Evaluating alternative approaches to managing animal disease outbreaks – the role of modelling in policy formulation

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Summary

Modelling is a powerful tool for informing development of policies for the control of animal diseases. By permitting the study of 'what if' scenarios, this tool can be used to help identify and evaluate strategies to reduce the number of animals destroyed to eradicate diseases. To be useful, models need to be fit for purpose and appropriately verified and validated. For informing disease control policy, modelling will be most useful when used before an outbreak, particularly in the areas of retrospective analysis of previous outbreaks, contingency planning, resource planning, risk assessments and training. Recent experience suggests that predictive modelling during actual outbreaks needs to be viewed and used with caution. It is important to recognise that models are just one tool for providing scientific advice and should not be considered in isolation from experimental studies and collection and analysis of epidemiological data. Collaborative studies and international cooperation can help address validation issues and improve the utility of models for emergency disease management. One such initiative, involving the 'Quadrilateral countries' (Australia, Canada, New Zealand and the United States), Ireland and the United Kingdom is discussed.

Keywords

Alternatives, Animal disposal, Control policy, Livestock disease, Model, Simulation, Stamping out.

Valutazione di metodi alternativi per affrontare epidemie animali – il ruolo della modellazione nella politica di gestione

Riassunto

La modellazione è un potente mezzo per comunicare lo sviluppo delle politiche per il controllo delle malattie animali. Utilizzando lo studio delle possibili situazioni, questo strumento può essere usato per aiutare ad identificare e valutare strategie per ridurre il numero di animali abbattuti per eradicare le malattie. Per essere utili i modelli hanno bisogno di essere adattati allo scopo e adeguatamente verificati e validati. Nel comunicare le strategie di controllo delle malattie, la

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modellazione sarà maggiormente utile quando usata prima di una epidemia, in particolare nelle aree dove sono state effettuate analisi retrospettive su precedenti epidemie, piani di contingenza, pianificazione delle risorse, valutazione del rischio e formazione. Recenti esperienze suggeriscono che modelli predittivi durante reali epidemie hanno bisogno di essere visionati e usati con cautela. È importante riconoscere che i modelli sono solo un mezzo per fornire consigli scientifici e non devono essere considerati isolatamente da studi sperimentali, raccolta e analisi di dati epidemio-logici. Studi di collaborazione e cooperazione internazionale possono aiutare a indirizzare i problemi di validazione e migliorare l'utilità dei modelli per la gestione delle malattie emergenti. Nel presente lavoro viene discussa una tale iniziativa che coinvolge le 'Quadrilateral countries' (Australia, Canada, Nuova Zelanda e Stati Uniti), Irlanda e Regno Unito.

Parole chiave
Abbattimento, Alternative, Malattia del bestiame, Modello, Politica di controllo, Simulazione, Smaltimento degli animali.

Introduction

Eradication of outbreaks of serious livestock diseases, such as foot and mouth disease (FMD), classical swine fever (CSF) (hog cholera) and highly pathogenic avian influenza (HPAI) is frequently based on movement restrictions and 'stamping out'. Stamping out involves the culling of animals that are infected and those suspected of being infected with a disease in a herd or flock and, where appropriate, those in other herds or flocks which have been exposed to infection either directly or indirectly (57). Carcasses are destroyed to prevent the spread of infection through products, and premises are subjected to cleansing and disinfection.

In a number of recent disease outbreaks, application of this policy has resulted in the destruction of large numbers of animals, both through direct culling of infected animals and those suspected of being exposed, and the destruction of animals for indirect reasons, such as those associated with animal welfare problems resulting from disease control measures, or with the desire to regain markets. For example, in the CSF outbreak in the Netherlands in 1997 approximately 10 million pigs were destroyed, with 7.3 million of these culled for animal welfare reasons (43). In Taiwan in 1997, more than 4 million pigs were culled as part of a programme to control an outbreak of FMD (58). In the FMD outbreak that occurred in the United Kingdom (UK) in 2001, some 4 million animals on 10 157 premises were culled and a further 2.5 million animals were slaughtered for welfare reasons (29) with some estimates placing the total number of animals culled as high as 10 million. In the Netherlands in 2001, approximately 260 000 animals were killed to eradicate FMD, 186 645 of these being vaccinated animals that were subsequently culled for trade reasons (5, 44). In Italy, over 16 million birds died or were culled on infected farms, or were pre-emptively slaughtered on premises considered at risk, to control an outbreak of HPAI in 1999 and 2000, resulting in serious market disruption, economic hardship and distress in the community (7, 8, 34).

