Potential for Wind-borne Spread of Foot-and-Mouth Disease in Australia

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A study was undertaken to assess the potential for wind-borne spread of FMD to occur under Australian conditions. Weather records and livestock distribution data were used to identify areas at risk. A herd disease model and a Gaussian plume model were used to estimate aerosol virus production and the extent of spread that could be expected from typical livestock enterprises in Australia. The study found that the risk of long distance wind-borne spread occurring from typical sheep, beef and dairy enterprises is low. Cattle feedlots would pose some risk and piggeries would pose a significant threat of spreading FMD to surrounding livestock.

1. COULD WIND-BORNE SPREAD OF FOOT-AND-MOUTH DISEASE OCCUR IN AUSTRALIA?

Foot-and-mouth disease (FMD) is one of the most contagious of animal diseases affecting cloven-hoofed animals. Animals may be infected by ingestion or, especially for ruminants, by inhalation. Movement of infected animals is the most important method of spread of FMD from one property to another. However, on occasions, movement of airborne virus particles by wind has been responsible for infecting properties some distance downwind. Under favourable climatic conditions wind-borne spread can be an important factor in FMD epidemics.

Australia is free of FMD and maintains stringent quarantine controls to protect this status. Contingency plans are in place to eradicate the disease should it be introduced. As part of this preparedness, a study was undertaken to assess the potential for wind-borne spread of FMD to occur under Australian conditions.

Such spread requires that virus becomes airborne, and remains airborne and infectious for long enough to reach another animal in sufficient quantities to cause infection. This paper considers the various steps required to analyse the issue.

2. WHAT WEATHER CONDITIONS ARE CONDUCIVE TO FMD VIRUS PERSISTING IN AN AEROSOL?

A survey of the literature suggested that the two main requirements for the persistence of FMD virus in aerosols are a relative humidity (RH) greater than 60% and temperature (T) less than 27°C. These two conditions form the basis of our analysis. Other conditions, such as strong sunlight, or UV radiation, would appear to have little, if any, effect on virus survival although they can have an effect on the dispersal of airborne particles.

3. HOW COMMON ARE SUCH WEATHER CONDITIONS?

Detailed records from 113 sites were obtained from the Bureau of Meteorology's Three Hourly Surface Data collection of weather observations. The sites were chosen to provide a wide coverage across Australia, and also as much data as possible. The information obtained varied from 2–8 readings per day collected over 10–40 years. All sites took 9 am and 3 pm readings. There were occasional gaps in the data.

Analysis of the data from these 113 sites showed that suitable conditions (RH > 60%, T <27°C) would not be uncommon, with greatest frequency (geographically) along the east and south coast of Australia, and in Tasmania, and (temporally) at night and in winter (see Figure 1). The same conclusions held when we did a sensitivity analysis based on an 8% increase or decrease of temperature and relative humidity conditions.

This detailed information was not in itself sufficient to extrapolate the proportion of days suitable to survival of FMD virus at any particular point in Australia. Obtaining daily data readings for other sites was both expensive and unnecessary given the level of precision needed for this broad summary of risk. Use was made of the Bureau of Meteorology's Climate Data CD-ROM, which provides long-term average monthly RH (9.00 am and 3.00 pm recordings), and average monthly maximum and minimum temperatures for some 721 weather stations across Australia. The detailed information from the 113 sites was used to find an **approximate** relationship between:

- average monthly RH and the number days with a RH less than 60%;
- average monthly temperature and the number of days less than 27°C; and
- temperature and RH.

