

Foot-and-Mouth Disease control costs compared: An Irish case study.

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The primary objective of this paper is to evaluate alternative control strategies for a number of simulated outbreaks of Foot-and-Mouth Disease (FMD) in four agriculturally diverse Irish regions, examining for the first time, the potential role of emergency vaccination in the country. The recent EU Directive (2003/85/EC) on FMD control permits the use of emergency vaccination as part of an FMD control strategy. While the slaughter of infected animals and “dangerous contacts” (susceptible animals on epidemiologically linked holdings) remains the principal tool for tackling an outbreak, the potential use of vaccination as an adjunct to the basic culling policy is now being considered. Using an integrated approach, combining epidemiological and economic modules, the alternatives of stamping-out both alone and in conjunction with emergency vaccination are examined using hypothetical outbreaks and their control costs compared. Overall, it cannot be said, a priori, that one control option is better than the other. Choice of control strategy would appear to be highly dependent on herd density, production type and other region specific issues. This analysis has focused on control costs only; taking wider economy costs into account may however change this overall conclusion.

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JEL subject codes: Q1; Q17; Q58.

“Epidemiology and economics are separate scientific areas but are very much complementary when the goal is the efficient management of animal health.” (FAO - Food & Agricultural Organisation of the UN)

1. Introduction

FMD is one of the list A diseases (most infectious and economically damaging) of the OIE (Office International des Epizooties - World Organisation for Animal Health). Following the 2001 Irish outbreak, after a lapse of sixty years, the vulnerability of the farm and non-farm economy to the threat of exotic livestock diseases was exposed. There has been some study of the economic consequences of the outbreak;¹ however little emphasis has been placed on an evaluation of control and eradication strategies. FMD is a highly contagious livestock disease with significant repercussions for livestock producers particularly in terms of productivity and trade effects, with many other sectors also being negatively affected by the measures which must be taken to control an outbreak. The disease has the ability to spread rapidly and survive under a variety of conditions and its control and eradication is hindered by the many ways in which it can be spread. Following the 2001 outbreak in various EU Member States, there was severe criticism throughout Europe of the culling policy used to contain the virus in the Member States affected and attention has turned towards the strategic use of emergency vaccination in the event of future outbreaks.

This paper examines the potential use of emergency vaccination in an Irish context, as an adjunct to the basic slaughter policy, and explores the cost-effectiveness of the alternative control strategies of stamping-out (SO) alone and stamping-out in conjunction with emergency vaccination (SOEV). The new emphasis placed on emergency vaccination as a disease control measure has been assisted by amendments to the OIE rules in May 2002, on the time required to regain FMD free status after the use of vaccination. Any decision in a country to employ emergency vaccination as part of a future control strategy would have to take account of the impact such a campaign would have on the trading environment. As in 2001, the basic disease control policy in the event of a future outbreak in Ireland would be the slaughter of susceptible animals on infected premises and those identified as dangerous contacts. In the Irish case it is envisaged that vaccinates would subsequently be slaughtered as this would result in fewer trade implications than if vaccinates were allowed enter the food chain. Once vaccinates are subsequently slaughtered, countries are officially allowed back into markets three months after the slaughter of the last animal. If vaccinates are not slaughtered market access is restricted for a further three months.²

The epidemiological model of disease spread used in the analysis is the North American Animal Disease Spread Model (NAADSM). The computable general equilibrium (CGE) model GTAP (Global Trade Analysis Project) is then used to assess the economic effects

¹ O'Toole, Matthews & Mulvey (2001), OIE/FAO (2001), EU (2002), INDECON (2002)

² Although official timeframes are in place, in reality it can often take countries longer to regain market share.

of the disease and its subsequent control strategies on both the agricultural sector and the wider economy. The effects on trade and tourism are examined in particular.

There are two main parts to the paper. The following section examines the epidemiology of the disease and the legislative background; a synopsis of the 2001 outbreak is also given. Section 3 outlines how by combining the epidemiological and economic modules contained in NAADSM, direct control costs are compared in an Irish context for a number of hypothetical outbreaks. Regions of differing herd density, production type, and location within the country were chosen for study to assess how well both control strategies would operate in a number of diverse areas. A discussion of results then follows.

2. Foot-and-Mouth Disease

FMD is, according to the classification of the OIE, the economically most important infectious livestock disease, with very significant consequences for livestock producers, related industries and consumers. It comes top of the list of all List A diseases which are defined as:

“Transmissible diseases that have the potential for very serious and rapid spread, irrespective of national borders, that are of serious socio-economic or public health consequence and that are of major importance in the international trade of animals and animal products.”