Large-scale culling and disposal of animals for disease control purposes is increasingly being questioned on political, economic, ethical, environmental and welfare grounds (29, 31, 37, 38, 44, 50). There is a need for disease managers and policy makers to examine and evaluate alternative approaches to disease control that address these concerns. The political repercussions of the outbreaks of FMD in the UK and the Netherlands in 2001 led to a meeting in Brussels sponsored by the UK and Dutch governments and the European Union (3). Both countries made it clear that the extensive slaughter that had been used to control FMD was no longer acceptable and alternate policies were required. The meeting called for greater flexibility in the control options available to member states to manage future FMD outbreaks, including emergency vaccination as a tool to reduce the numbers of animals destroyed.

However, evaluating alternative approaches to control infectious diseases is not a simple task as there are a range of issues that need to be considered. These considerations include resource requirements, trade and economic implications, access to appropriate technology (e.g. vaccines or diagnostic tools), consumer concerns and public health ramifications. Of particular concern for countries exporting livestock and livestock products is the attitude of trading partners, since the major economic impact of diseases like FMD may be due to loss of export markets rather than the productivity losses associated with the disease *per se* (17, 55). In the case of zoonotic diseases, there may be occupational health and safety issues that need to be considered. Finally, the choice of control measures is often a compromise between the requirement for large-scale implementation and what is logistically and economically feasible (53). Clearly, developing policy options under such circumstances is challenging. In considering control strategies, it is important that the interests of all stakeholders and all costs should be taken into account (6). Modelling is a useful tool that can assist with these types of evaluations. In a policy context it is common to link epidemiological and economic models. Indeed, a range of such studies to evaluate control strategies for emergency diseases like CSF and FMD have been published (1, 4, 10, 16, 33, 36, 41, 47, 49).

This paper:

- considers how disease modelling can be used to assist in the development and evaluation of different approaches to disease control
- briefly reviews the use of modelling in FMD control in the UK 2001
- discusses an international initiative to strengthen linkages between modelling and policy development.

Overview of disease models

Models are simplifications of more complex systems. Disease models can vary from simple deterministic mathematical models through to complex spatially explicit stochastic simulations. The approach used may vary depending on how well the epidemiology of a disease is understood, the amount and quality of data available and the background of the modellers themselves. The most appropriate type of model to use in a given situation will depend on the sorts of issues being studied. For example, while deterministic models, which are typically based on average or expected value parameters, may be useful for understanding basic infection dynamics, they are of limited use as a predictive tool since any one epidemic is unique and unlikely to follow an 'average' pattern (19).

Models may be spatial or non-spatial. Non-spatial models assume that all members of the population are at equal risk of infection while spatial models incorporate spatial attributes such as farm locations into disease transmission computations. Spatial models can also provide high quality outputs that are useful for training and disease control exercises (Fig. 1). The increasing sophistication of computers, together with greater recognition of the importance of spatial elements in the spread of disease, and interest in specific spatially targeted strategies like emergency ring vaccination or contiguous slaughter, mean that models which incorporate spatial components are becoming more important in epidemiological studies (4, 18, 25, 26, 30, 39, 49, 51).

Models also vary in how much detail they incorporate. The level of complexity to include in a model is an art as well as a science (19). Adding additional elements may increase complexity without necessarily improving the quality of outputs. On the other hand, ignoring factors that are clearly important in the epidemiology of a disease may result in model findings that are misleading. Availability of data may also be an issue. As Kitching *et al.* (28) have observed, identifying additional factors is not a difficulty, but quantifying their respective effects may be problematic. For a more detailed description of the characteristics of contemporary models used to study disease transmission and control, the reader is referred to the following recent publications (24, 30, 52).

A model needs to be validated and verified to ensure that it behaves like the system it is designed to represent (52). Model validation is defined as a process of assessing the accuracy of model output and ensuring its usefulness