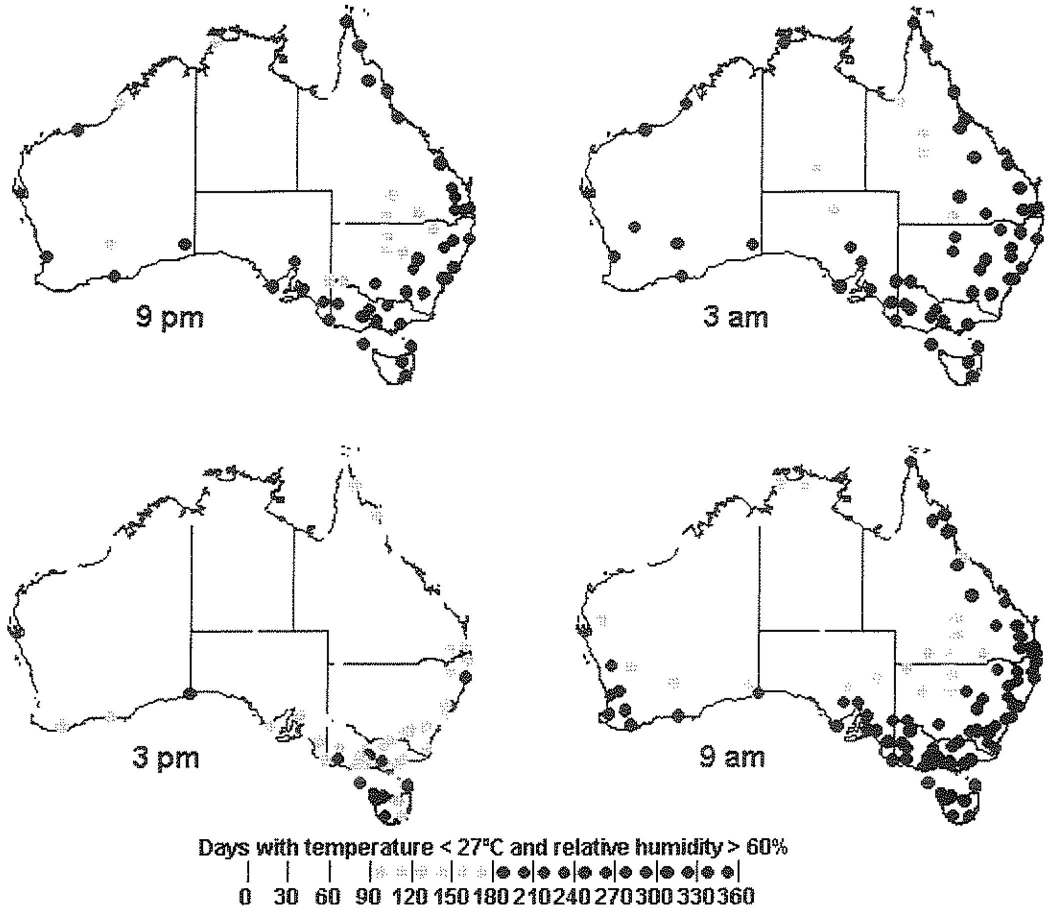

Figure 1: Number of days per year that sites meet the criteria for survival of FMD virus in aerosol

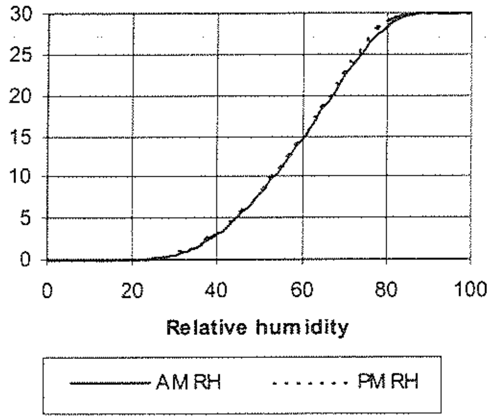

Figure 2: Estimated number of days in the month with RH > 60% based on the monthly average RH reading.