It is one of the most contagious of viral animal diseases and is caused by strains of one or more of the seven distinct serotypes of FMD virus, genus *Aphthovirus*, family *Picornaviridae*. The seven serotypes – O, A, Asia 1, C, SAT1, SAT2, and SAT3 – have different geographical distributions and vaccines protective against strains in one serotype will normally not protect against strains from different serotypes and may not protect against different strains within the same serotype. There are also several subtypes within each. The infections caused by different serotypes are clinically indistinguishable. The disease predominantly affects cloven-hoofed animals, affecting almost all farmed species, hence its economic significance. If not controlled, it generally causes very high morbidity within herds without causing high mortality in adult animals; however, it can cause significant mortalities in young lambs and piglets. It is characterised by fever and the formation of painful vesicles (fluid-filled blisters) and erosions in the mouth, nose, teats and feet. As a result, it causes serious production losses and welfare problems (Dept. of Agriculture and Food, 2003:3).

The most important characteristics in the epidemiology of the disease include the rapid spread of the virus, its stability under a variety of conditions and the occurrence of serotypes (Donaldson, 1991:34). Cattle are important in the epidemiology of FMD because of their high susceptibility to airborne virus, because they may excrete the virus for at least four days before the first symptoms appear, and because of their overall economic importance. Even though sheep and goats can also be infected, their symptoms

are often less severe or are subclinical. Pigs are the most important source of air dissemination of the virus; once infected, they excrete vast quantities of the virus. They also have a high susceptibility to infection by the oral route (Donaldson and Doel, 1994:51). Thus pigs can be described as amplifying hosts and cattle as indicators. Sheep can be described as maintenance hosts because they quite often have mild or even inapparent signs that can easily be missed (Donaldson and Doel, 1994:35).

FMD is a difficult disease to control and eradicate because of the various mechanisms by which the virus can be transmitted (Sellers, 1971). Several factors affect the spread of the disease. The most important are the species infected, the number of direct and indirect contacts among animals (mainly movement of animals and humans), animal density in the area, husbandry methods, environmental conditions, and delays in identifying the disease and applying control measures. The most common mechanism is the movement of infected animals to susceptible animals (Donaldson et al., 2002:4). The rate of spread within a herd depends on the stocking density. The primary methods of FMD transmission are aerosol, direct contact and ingestion. Of all mechanisms of transmission, movements of infected animals are by far the most important, followed by movement of contaminated animal products. Once one or more animals in a herd have been infected, the quantity of virus in the environment will be greatly amplified, and transmission by different routes will be possible. The virus can be spread over long distances by incubating or asymptomatic carrier animals; by vehicles such as feed trucks; by birds, domestic animals, rodents and by fomites (inanimate communicators of infection). Humans may inhale and harbour the virus in the respiratory tract for as long as 24 hours, and may serve as a source of infection to animals (APHIS, 1991). Under certain epidemiological and climatic conditions, FMD virus can be spread by the wind. Of all mechanisms, spread by air is least controllable.

2.1 Legislative background

The advent of Denmark, Ireland and the UK to the European Community in 1973 foresaw considerable adjustments to the Intra-Community Trade Directive (64/432/EEC), as these new Member States practised a non-vaccination policy for FMD.³ This included full stamping-out (SO) in the case of an outbreak, enabling them to retain their national rules for protection against the disease. Other Member States continued their policy of routine (annual) vaccination as before. The impossibility of continuing the differential system of vaccination versus non-vaccination was immediately evident (Commission of the European Communities, 1989:6). In 1985 the Council adopted Directive (85/511/EEC) on the control of the disease throughout the Community and essential common measures were laid down to deal with an outbreak in a uniform manner. With the imminent completion of the single market, it was decided in 1989 that a cost-benefit analysis of alternative control strategies for FMD be undertaken. On the evidence provided by the report, a non-vaccination policy was found to be safer and cheaper. More than a decade later the debate has turned to whether or not emergency vaccination should be adopted in the event of future outbreaks.

³ Other Member States pursued a policy of annual (routine vaccination).

This section describes the most recent FMD Directive (2003/85/EC), which made important amendments to the incomplete measures of Directive (85/511/EEC). It allows the EU to maintain its internationally recognised status of “free from FMD without (routine) vaccination”. The basic approach of eradicating FMD by culling of Infected Premises and known dangerous contacts is retained but greater prominence is given to the role of emergency vaccination as a control option for use alongside stamping out in some circumstances; providing for “suppressive” vaccination,⁴ which generally means that the vaccinated animals would subsequently be killed and “protective” vaccination⁵ which would allow the vaccinated animals to live out their normal economic lives. A brief summary of the Directive follows (Department of Agriculture, 2004):

- a) The new Directive puts forward emergency vaccination as an important means of controlling an epidemic of animal disease and lays down conditions for the possible marketing of meat from animals vaccinated on Union territory during an outbreak of animal disease;
- b) It extends the Community requirements as regards contingency plans and requires Member States to review them every five years in the light of real-time alert exercises;
- c) It gives five separate criteria,⁶ any of which may be used as the basis for declaring an outbreak of FMD on a holding; this should help to set preventive measures in motion more quickly;
- d) It requires the Member States to introduce systems of penalties to be applied in cases of infringement of the national provisions adopted pursuant to Community directives;
- e) It requires Member States to provide information about the dates on which the Community measures were implemented. This should enable the Commission to determine the extent to which Community reimbursement is due.