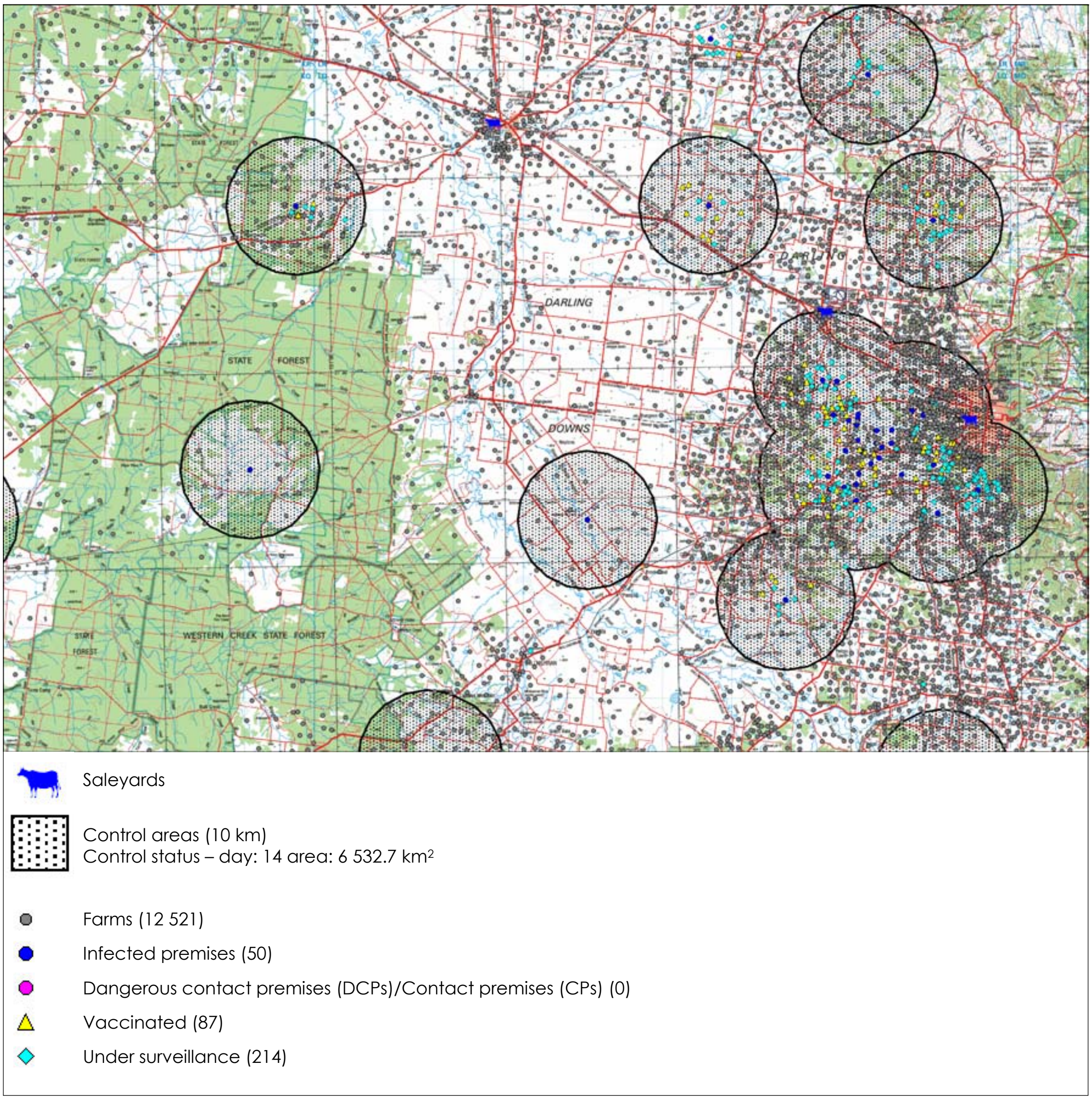

Figure 1
Spatial disease outbreak simulation
This example is from the Australian foot and mouth disease simulation model *AusSpread* (18)

and relevance (48). This implies that the assumptions underlying the model are correct and that the representation of the study system of the model is reasonable for the intended purpose. A more comprehensive view of validity considers 'data validity', or the correctness of the data used to construct and parameterise the model; 'conceptual validity', or the correctness of the mathematical and epidemiological logic upon which the model is built; and 'operational validity', or the ability of the model, as implemented, to produce results of sufficient accuracy (48). Verification is a separate process to establish that the logic upon which the model is based has been correctly written down as code.

Using models to assist disease control policy development

Control of infectious diseases in animals relies on three basic principles, as follows:

- preventing contact between susceptible animals and the infectious agent
- stopping production of the infectious agent by infected animals
- increasing the resistance of susceptible animals.

These principles can be applied through a range of measures, such as quarantine and movement controls to stop the spread of infection; rapid tracing and surveillance to identify sources of infection; removal of infected and exposed animals to eliminate sources of infection (stamping out); disposal and decontamination of contaminated premises, vehicles, equipment and products; and building immunity in susceptible animals by vaccination. It is the detail of what, how, when and where these measures are applied that will determine the effectiveness and efficiency of a control programme.