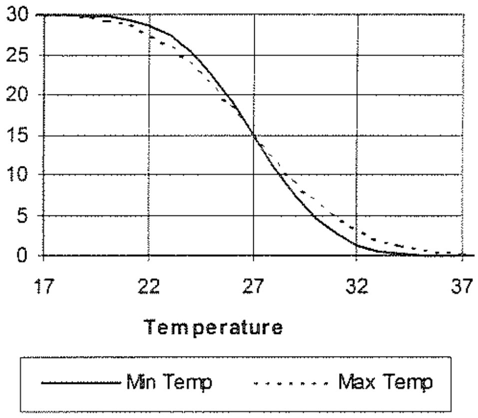

Figure 3: Estimated number of days in the month with temperature less than 27°C based on the monthly average minimum and maximum temperatures.

These relationships are shown in Figures 2 and 3. The minimum temperature and morning RH and were used to estimate the proportion of nights suitable for virus survival, and the maximum temperature and afternoon RH the proportion of days. This provided sufficient points, using a GIS (ArcInfo), to interpolate a surface map based on ¼° grid cells for the frequency of weather conditions suitable for the persistence of FMD virus in aerosols across Australia (Figure 4).

4. DOES LIVESTOCK DISTRIBUTION COINCIDE WITH THESE CONDUCIVE WEATHER CONDITIONS?

Livestock numbers (Australian Bureau of Statistics) were expressed in terms of the cattle equivalent of the various species' potential for virus production and receptiveness to airborne infection (as shown in Table 1). By overlaying the weather information derived in Section 3 and livestock distribution maps, a national overview of the *relative potential* for wind-borne spread of FMD to occur was produced. This could be considered in terms of virus production potential, susceptibility to virus or a combination of both. Such maps (e.g. Figure 5) provide a useful way of comparing the **relative risk** of virus survival but not necessarily the probability that wind-borne spread would occurin different parts of Australia.

Table 1: Virus production capability and susceptibility to airborne infection in infectious units (Donaldson [1988], Garland and Donaldon [1990])

	Cattle	Sheep	Pigs
Virus production (IU/day)	1.8×10^5	1.8×10^5	2.8×10^8
Cattle equivalent	1	1	1585
"Infective" dose (IU)	18	7	11
Air sampling capacity (m^3/day)	144.0	14.4	7.2
Cattle equivalent	1.00	0.25	0.08

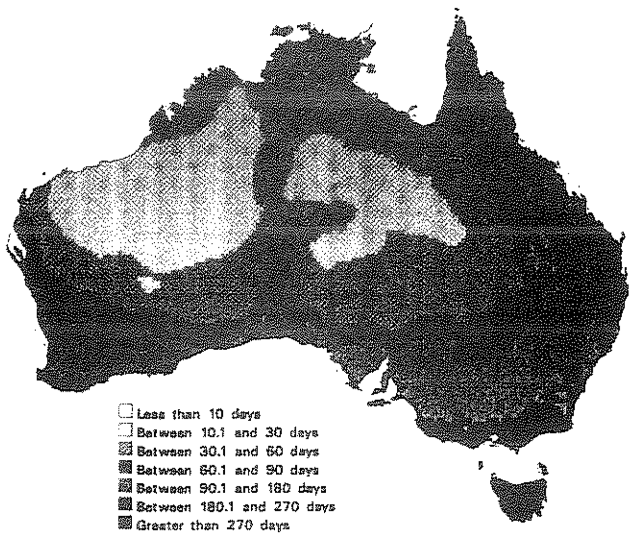

Figure 4: Average number of days per year conducive to the survival of FMD virus in aerosol

5. WHAT VIRUS CONCENTRATION IS ENOUGH TO INFECT AN ANIMAL?

Establishment of infection in a susceptible animal depends on the dose of airborne virus to which it is exposed. The dose is determined by the concentration of virus, the air sampling capacity of the animal, and the period of exposure. Because animals downwind will be inhaling an occasional small dose, most models of FMD spread consider whether the infectious dose is inhaled over a period. Strictly speaking the term infectious dose should always be qualified with some probability level giving the proportion of animals that will succumb. Indeed, a single virus particle is sufficient to infect an animal, albeit with a very small probability.