2.2 The 2001 outbreak

The speed, at which FMD of the Pan-Asia O type spread within the EU, particularly the UK, in 2001, was unprecedented in the history of FMD, as was the scale of the outbreaks. 6.5m animals were slaughtered in the UK, 285,000 in the Netherlands, 63,000 in France and 53,000 in Ireland. The presence of the disease was confirmed in the UK, France, Ireland, and the Netherlands on the 21st February and the 14th, 21st and 22nd March

⁴ Suppressive vaccination - emergency vaccination which is carried out exclusively in conjunction with a stamping-out policy in a holding or area where there is an urgent need to reduce the amount of foot-and-mouth disease virus circulating and to reduce the risk of it spreading beyond the perimeters of the holding or the area and where the animals are intended to be destroyed following vaccination (Article 2).

⁵ Protective vaccination - emergency vaccination carried out on holdings in a designated area in order to protect animals of susceptible species within this area against airborne spread or spread through fomites of foot-and-mouth disease virus and where the animals are intended to be kept alive following vaccination (Article 2).

⁶ See Appendix A

respectively. The UK outbreak lasted 10 months, with 2,034 outbreaks of infection extending to 10,124 farms and leading to the slaughter of some 4 million animals. In addition, more than 2 million animals were slaughtered because of the welfare problems that arose when they were confined to farms following movement restrictions. It was not possible to contain the disease to the UK and it spread quickly to three other Member States where more than 6.9m animals were slaughtered overall. An immediate ban was imposed on the import of live susceptible species and of products of susceptible species from these countries (unless appropriately treated).

Because the last Irish outbreak was confined to one case and stringent movement restrictions were subsequently put in place, the 2001 outbreak was less serious than might have been. The Indecon report on the single Irish outbreak found that it cost the Exchequer €107m but that had efforts to prevent further spread not been successful, the adverse impact on Ireland's GDP could have reached €5.6 billion (a decrease of 6%), with job losses of up to 12,000 and the potential devastation to 20 million susceptible livestock (Indecon, 2002). Tourism was the main loser with losses estimated to be €210m in the first six months of year. The Agri-Food sector actually benefited by around €107m due to the impact of the UK outbreak, which resulted in higher than expected export prices for livestock exports, particularly sheep meat with exporters benefiting from the simultaneous and more severe outbreak in the UK. Indecon found that 75% of the increase in the volume of pig exports to the UK that year was due to the outbreak, and 50% for sheep (Indecon, 2002:13). The beef sector was given a minor boost; however, the on-going effects of BSE were felt. Overall, export values were found to be up from the previous year by about €63m in 2001 (Indecon, 2002:13). It is important to note that another outbreak could potentially prove more serious; estimates suggest that in the best-case scenario of a worldwide 3-month export ban, the reduction in food exports would be equal to €0.9bn. If non-EU markets imposed a longer 6-month ban, the overall cost would amount to €1.2bn (Indecon, 2002:16).

Table 1: Estimated gains (losses) as a result of the 2001 outbreak (Source: Indecon, 2002)

Estimated gains (losses)	€ million
Agriculture	107
Tourism and other sectors	(210)
Exchequer costs	(107)
Total	(210)
Total as a % of GDP	-0.2%

The European Court of Auditors report on the 2001 European outbreak found that Member States were not adequately prepared for an outbreak and that the Commission had not revised its response strategy in light of changes in risk factors. Member States are therefore now required to update contingency plans, to undertake a cost-benefit

analysis of alternative control strategies and to clarify the financial framework as applied to epidemics of animal disease. In the event of future outbreak, the decision to be taken on the appropriate control/ eradication measures to be put in place would not be an easy one, but is one that would have to be taken and implemented quickly to ensure minimum long-term damage. The potential economic impact of a future outbreak is difficult to quantify, however a prompt control response policy is the most important defence against potentially catastrophic spread. It is of huge importance that movement restrictions and controls be put in place as soon as possible in the event of an outbreak, indeed the delay in implementing these during the 2001 UK outbreak was found to double the overall cost of the outbreak there. The total cost was estimated to be about £3.1 billion to the agriculture and the food chain (including costs compensated by the exchequer) and a further £2.7 to £3.2 billion to businesses directly affected by tourist expenditures (Department for Food, Environment and Rural Affairs and the Department for Culture, Media and Sport). The effects of an outbreak of that scale on the Irish economy and the subsequent closure of markets would be devastating. The role which emergency vaccination can play in an Irish context, in controlling an outbreak, alone or in conjunction with culling therefore needs to be assessed on economic grounds.