When compared to a traditional stamping-out approach, the nature of strategies that might be considered to reduce the numbers of animals culled in an outbreak could include the following:

- modified stamping out: only culling animals in a herd showing clinical signs, used with or without vaccination (45)
- vaccination: emergency vaccination has been recognised as a method for addressing logistic problems associated with stamping out in high-density livestock areas (11, 54)
- test and cull: development of rapid tests and point of care ('pen-side') tests offer the opportunity of confirming presence of infection in a herd (15)
- targeted pre-emptive culls: selective culling of potentially exposed herds based on veterinary risk assessment and judgement (22)
- modified movement restrictions: selective movements under controlled conditions (e.g. direct to abattoirs) may be useful to reduce welfare issues.

The value of models lies in their ability to test 'what if' questions. They allow large amounts of information to be combined in a structured way. Models can be used to explore the effects of various combinations of measures and to assess the effects of these measures when applied in different ways, e.g. how does a pre-emptive culling strategy compare with a test and cull strategy? How effective is a 3-km ring vaccination strategy in restricting the spread of disease?

Keeling (24) describes three main roles for modelling to assist policy development. First, models can be used to predict the future, based on the current situation and known behaviour. Second, models can be used for extrapolation using the known dynamics with one set of parameters to construct the probable dynamics for another. Third, models can be used experimentally to test outbreak scenarios and control strategies under simulated conditions, avoiding the risks of testing during a real epidemic. Here, we will give several examples of how disease modelling has been used to inform development of disease control policy.

In the Netherlands, a stochastic simulation model (*InterCSF*) was used to recreate the 1997-1998 CSF outbreak. This was linked with an economic model and used to evaluate various culling and vaccination strategies (35, 41). The major finding from these studies was that a pre-emptive culling policy was an effective strategy to reduce the size of an epidemic if applied early in the control programme. Economically, the policy was not as expensive as expected because of the smaller epidemic size and reduced welfare slaughter. Emergency vaccination appeared to be an effective alternative approach for reducing the size of an epidemic, although under European Union regulations, reduction in costs associated with reduced welfare slaughter would be offset by the need to cull vaccinated animals. Acceptance of trade in meat from vaccinated animals (assuming a reliable diagnostic test for the causative pathogen was available) was found to be significantly cheaper than other strategies, as well as, from an ethical perspective, reducing the need to destroy healthy pigs.

In Australia, several studies (16, 46) have shown that while in some circumstances emergency vaccination used with stamping out can reduce the size of FMD outbreaks and the number of animals culled to achieve eradication, under international trade guidelines, the effect of market closures associated with vaccination means that the approach is uneconomic when compared with stamping out alone. However, recognising the importance of resource issues, Abdalla *et al.* (1) used epidemiological and economic modelling to explore situations under which vaccination may become cost effective. Their study, in an intensive livestock-producing region of Australia that was expected to favour spread of FMD, compared three control strategies involving stamping out with or without emergency vaccination. The comparisons took into account resource constraints, different levels of severity of the outbreak and delays before first detection. The modelling showed that with stamping out, two outcomes were possible, namely: an outbreak would be controlled relatively quickly (resources were adequate) or a large prolonged outbreak would occur (resources were inadequate to contain the disease) (Fig. 2). Not surprisingly, the study found that vaccination may be a cost-effective option where the disease spreads rapidly because available resources are insufficient to maintain effective stamping out. Under these conditions, it was likely that the disease could spread widely, leading to extended periods of market closure. The study also reinforced the importance of early detection as a key factor influencing the probability of containment.

Yoon *et al.* (59) used *InterSpread Plus*, a stochastic spatial simulation model of between-farm spread of disease, to evaluate the effect of alternative strategies for controlling the 2002 epidemic of FMD in the Republic of Korea. The starting point for these analyses was the simulation of a reference strategy which predicted a similar number of infected and depopulated premises as that which occurred during the actual epidemic. The results of simulations of alternative epidemic control strategies were compared with this reference scenario. Ring vaccination (when used with either limited or extended pre-emptive culling) reduced both the size and variability of the predicted number of infected farms (Fig. 3). Reducing the time between disease incursion and commencement of controls had the greatest effect on reducing the predicted number of infected farms.