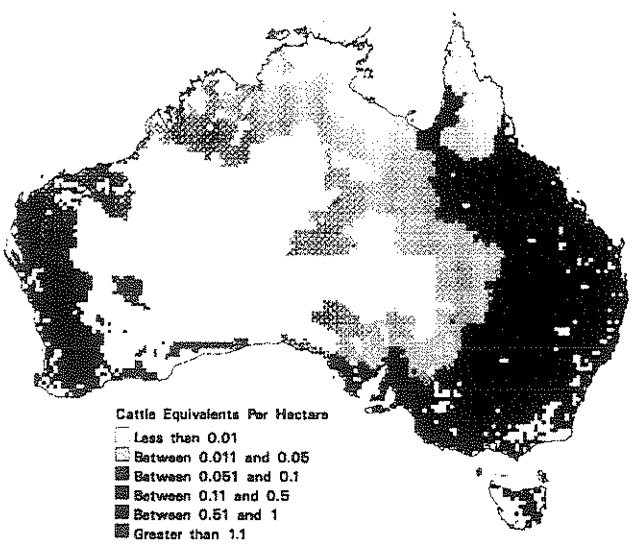

Figure 5: Receptiveness to airborne infection

The probability of infection was based on the binomial distribution, using this probability and the number of particles inhaled by all the animals in a group. We treated each inhaled particle as having the same probability θ of infecting an animal. The probability P that at least one animal in a group will become infected following exposure of the group to a combined dose D is given by:

$$P = 1 - (1 - \theta)^D \qquad (1)$$

The probability of infection following exposure to a low dose is small, but increases with the size of the dose.

There is a limited amount of experimental work on the response of animals to aerosol doses of FMD virus. Effectively we observe a yes/no response to a particular dose — all we know is that at least one particle of the dose caused disease. If we use x_i to repesent the doses that resulted in infection and y_j for those that didn't, the maximum likelihood estimator for θ satisfies:

$$\sum \frac{x_i}{1-(1-\theta)^{x_i}} = \sum x_i + \sum y_j \qquad (2)$$

By re-analysing the work by Gibson and Donaldson [1986] and Donaldson et al. [1987] undertaken to estimate minimum infective doses, we estimated θ = 0.06 for sheep, and θ = 0.03 for calves.

6. WHAT IS THE VIRUS CONCENTRATION DOWNWIND OF THE SOURCE?

A Gaussian plume was used to model the concentration of the virus downwind. The simple Gaussian plume assumes that there is no loss of infective material. Often this does not matter. The severity of the response to a toxic chemical is related directly to the level of exposure and a low exposure level may not be severe, even if it is over a very wide area. However with a plume of virus particles, the response to a virus dose is either 'becomes infected' or 'remains uninfected'. Since the probability of infection depends on the dose, there is a minute probability that a very small dose can cause infection. Because of the highly infectious nature of FMD, it takes only one animal in a herd to become infected for the disease to spread rapidly through the herd by close contact.

With no deposition, the mathematics of the model shows that while the concentration decreases with distance, the area covered by the plume increases in such a way that it is inevitable that an animal further downwind will become infected. This is not realistic.

6.1 The Gaussian plume model

For wind-borne spread of FMD virus, both the height of the source and the height of the recipient above ground level can be treated as zero. With deposition, the concentration in infectious units per cubic metre at ground level C(x,y) at a distance x metres downwind and y metres at right angles to the wind from a source at ground level is:

$$C(x,y) = Q(x) \exp(-\tfrac{1}{2}y^2/\sigma_y^2) / \pi u \sigma_y \sigma_z \qquad (3)$$

The term Q(x) is the effective source strength and is included in the model to account for deposition. (If there were no deposition, Q(x) is simply a constant.) The speed of the wind is u. The remaining two parameters, $\sigma_y(x)$ and $\sigma_z(x)$, are dispersion coefficients and both are functions of the distance downwind.