3. The Epidemiological model - North American Animal Disease Spread Model

NAADSM is a stochastic state-transition model allowing for three mechanisms of disease spread: infection by air (airborne), infection as a consequence of susceptibles coming directly into contact with contagious animals (direct) and infection through indirect means i.e., spread by farm vehicles, people etc. (indirect). The methodology is based on a more elaborate form of the Reed-Frost algorithm.⁷ It allows for additional transition states and a spatial component, which the traditional theory does not. It is designed to simulate the spread and control of foreign animal diseases in a population of susceptible livestock herds and is the product of collaboration among academic and governmental institutions in the United States and Canada (www.naadsm.org). It is a stochastic simulation model, incorporating both epidemiologic and economic modules. The linking of the two allows for tracking and comparing of costs of hypothetical FMD outbreaks and related control strategies.

The model is herd-based with disease manifestation and transmission represented at herd as opposed to individual animal level. Each herd (unit) has a production type (cattle, sheep, pigs, etc.), size, location and disease state. The simulation proceeds in time steps of one day. During each time step herds are affected by biological processes happening in the animals (e.g., progress of the disease), the environment (e.g., airborne spread) and/or human actions (e.g., vaccination). The “model” is the sum of these processes and actions (Harvey et al. 2006:5 Appendix A). The model is stochastic, attempting to imitate the random processes responsible for disease spread. Both spatial and temporal aspects of the disease are simulated. Outputs of the epidemiological module are linked to

⁷ For further details, see Dillon (2007).

an economic module that tracks various cost and price values – allowing for tracking and comparing of costs of hypothetical outbreaks and related control strategies. It is based on a previously designed stochastic state-transition model (Garner and Lack, 1995). Chance occurrences such as spread of infection are simulated with Monte-Carlo methods to maintain a stochastic basis (Schoenbaum et al, 2003).

Units move between the various states and probability functions characterise the duration for which a herd remains in each state, this being determined stochastically. Five discrete disease states are modelled in NAADSM i.e., susceptible, latent (incubating), infectious subclinical, infectious clinical and immune. Time periods of these transition states are modelled with triangular density functions. During the running of the model, herds shift (make transitions) among these states. Spread of infection by direct and indirect contact is based on simulated contact/movements among infected and susceptible herds. Probabilities (input parameters) determine whether or not disease transmission occurs from simulated contact among infected and susceptible herds. An illustration of the differing states can be seen in figure 1 below:

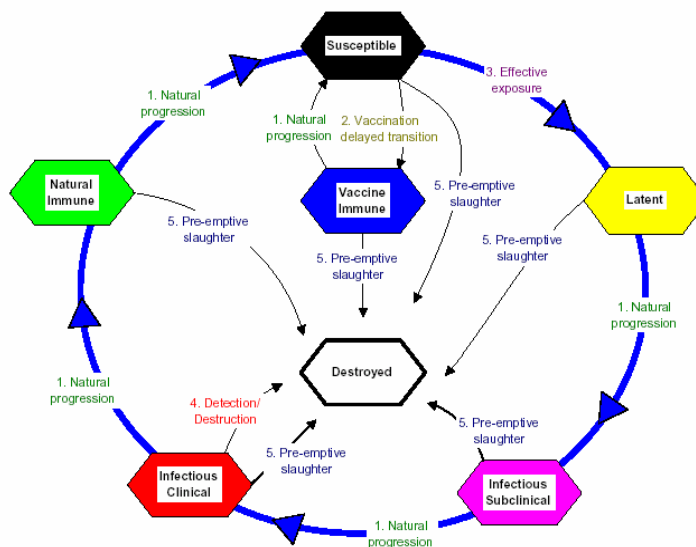


Figure 1: States and transitions in the NAADSM model (Source NAADSM model description)

At the beginning of each replicate (simulation) one herd at the centre of the general circle is said to be latent (incubating), all other herds are thought of as susceptible. Some disease models (e.g., Garner and Lack, 1995) have previously used the Reed-Frost model to model spread, however, this alone does not provide for the spatial spread of infection as the algorithm assumes that each herd is equally likely to contact every other herd. NAADSM bases spread on this plus risk, contact rates and other input parameters.

Where possible Irish specific values were chosen to parameterise the model; although where these were unavailable values were taken from the literature.⁸ There are six basic types of model input parameters: yes/no values, integer values, real numbers, probabilities, probability density functions, and relational functions. These apply to the following broad categories:

- 1) Animal populations
- 2) Disease manifestation
- 3) Disease transmission
- 4) Disease detection and surveillance
- 5) Disease control
- 6) Direct costs

The model is flexible as regards the alteration of such parameters. The application of NAADSM in Irish circumstances is investigated for four regions of varying characteristics. It is undertaken for sheep and cattle herds in three regions and pigs are taken into account in the fourth, Co. Cavan (where 61% of the national pig herd is located).