Modelling is being used in the United States to assist with emergency disease preparedness. In October 2006, the North American Animal Disease Spread Model (*NAADSM*) (21, 40) was used to simulate an outbreak of HPAI in the

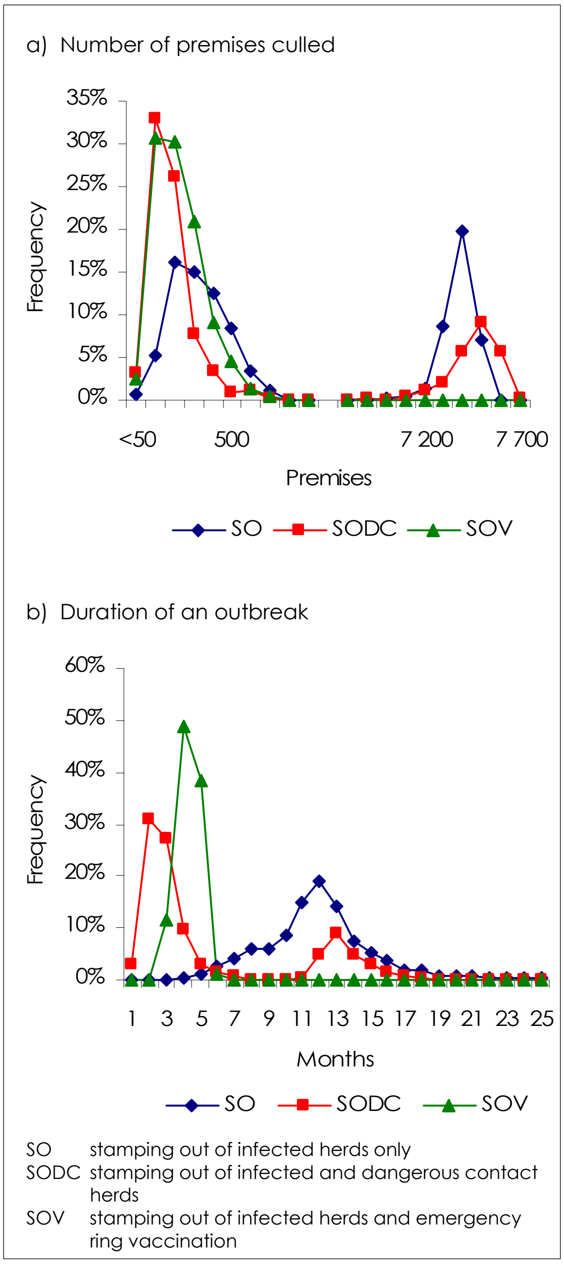

Figure 2
Comparing control strategies for foot and mouth disease
Results based on 1 000 iterations of a stochastic simulation model (1)

State of Georgia. The outbreak simulation was used during a tabletop exercise organised by the United States Department of Agriculture's National Veterinary Stockpile (NVS) staff and the Georgia Department of Agriculture. The simulated scenario was used as an example of the potential scope and impact of a HPAI outbreak for planning purposes, rather than as a prediction of the direction or magnitude of disease spread. The purpose of the exercise

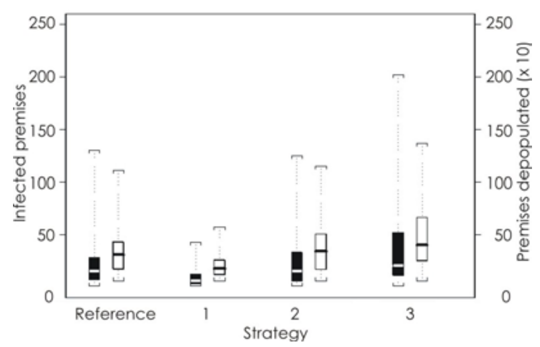

Figure 3
Simulation studies of foot and mouth disease in the Republic of Korea, 2002, using *InterSpread Plus* (58)
Scenarios where controls commenced, relative to the actual epidemic:
1 five days earlier
2 two days later
3 five days later
The distributions shown are based on 99 simulations of each scenario

was to identify resources that would be needed during a HPAI outbreak, to test some aspects of the Georgia response plan for HPAI with Federal and State agencies and poultry industry representatives, and to test the capacity of their current response teams and resource management methods. Response groups were formed to address the operational activities that have to be performed during an outbreak response, including identifying human resource needs for activities, such as surveillance, appraisal, depopulation, disposal, and cleaning and disinfection. The exercise assisted participants to better understand their responsibilities and identify any gaps in the Federal and State response plans.