Table 2: Atmospheric stability categories and parameters used to model the dispersion coefficients

Pasquill category	Atmospheric stability	α	β	γ	δ
A	Very unstable	1.38	0.76	0.32	0.95
B	Mod unstable	1.00	0.76	0.68	0.81
C	Slightly unstable	0.71	0.76	0.96	0.67
D	Neutral	0.50	0.76	1.32	0.53
E	Slightly stable	0.33	0.76	1.98	0.39
F	Moderately stable	0.27	0.76	2.28	0.31

6.2 Dispersion coefficients

Pasquill [1961] defines six categories (A-F) for describing atmospheric stability and these depend on wind speed, amount of daylight, and cloud cover. The dispersion coefficients, $\sigma_y(x)$ and $\sigma_z(x)$, are a function of downwind distance and atmospheric stability. In order to derive a formula for Q(x), a suitable form for $\sigma_y(x)$ and $\sigma_z(x)$ was required. One relationship used by several authors is a simple power relationship:

$$\sigma_y(x) = \alpha\, x^\beta \quad \text{and } \sigma_z(x) = \gamma\, x^\delta \qquad (4)$$

The values of the parameters α, β, γ and δ given in Table 2 were fitted to match the widely used formulas recommended by Briggs [1973].

6.3 Effective source

A common method of adding deposition to the plume model is to use the source depletion model in which the apparent strength of the source is reduced as one goes downwind, to allow for the diminishing amount of virus remaining aloft (Hanna et al. [1982]). The constant source Q in the Gaussian plume equation is replaced by a function Q(x) so that virus concentration reduces with distance downwind. The starting point in deriving Q(x) is to calculate the amount of virus G(x) in contact with the ground at a distance x from the source. This is given by:

$$G(x) = \int C(x,y)\, dy = \sqrt{(2/\pi)}\, Q(x) / u\, \sigma_z \qquad (5)$$

The rate that Q(x) changes is proportional to the amount of virus in contact with the ground

$$dQ(x)/dx = -\, v\, G(x) = -\, v \sqrt{(2/\pi)}\, Q(x) / u\, \sigma_z \qquad (6)$$

The constant v is called the deposition velocity and depends on the size of particles and the roughness of the terrain. For FMD virus it is typically 0.01 metres/sec (Rumney [1986]).

For $\sigma_z = \gamma\, x^\delta$, the strength of the apparent source becomes:

$$Q(x) = Q(0) \exp(-\sqrt{(2/\pi)}\, v\, x / u\, \sigma_z\, (1-\delta)) \qquad (7)$$

7. WHAT ARE THE RISKS ASSOCIATED WITH TYPICAL AUSTRALIAN LIVESTOCK ENTERPRISES?

To assess the risk associated with wind-borne spread under Australian conditions, a set of simulations was done linking a virus production model with the plume model to estimate the total number of virus particles inhaled by animals downwind. The six different enterprise types considered, together with some of the parameters used are give below:

Beef cattle: 500 cow breeding/fattening property in the central Queensland coastal area, density of susceptible animals (in cattle equivalents) in the region 0.2, with the detection of FMD in 14 days.

Beef cattle feedlot: 10,000 head operation in south eastern Queensland, density 0.3, detected in 10 days.

Dairy herd: 130 cow herd in Gippsland, Victoria, density 1.0, detected in 7 days.

Sheep property: 4,000 ewe self-replacing merino ewe flock on the north west slopes of NSW, density 0.5, detected in 21 days.

Pig herd: 100 sow unit producing heavy porkers from WA, density 0.4, detected in 7 days.

Backyard pigs: 5 pigs, Tasmania, density 0.3, not detected

The parameters of the model were chosen to be as realistic as possible. For those for which there was not good information a conservative approach was adopted. The values were chosen to overestimate, rather than underestimate, the concentration of FMD virus downwind.