3.1 Strategies of control and eradication

Stamping-out (culling): With an infectious disease like FMD affected animals can be a source of infection to others. In such circumstances it may be economically and technically expedient to slaughter the affected animals. In eradication campaigns, infected or in-contact animals may be slaughtered to remove sources of infection (Thrusfield, 1986:216). It is important to make the distinction between slaughter and culling; both involve the destruction of animals: slaughtered animals are subsequently processed for food whereas culled animals are disposed of. It is debateable as to whether or not vaccines would be accepted in the food chain for the Irish case and therefore it is culling that will be examined in depth here.

Vaccination: Vaccines can confer immunity to many bacteria and viruses. They are used routinely to prevent disease, and may be used during epidemics to decrease the number of susceptible animals, thus assisting in terminating an epidemic (Thrusfield, 1986:216).

Both policies are supported by import controls, regular surveillance of the livestock populations at risk, the provision of diagnostic laboratory facilities and, in the event of disease, controls on the movement of livestock.

⁸ A broad overview is given here only; input parameter values used in the model will be outlined in a forthcoming paper.

3.1.2 Costs associated with control

As the control and eradication of FMD is clearly beneficial for Ireland, the relative costs of alternative control strategies only need be examined here in a cost-effectiveness framework. The relative costs of the alternative control strategies have to be identified and measured. Direct costs of control measures are relatively easily identified and can be equated with resource costs incurred by farmers and relevant public authorities. Consequential costs, secondary in nature but not in importance are more difficult to identify and measure since they concern society as a whole.⁹ A further difficulty associated with consequential costs (benefits) is the ‘transfer problem’; the possibility of inadvertently double counting certain effects: a loss (gain) in one sector is not a loss (gain) to society as a whole if offset by a gain (loss) in another sector (multiplier effects for agriculture, tourism and retail).¹⁰ Also some of the costs cannot be quantified, at least in monetary terms. Benefits would include increased trade and the psychological well being accompanying the decreased disease incidence.

Disease control campaigns incur a cost, it is important therefore to assess before they are instituted both the costs arising from the disease itself and the cost associated with its control. It is possible to weigh the cost of the control campaign against the benefits (e.g. increased production) that would accrue from control of the disease in order to determine the economic viability of the campaign. Clearly, if the control campaign costs more than the losses due to the disease then the campaign is not economically viable.

There are four potential cost elements in an FMD eradication programme:

The **Direct costs** of FMD eradication are relatively easily quantified as they can be equated with certain resource expenditures incurred by producers of livestock and by relevant government authorities.

- (i) *Eradication costs* include cost of slaughter, compensation for destroyed animals and materials, cleaning and disinfection (C and D) of infected premises, and quarantine enforcement.
- (ii) *Production losses* arise from lost production in depopulated premises and industries linked to the livestock sector. Although FMD has a very high mortality rate among young animals, it usually only reduces milk and beef production in older animals. Physical losses arising from stamping out and depopulation are included.

⁹ Indeed many consequential costs are by their nature non-measurable and can only be discussed qualitatively.

Indirect or consequential costs are more difficult to identify and measure since they theoretically extend to all sectors of the economy:

- (iii) *Trade restrictions:* Revenue foregone as a result of denied access to markets. Access to markets (if any) may be restricted to lower price markets (the international beef market is segmented into FMD-free and FMD endemic markets with the price difference between the two segments for meat of similar quality being as high as 50%).
- (iv) *Knock-on effects for the non-agricultural sector:* e.g. downstream effects for tourism and other sectors as a result of movement restrictions etc. should prove important. Tourism was the big loser during the 2001 outbreak.

Control and eradication costs will depend primarily on the scale and duration of the outbreak. Expected losses are defined as the probability of an outbreak multiplied by the estimated cost. Estimating the probability of an occurrence is difficult; however the rapid spread of a pandemic strain of FMD in 2001 clearly demonstrates the ability of the virus to infiltrate a wide geographical area. Factors crucial in determining the magnitude of the economic impact include: trading partner reactions, rate of disease spread, containment, eradication and multiplier effects.

In this research, the cost effectiveness of employing emergency vaccination as an adjunct to the basic culling strategy in the event of an outbreak for a number of simulated outbreaks Irish outbreaks is assessed using an epidemiological module to simulate the disease dynamics, and an economic module to convert outbreak and control effects into estimates of direct control costs and export losses.¹¹

Costs in the model are calculated as follows (taken from Hill and Reeves, 2006:86):

The total cost of destruction for each herd (unit) = (*Appraisal cost + Cleaning and disinfection cost*) + [(*Number of animals in the unit*) × (*Cost of euthanasia + Cost of indemnification + Cost of disposal*)]

The total cost of destruction for all herds = (*Number of units destroyed*) × (*Appraisal cost + Cleaning and disinfection cost*) + [(*Total number of animals destroyed*) × (*Cost of euthanasia + Cost of indemnification + Cost of disposal*)]

Similarly there are both fixed and variable costs associated with vaccination; there is a fixed cost associated with vaccination site set up and an additional cost per animal vaccinated. A baseline vaccination cost applies to animals up to a certain threshold (500,000 in this case) where after an additional cost applies. The total cost of vaccination for all herds is calculated as follows (also taken from Hill and Reeves, 2006:86):

¹¹ An analysis of indirect costs are contained in a forthcoming publication.

