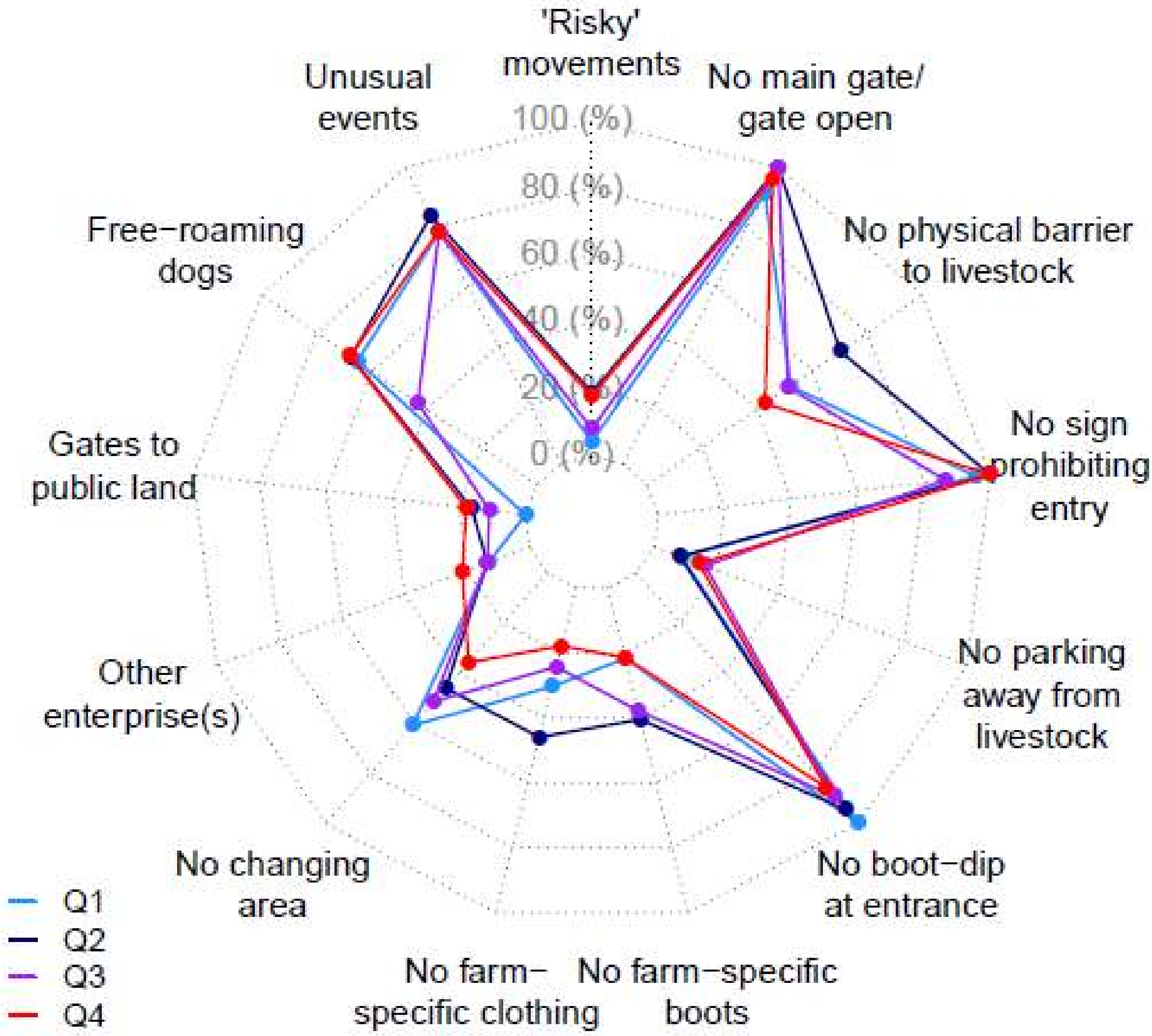


Figure 14.2: Radar chart showing proportion of holdings undertaking each biosecurity risk component in Ayrshire, by quantiles of FMD susceptibility (as defined in methods). Quantile 1 (Q1): <31.8, quantile 2 (Q2): <37.8, quantile 3 (Q3): <43.1, quantile 4 (Q4): $\geq$ 43.1.

| | Smaller holdings | | Larger holdings | |
|---|---|---|---|---|
| | Number | Percentage | Number | Percentage |
| **No/open gate at main entrance to farm** | 34 | 100.0% | 40 | 97.6% |
| **No physical separation between public access areas and livestock areas** | 21 | 61.8% | 33 | 80.5% |
| **There are gates onto public land which are not locked** | 7 | 20.6% | 19 | 46.3% |
| **There is no sign prohibiting entry at entrance to farm** | 34 | 100.0% | 41 | 100.0% |
| **There is no car parking away from livestock areas** | 14 | 41.2% | 9 | 22.0% |
| **There is no boot dip used at the entrance to the farm (for visitors that come into contact with animals)** | 31 | 91.2% | 36 | 87.8% |
| **Farm-specific boots are not provided for all staff and family** | 16 | 47.1% | 28 | 68.3% |
| **Farm-specific clothing are not provided for all staff and family** | 15 | 44.1% | 22 | 53.7% |
| **There is no clothes-changing area available** | 28 | 82.4% | 35 | 85.4% |
| **There is a farm shop/other enterprise on the premises** | 5 | 14.7% | 9 | 22.0% |
| **Dogs are free-roaming on the farm/accompany staff around the farm premises** | 18 | 52.9% | 34 | 82.9% |
| **'Unusual events' occurred in the 3 weeks preceding survey** | 14 | 41.2% | 15 | 36.6% |
| **'Risky' movements** | 7 | 20.6% | 19 | 46.3% |