As these examples show, disease models have been useful in supporting policy development, although up until recently, they have rarely attracted much attention and have had relatively little impact beyond the scientific realm (42). This is probably because their use has been largely confined to studies of hypothetical outbreaks, or they have been used retrospectively in analyses of past outbreaks. In the UK FMD epidemic in 2001, models were developed and, for the first time, used to direct and justify control policy during an actual outbreak (2, 19, 52, 56). The experience has produced differing views as to the value of modelling, with some authors commenting on the important role that it played (23, 56) while others have condemned it (27).

It is useful to briefly review this experience because the large-scale culling of apparently healthy livestock, used to ostensibly bring FMD under control, caused widespread community concern. The financial and social costs led to changes in national and international legislation and guidelines for controlling future epidemics (29). The experience also generated varying opinions about the validity and usefulness of the models and their predictions (19, 20, 23, 52).

Lessons from the 2001 foot and mouth disease epidemic in the United Kingdom

Early in the outbreak, findings from predictive mathematical modelling (13, 14), were used as evidence to support conclusions that the epidemic was out of control and that current measures were insufficient to establish control. It was recommended that a rapid cull of suspected infected premises and all farms contiguous to infected premises was essential to control the disease (13, 56). An aggressive control policy based on culling susceptible animals on infected premises (within 24 h) and pre-emptive culling of dangerous contact premises and premises adjacent to infected premises ('contiguous cull' policy) within 48 h was introduced (23). This policy was credited with bringing the outbreak under control (2, 56). However, subsequent analyses have labelled contiguous premise culling as 'a blunt policy instrument' (2) and questioned whether the extensive culling programme and particularly culling of contiguous premises, was necessary (28, 53).

It has been suggested that the models at the time were not validated, particularly for the type O pan-Asia strain of the virus, and contained simplifications and assumptions which biased the outcomes and heavily influenced conclusions about the effectiveness of different control strategies (27, 29, 52). For example, a recent study showed that premises close to an infected premises do not inevitably become infected – a significant proportion remain uninfected even under intense infection pressure (53). Further, Honhold *et al.* (22) found that field veterinary judgement by means of qualitative risk assessment was a highly effective method of identifying groups of stock at risk of infection. These retrospective findings suggest that selective culling of dangerous contacts would have been a viable alternative to the mass culling policy.

Unfortunately, one of the legacies of the UK experience has been a questioning of the role of modelling and loss of confidence in scientific advice based on modelling (9).

International collaboration – Quads initiative

In light of the UK experience and due to the fact that many countries are using simulation modelling for disease policy development, the Quadrilateral (Quads) group of countries (Australia, Canada, New Zealand and the United States) organised a FMD modelling and policy workshop in 2005 to learn from the UK experience and strengthen relationships among policy makers and modellers, both nationally and internationally. The main outcome was the creation of the Quads EpiTeam, a small technical group, including epidemiologists from the Quads countries, Ireland and the UK. The team's work programme includes a project to jointly verify and validate models for use in FMD policy development in their respective countries.

Validation of models for use in emergency disease situations is a particularly difficult issue for countries with limited or no recent experience with the disease of concern. By definition, incursions tend to be rare and it cannot be assumed that experience from one outbreak can be used to infer the behaviour of another, particularly when this may be based on limited and incomplete data from another country. One approach that can be used to increase the confidence in models by disease managers is to compare outputs of different models using standardised scenarios.

A formal comparison of three spatial simulation models used for FMD policy development was made, as follows: Australia – *AusSpread* (18), New Zealand – *InterSpread Plus* (51), Canada and United States – *NAADSM* (40). All models are stochastic spatial simulation models that have been developed independently. The study (12) included a comparison of the approaches used, based on written model descriptions and a comparison of a series of model outputs from eleven scenarios of increasing complexity that evaluated various spread mechanisms and control measures (Table I). Despite different approaches to model building, and some statistically significant differences in outputs from the three models, the differences were generally small and, from a practical perspective, the outputs were quite similar. Figures 4 and 5 provide examples of the scenario comparisons. From a policy perspective, it was reassuring that despite the different approaches used, the models produced consistent outcomes and it was concluded that any decisions based on the findings of each model would not have differed. In addition, the study was a useful verification exercise as it required the modellers to re-examine in-depth the way core functions had been implemented, and minor programming and logic errors were found and corrected.