If the threshold is not reached: [(Number of units vaccinated) × (Cost of site setup)]
+ [(Total number of animals vaccinated) × (Baseline cost per animal)]

If the threshold is reached: [(Number of units vaccinated) × (Cost of site setup)]
+ [(Threshold level) × (Baseline cost per animal)] + [(Total no. of animals vaccinated –
Threshold level) × (Baseline cost per animal + Additional cost per animal)]

3.2 Simulation scenarios

Two methods of control are modelled (both are in line with EU FMD legislation):

(1) SO: stamping-out of infected herds and dangerous contacts within a 3km radius and;

(2) SOEV: stamping-out of infected herds and dangerous contacts in conjunction with emergency vaccination (and the subsequent slaughter) of animals within a 5km radius i.e., herds are culled as above within a 3km radius, with herds for a further 2km vaccinated and then subsequently slaughtered.¹²

In adopting SOEV here it is assumed that vaccinates are to be slaughtered subsequently. In the event of slaughtering these animals the ‘official’ length of time out of markets remains at 3 months not 6 (if vaccinates were allowed enter the food chain). The benefit of employing emergency vaccination in this case would be, it is hoped, to ‘close-in’ on the disease more quickly and dampen down virus spread. As vaccinates are subsequently slaughtered it would appear that SOEV will involve the culling of more animals (over a larger area – given the radius). However, as emergency vaccination is to be used in an effort to minimise the scale of an outbreak, it is hoped that there are in fact less infected premises, dangerous contacts and thus casualties. This is the hypothesis to be tested by the model in the analysis here.

3.2.1 Data

Herd data for cattle herds and sheep flocks are used (with pig census data used for the analysis in Co. Cavan).¹³ Data on cattle herds was obtained from animals that were TB tested in 2005 (this test is obligatory for all cattle herds). There is no differentiation between beef, dairy or suckler¹⁴ herds. For sheep flocks, 2005 sheep census data are used. Pig census data from 2001 is used; this is the most up-to-date source available. The data was provided by the Department of Agriculture.¹⁵ Each herd or flock has a unique herd ID number and production type with each holding having a latitude/longitude point. Knowledge of the exact geolocation of each herd ensures the dissemination of the virus is modelled more accurately. In preparing for simulation, data was grouped on a

¹² This can be anything up to 10km but it is envisaged here that it would occur 2km outside the 3km zone initially. Other options have also been tested; the model is flexible in that regard.

¹³ Lat/Lon points not available for all so there are a small number of herds unaccounted for.

¹⁴ Cows other than those kept principally to produce milk for human consumption.

¹⁵ Herd census and flock data courtesy of CVERA (UCD), with a special thanks to Guy McGrath in this regard.

county-by-county basis. Herds (as opposed to animals) are the unit of concern in the model.

An important issue in terms of an analysis using Irish herd data is the fragmentation of farms - half of the farms in the State consist of two or more land parcels while almost 10% comprise four or more parcels (Lafferty et al., 1999:25). Difficulties arise as a result when modelling on a herd-by-herd basis. As it is not unusual in the Irish case for one farm to comprise four or five separate parcels of land the herd is not located at one single point and the disease could be more widespread than anticipated (i.e., a multiple point disease source). From the modelling point of view each of these points has the same herd/farm ID number. The solution used in this analysis to deal with the problem is to use the herd number with associated latitude and longitude points in decimal degrees based on the centroid of the largest fragment of land used by the farmer, thus there is only one record per farm. As a consequence, the model may underestimate the occurrence of the disease. One initial hypothetical outbreak is assumed to occur at the centre point of the region with one 'latent' herd.

3.2.2 The regions

A brief summary of the simulation results only are given for each region in this paper (more detailed results are available from the corresponding author). For all simulations the discussion of results is mainly focussed on the mean values however some reference is also made to the distribution.