Table 14.3: Table showing breakdown of biosecurity risks on holdings by holding size, Aberdeenshire.

| | Smaller holdings | | Larger holdings | |
|---|---|---|---|---|
| | Number | Percentage | Number | Percentage |
| **No/open gate at main entrance to farm** | 50 | 96.2% | 72 | 98.6% |
| **No physical separation between public access areas and livestock areas** | 33 | 63.5% | 36 | 49.3% |
| **There are gates onto public land which are not locked** | 6 | 11.5% | 9 | 12.3% |
| **There is no sign prohibiting entry at entrance to farm** | 50 | 96.2% | 69 | 94.5% |
| **There is no car parking away from livestock areas** | 2 | 3.8% | 13 | 17.8% |
| **There is no boot dip used at the entrance to the farm (for visitors that come into contact with animals)** | 50 | 96.2% | 65 | 89.0% |
| **Farm-specific boots are not provided for all staff and family** | 17 | 32.7% | 23 | 31.5% |
| **Farm-specific clothing are not provided for all staff and family** | 20 | 38.5% | 18 | 24.7% |
| **There is no clothes-changing area available** | 27 | 51.9% | 33 | 45.2% |
| **There is a farm shop/other enterprise on the premises** | 7 | 13.5% | 12 | 16.4% |
| **Dogs are free-roaming on the farm/accompany staff around the farm premises** | 37 | 71.2% | 38 | 52.1% |
| **'Unusual events' occurred in the 3 weeks preceding survey** | 43 | 82.7% | 57 | 78.1% |
| **'Risky' movements** | 5 | 9.6% | 11 | 15.1% |

Table 14.4: Table showing breakdown of biosecurity risks on holdings by holding size, Ayrshire.

| | 'Risky' movements | | Less 'risky' movements | |
|---|---|---|---|---|
| | Number | Percentage | Number | Percentage |
| **No/open gate at main entrance to farm** | 26 | 100.0% | 48 | 98.0% |
| **No physical separation between public access areas and livestock areas** | 21 | 80.8% | 33 | 67.3% |
| **There are gates onto public land which are not locked** | 12 | 46.2% | 14 | 28.6% |
| **There is no sign prohibiting entry at entrance to farm** | 26 | 100.0% | 49 | 100.0% |
| **There is no car parking away from livestock areas** | 10 | 38.5% | 13 | 26.5% |
| **There is no boot dip used at the entrance to the farm (for visitors that come into contact with animals)** | 21 | 80.8% | 46 | 93.9% |
| **Farm-specific boots are not provided for all staff and family** | 19 | 73.1% | 25 | 51.0% |
| **Farm-specific clothing are not provided for all staff and family** | 13 | 50.0% | 24 | 49.0% |
| **There is no clothes-changing area available** | 24 | 92.3% | 39 | 79.6% |
| **There is a farm shop/other enterprise on the premises** | 6 | 23.1% | 8 | 16.3% |
| **Dogs are free-roaming on the farm/accompany staff around the farm premises** | 19 | 73.1% | 33 | 67.3% |
| **'Unusual events' occurred in the 3 weeks preceding survey** | 11 | 42.3% | 18 | 36.7% |

Table 14.5: Table showing breakdown of biosecurity risks on holdings by whether or not holdings make 'risky' or less 'risky' movements of livestock, Aberdeenshire.

| | 'Risky' movements | | Less 'risky' movements | |
|---|---|---|---|---|
| | Number | Percentage | Number | Percentage |
| **No/open gate at main entrance to farm** | 16 | 100.0% | 106 | 97.2% |
| **No physical separation between public access areas and livestock areas** | 9 | 56.3% | 60 | 55.0% |
| **There are gates onto public land which are not locked** | 2 | 12.5% | 13 | 11.9% |
| **There is no sign prohibiting entry at entrance to farm** | 16 | 100.0% | 103 | 94.5% |
| **There is no car parking away from livestock areas** | 1 | 6.3% | 14 | 12.8% |
| **There is no boot dip used at the entrance to the farm (for visitors that come into contact with animals)** | 15 | 93.8% | 100 | 91.7% |
| **Farm-specific boots are not provided for all staff and family** | 5 | 31.3% | 35 | 32.1% |
| **Farm-specific clothing are not provided for all staff and family** | 5 | 31.3% | 33 | 30.3% |
| **There is no clothes-changing area available** | 7 | 43.8% | 53 | 48.6% |
| **There is a farm shop/other enterprise on the premises** | 2 | 12.5% | 17 | 15.6% |
| **Dogs are free-roaming on the farm/accompany staff around the farm premises** | 13 | 81.3% | 62 | 56.9% |
| **'Unusual events' occurred in the 3 weeks preceding survey** | 15 | 93.8% | 85 | 78.0% |

Table 14.6: Table showing breakdown of biosecurity risks on holdings by whether or not holdings make 'risky' or less 'risky' movements of livestock, Ayrshire.

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