7.1 Virus production

Virus production was based on a simplified within-herd FMD simulation model for FMD developed by Garner and Lack (1995) to consider vaccination strategies for FMD control. The model, based on a Markov chain, simulated the spread of disease within the outbreak herd. Each animal can be in one of a number of 'states': *susceptible* to the disease, *infected* with the disease, *immune* after recovery from the disease or after vaccination, *dead* (or *destocked*) as a result of the disease. During any time period an animal may remain in that state or move to another depending on various probabilites. The numbers of stock infected was simulated for each day until the disease was recognised, and the herd slaughtered. The amount of virus produced was converted to an hourly amount. The time until the disease was recognised was based on the latent period before the disease causes clinical signs and the typical animal husbandary practices of the type of enterprise.

While there is information on virus production from individual animals, there is little information on how much of this virus will remain airborne outside of the immediate vicinity of the animal and so contribute to the plume. The model assumes that 100% of the virus exhaled becomes airborne and this is certain to be an overestimate.

7.2 The plume

The Bureau of Meteorology's three-hourly weather data was used to determine both the suitability of conditions for survival of airborne FMD virus and the parameters for the Gaussian plume model. The nearest site that had a full range of weather data was used to provide the weather data. The model uses the varying hourly level of virus production from each enterprise, based on the within-herd disease spread model.