The four regions examined here are based on areas of differing farming types and herd densities in various geographic locations within the country. See table 2 below:

Table 2: Regional information

Region	Farming type/ County	Area	Total Animals	Animal density
1	Marginal/Mixed: Counties Galway, Roscommon (West)	869,856 ha. (8699km ²)	1,368,097	High 157 per km ²
2	Dairying: County Cork (South)	750,758 ha. (7,508 km ²)	344,667	Low 46 per km ²
3	Intensive fattening/mixed crops: Counties Laois, Offaly (Midlands)	370,927 ha. (3,709 km ²)	600,115	High 162 per km ²
4	Mixed/pigs: County Cavan (Border North)	193,188 ha. (1,932 km ²)	289,123 (+176,270 with pigs)	High 150 per km ²

3.3 Region 1: Galway, Roscommon – marginal/mixed farming

This region in the western province of Connaught can be described as an area of mixed farming. The area of the two counties combined is 869,856 hectares. The total number of cattle in the region is 673,677 with an average herd size of 40. Sheep in the region total 694,420 with an average herd size of 101. Herd density is high (157 animals per km²). Information relating to both counties is contained in table 2:



Fig. 2: Region 1: Galway/Roscommon¹⁶

Table 3: Region 1 – Galway, Roscommon

	Galway	Roscommon	Total
Area (hectares)	615,052	254,804	869,856
Holdings	13,089	6,174	19,263
Sheep flocks	4,922	1,964	6,886
Total Sheep	496,883	197,537	694,420
Average flock size	101	101	
Cattle herds	11,343	5,436	16,779
Total Cattle	458,451	215,226	673,677
Average herd size	40	40	
Total herds/flocks	16,265	7,400	23,665
Total animals	955,334	412,763	1,368,097

Source: All Herd census and flock data courtesy of CVERA

57% of the land in Connaught is classified as ‘difficult’ for agriculture, i.e., stony and infertile soils, steep slopes and rock outcrops. Moreover, small farm size and fragmentation are particular issues in the west (Lafferty et al., 1999:13). Pasture is particularly important in east Connaught with more upland areas used for rough grazing. Sheep rearing is significant in east Galway, south Roscommon and in the western mountain ranges (Lafferty et al., 1999:103). Mixed farming is particularly evident in the lowlands of east Galway and south Roscommon (Lafferty et al., 1999:105).

The combined total of herds and animals in region 1 are 23,665 and 1.37m respectively.

¹⁶ All maps from www.asthmacare.ie/images/map.jpg

3.3.1 Region 1 simulation results¹⁷

The overall mean values after 80 iterations conclude that stamping-out (SO) alone would appear to be more cost-effective than carrying it out in conjunction with a campaign of emergency vaccination (SOEV).

Adopting a campaign SO only, 499 units were culled on average (with a standard deviation of 331 units, 131 at the 5th percentile and 983 at the 95th percentile). This amounted to 17,377 animals destroyed on average over the course of the outbreak here. Average outbreak length was found to be 63 days (with a standard deviation of 25 days, 34 at the 5th percentile and 109 at the 95th percentile). In terms of dissemination of the virus - on average 23 units were infected by airborne spread, 25 by direct spread and 6 by indirect spread. 18 units were destroyed on average because they were detected positive (with a standard deviation of 11 units, 6 at the 5th percentile and 33 at the 95th percentile) and 481 because they were in the destruction ring (standard deviation was found to be 321 herds with 126 at the 5th percentile and 941 at the 95th percentile). The total cost associated with destruction came to €21.8m on average (with a standard deviation of €17.5m, €5m at the 5th percentile, and €44.9m at the 95th percentile).

On the other hand SOEV led to the destruction of 118 more herds with 617 units destroyed on average (with a standard deviation of 369 units, 133 at the 5th percentile and 1,240 at the 95th percentile). This amounted to 2,401 more animals (19,778) on average. Vaccination (and subsequent slaughter) was carried out on 235 holdings (standard deviation of 339, 0 at the 5th percentile and 958 at the 95th percentile) with 10,318 animals vaccinated on average over the course of an outbreak. In terms of disease dissemination; 20 units were infected by airborne spread, 28 by direct spread and 5 by indirect spread, on average. 22 units were destroyed because they were detected positive (with a standard deviation of 22 units also, 3 at the 5th percentile and 65 at the 95th percentile) and 595 (352 standard deviation, 131 at the 5th percentile and 1,194 at the 95th percentile) because they were in the destruction ring. The average outbreak length was found to be twelve days less at 51 days (with a standard deviation of 17 days, 32 at the 5th percentile and 78 at the 95th percentile), but overall destruction and vaccination costs came in at approximately €5m higher on average, at €26.6m, this was made up of destruction costs totalling €26.4m and vaccination costs of €153,986. Total costs were found to be €5.1m at the 5th percentile and €58.1m at the 95th percentile with a standard deviation of €18.4m.

In this high-density region then a campaign of SO alone would appear to be more cost-effective (in terms of control) however, the strategic use of emergency vaccination does shorten the duration of the outbreak.

¹⁷ For space reasons, only a summary of the results is provided for each region. See Dillon (2007) for more details.