Table I
Scenarios used to compare models in Quads modelling study

Scenario	Description
1	Direct contact spread
2	Airborne spread
3	Direct contact and airborne spread
4	Direct contact and indirect contact unrealistic parameters
5	Direct contact and indirect contact realistic parameters short duration
6	Direct contact and indirect contact realistic parameters long duration
7	Detection and movement controls
8	Vaccination: small rings
9	Vaccination: large rings
10	Contiguous slaughter: small rings
11	Contiguous slaughter: large rings

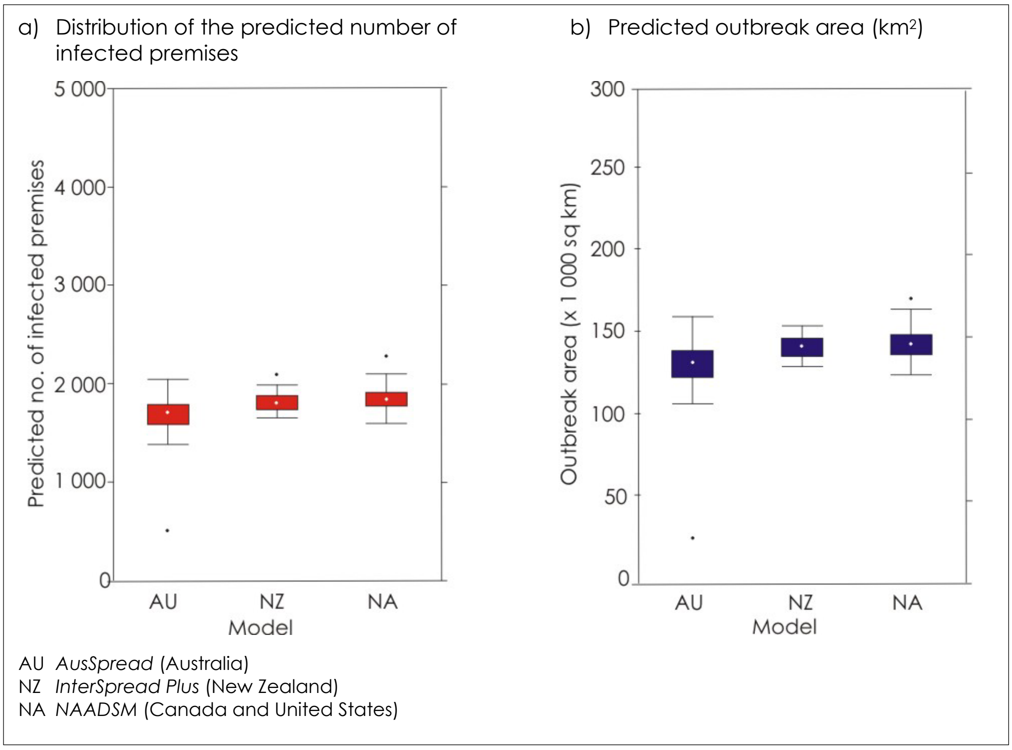

Figure 4
Quads model comparison project – results for scenario 10
Based on 40 iterations

Discussion

There is increasing concern over the large-scale culling of animals for disease control. This culling may be associated with direct efforts to control the disease, or be an indirect consequence of control measures that lead to marketing and welfare problems. Indeed in some cases, culling of animals for indirect reasons during an outbreak may exceed that which is necessary to control the disease itself, as was the case with CSF in the Netherlands in 1997 (43). In some cases, culling of otherwise healthy vaccinated animals may be required at the end of the outbreak to regain markets. It is important to differentiate between culling to control the disease and culling to address other issues. In the former case, alternative control measures might be considered to reduce the number of animals culled. In the latter case, viable strategies might be based on developing enhanced diagnostic tools or on efforts to change international trade guidelines rather than on necessarily using a different control policy. One such example would be adoption of serological tests or use of marker vaccines that would differentiate between infected and vaccinated animals obviating the need to slaughter all vaccinated animals in order to regain market access (32).

Epidemiological and economic modelling are recognised as valuable tools that can assist disease managers in identifying and evaluating alternative approaches to disease control. They are particularly useful for gaining insight into the conditions under which controversial control measures, such as emergency vaccination, might become an economically viable option (6). Suitably designed models can simulate outcomes under different assumptions concerning types of strategy, availability of resources, reactions of trading partners, etc. and thus help identify conditions under which different approaches might or might not be beneficial. These findings do need to be kept under review as new technologies (such as new diagnostic methods or vaccines) and changes to international guidelines and trading protocols might alter the balance.