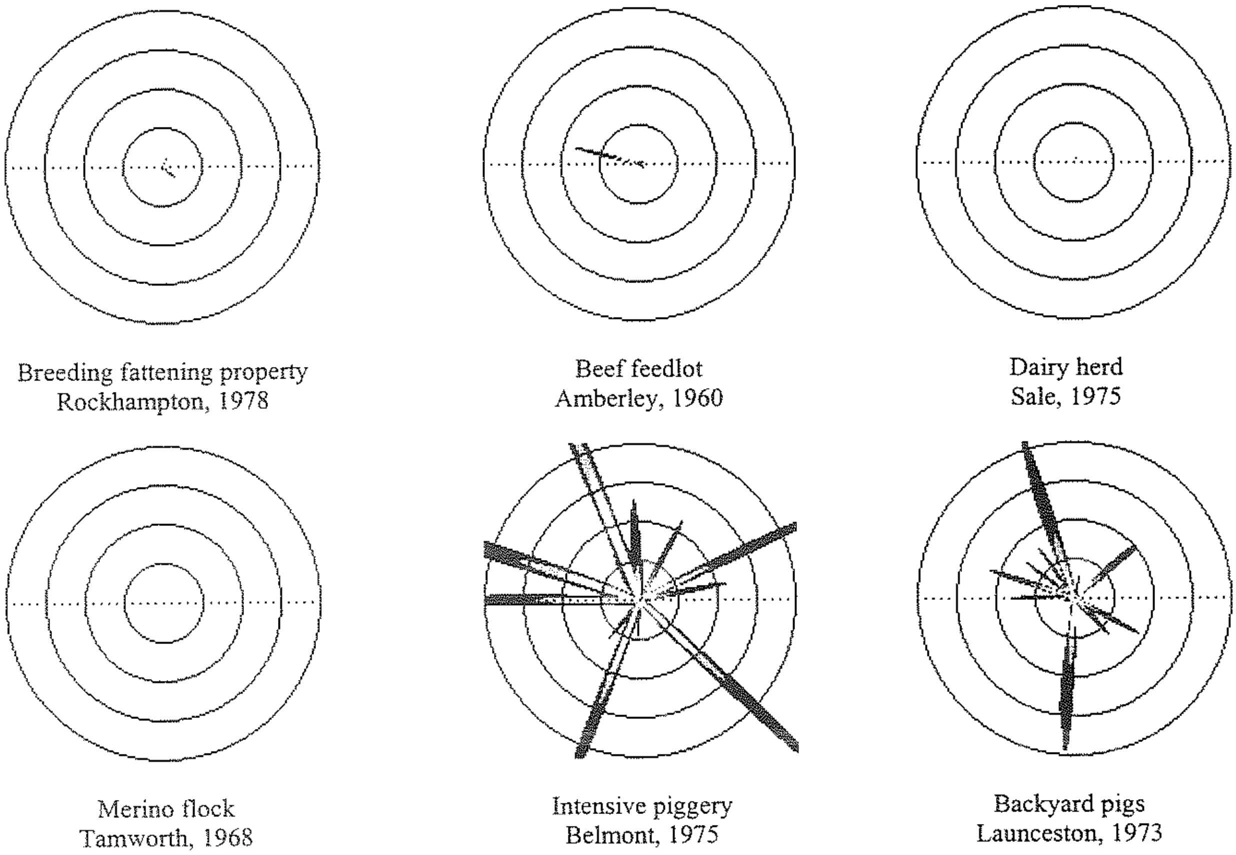

Figure 6: Actual weather data was used with simulated FMD outbreaks starting on New Year's Day for six typical production units. The diagrams show the relative potential for wind-borne spread from an infected property by plotting the number of virus particles (IUs) inhaled per hectare for up to 20 km from the source.

> 0.10 > 0.50
> 0.25 > 1.00

The model assumed a virus deposition velocity of 0.01m/s. Since deposition velocity depends on size of particles and roughness of terrain, in many practical situations the rate of deposition will be much greater than this.

A year's weather data was randomly selected. To allow for different effects associated with outbreaks occurring at different times of the year, outbreaks were simulated to start on the first day of each month over the 12 month period, although only January's result is shown in Figure 6.

7.3 Uptake

The density and species of animals surrounding the outbreak site was assumed to be uniform, and consistent with animals numbers in the area. The animal numbers were converted to cattle equivalents on the basis of the dose-response model outlined in Section 5 and the respiratory capacity of Table 1.

7.4 Output

The model looked at the concentration of virus at each point of a 250 m by 250 m grid within 20 km radius around the source. It tracked the position of the emitted virus particles as they travel downwind until the weather conditions become unfavourable to FMD aerosol virus survival. The amount of virus to which animals in each grid cell would be exposed was accumulated over the period of aerosol virus excretion.

The results were depicted in rosette diagrams (Figure 6) to show graphically the amount, direction and extent of FMD virus exposure of areas surrounding the outbreak. The spikes in the diagrams result partly from the simulations being calculated hourly coupled with the accuracy of the wind direction data (22.5°), and partly because night time conditions are more suitable for spread than daytime conditions.

8. CONCLUSIONS

Detailed results of the study are available (Garner and Cannon, 1995). Briefly the study showed that it is not weather conditions that will be the limiting factor for the occurance of wind-borne spread of FMD for much of Australia. The risk of spread is proportional to the density of livestock downwind of the infected property, with large concentrations of animals such as saleyards and feedlots being particulary vulnerable. Cattle are more likely to be infected than are sheep or pigs. On the other hand pigs provide by far the greatest source of virus particles. Consequently the typical pattern for wind-borne spread is from pigs to cattle.

The simulated outbreaks illustrated this and suggested that the threat of long-distance wind-borne spread is low from typical Australian beef, dairy and sheep enterprises. Cattle feedlots pose some risk especially under favourable weather conditions. Piggeries — even small ones — pose the greatest threat for long-distance (>10 km) spread of FMD.

While modelling can give an indication of the likelihood of wind-borne spread of FMD occuring, it is important to remember that it is the weather conditions at the time of an outbreak and not any long-term average that will determine if wind-borne spread of FMD occurs. It is recommended that a tactical wind-borne spread model by used by disease control supervisors to assess the risks in the event of an outbreak.

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