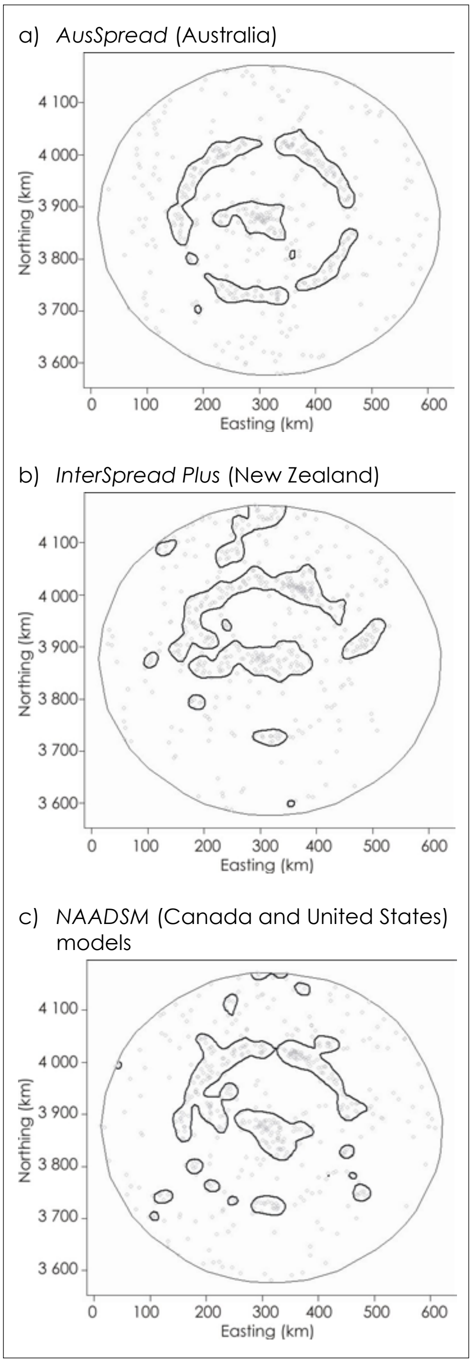

Figure 5
Quads model comparison project
Point maps showing the location of premises predicted to become infected for one iteration of scenario 5, predicted by the three different models
Superimposed on each plot are contour lines delineating areas where the density of farms predicted to become infected was greater than 0.004 per square kilometre

However, it is important that models used to inform disease control policies are implemented appropriately (20). While there is general recognition of the value of modelling to support policy development through retrospective analyses and contingency planning, the role of predictive modelling as a tool to support tactical decision-making in an actual outbreak is less clear. Any model ultimately depends for its validity on the accuracy and completeness of the data underpinning it (19, 23). Unfortunately the data are not always available or reliable, particularly early in an outbreak when decisions taken typically will determine the size of the subsequent epidemic (39). This data issue creates a serious problem for prediction using models. The models used in the 2001 UK epidemic have been criticised because they were constructed with out-of-date and poor quality data, and poor epidemiological knowledge (29). Recent analyses have cast doubts on the appropriateness of policy made at the time that was based on these models (22, 29, 53). In his comprehensive review, Taylor (52) concluded that use of predictive models to support tactical decision-making is not recommended. Decisions should be based more on veterinary intelligence rather than on predictive modelling, although modelling can play a role in the interpretation of veterinary intelligence. Another view is that modelling can be valuable in making rapid and informed decisions about control strategies in an outbreak, provided that the model has been developed, tested and is ready for immediate application (39).

Modelling is a specialised field, and modellers are often seen by management and field staff as remote from the real world and their outputs may be viewed with suspicion. It is important that modellers do not work in isolation and that they understand that models are just one tool for providing scientific advice. Any findings should not be considered in isolation from those of experimental studies, and from the collection and analysis of epidemiological data. Proof of validity of any model should be required before it is used to influence policy (19). Communication of results to decision-makers is also an important issue. Findings reported from modelling studies should be accompanied by full disclosure of the assumptions used and any limitations of the approach (20, 24, 42, 52).

Notwithstanding these concerns, modelling can contribute to better disease control through:

- retrospective analysis of past outbreaks and evaluation of alternative approaches
- exploration of different strategies in hypothetical outbreaks (contingency planning)
- assessment of resource needs of different strategies and optimal use of resources in hypothetical outbreaks (resource planning)
- risk assessments to identify areas, subpopulations, or production systems that might be at greater risk to better target preparedness and surveillance activities
- evaluating effectiveness of various surveillance and control strategies
- underpinning economic impact studies
- providing realistic scenarios for preparedness/training exercises
- providing tactical support during epidemics through analysis and hypothesis testing.

Recent initiatives, like the formation of the Quads EpiTeam, have demonstrated the value of international cooperation in developing and validating modelling tools for use in animal health emergencies.

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