3.4 Region 2: Co. Cork – a dairying region

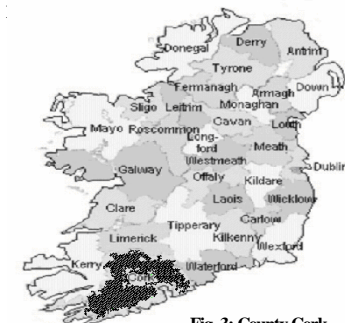


Fig. 3: County Cork

Table 4: Region 2 -Cork

Area (hectares)	750,758
Holdings	6,750
Sheep flocks	667
Total Sheep	26,625
Average flock size	40
Cattle herds	6,085
Total Cattle	318,115
Average herd size	52
Total herds/flocks	6,752
Total animals	344,667

This region in the south of the country can be described as a dairy intensive region. It is the country's largest county at 750,758 hectares. The total number of cattle in the region is 318,115 with an average herd size of 52. This is a region of a much lower herd density (46 animals per km²).

This region enjoys very favourable climatic and soil conditions for dairying based on a long growing season with low costs of housing and winter-feeding. Dairying has become a more specialised type of farming – by 1991 approximately 93% of all dairy cows were enumerated on 42,000 specialist farms. The south-west dairying region includes north and east Kerry, almost all of Cork, Limerick and substantial parts of Tipperary, Waterford and Kilkenny as well as south-west Clare (Lafferty et al., 1999:82).

The combined total of herds and animals in the region are 6,750 herds and 344,667 respectively. A brief summary of the findings is contained below.

3.4.1 Region 2 simulation results

The overall mean values after 80 iterations conclude that stamping-out in conjunction with emergency vaccination (SOEV) would appear to be more cost-effective than stamping-out alone (SO) in this case.

Adopting a campaign of SO only, 967 units were destroyed (with a standard deviation of 597 units, 219 at the 5th percentile and 1,982 at the 95th percentile). This amounted to the destruction of 39,108 animals on average over the course of the outbreak. Average outbreak length was 63 days (with a standard deviation of 25, 28 at the 5th percentile and 103 at the 95th percentile). In terms of dissemination of the virus - 22 units were infected by airborne spread, 33 by direct spread and 7 by indirect spread on average. 38 units were destroyed on average because they were detected positive (with a standard deviation of 38, 2 at the 5th percentile and 96 at the 95th percentile) and 930 on average because they were in the destruction ring (standard deviation 563, 216 at the 5th percentile and 1,909 at the 95th percentile). The total cost associated with destruction came to €61m

(with a standard deviation of €38.9m, €14.2m at the 5th percentile and €126.2m at the 95th percentile).

On the other hand SOEV resulted in the destruction on average of 224 less herds at 743 units (with a standard deviation of 461, 127 at the 5th percentile and 1,434 at the 95th percentile) and 9,394 less animals (29,714) on average. Vaccination (and subsequent slaughter) was carried out on average on 349 holdings (with a standard deviation of 456 units, 0 at the 5th percentile and 1,129 at the 95th percentile) with 14,134 animals vaccinated. On average 15 units were infected by airborne spread, 28 by direct spread and by 5 indirect spread. 27 units were destroyed because they were detected positive and 716 because they were in the destruction ring. The average outbreak length was found to be 9 days less at 54 days (with a standard deviation of 21 days, 19 at the 5th percentile, 82 at the 95th percentile) with an overall saving on average on destruction and vaccination costs of €14m with total control costs amounting to €46.9m (standard deviation €30.2m, €7.6m at the 5th percentile, €90.9m at the 95th percentile). The average total cost was made up of €46.7m for destruction and €0.227m for vaccination.

In this low-density region then a campaign of SOEV would appear to be more cost-effective (in terms of control) than one of SO alone.

3.5 Region 3: Laois/Offaly – intensive fattening/mixed crops

This region in the midlands is important in the context of a national outbreak given the implications for disease spread. The combined area of these two counties is 370,927 hectares. Herd density can be described as high (162 animals per km²).

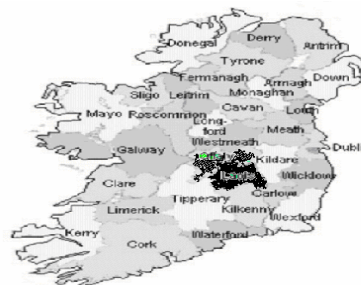


Fig. 4: Region 3 - Counties Laois and Offaly

Table 5: Region 3 – Laois and Offaly

	Laois	Offaly	Total
Area (hectares)	171,946	198,981	370,927
Holdings	3,272	3,397	6,669
Sheep flocks	523	733	1,256
Total Sheep	65,638	99,901	165,539
Average flock size	126	136	
Cattle herds	2,635	2,785	5,420
Total Cattle	222,135	212,441	434,576
Average herd size	84	76	
Total herds/flocks	3,158	3,518	6,676
Total animals	287,773	312,342	600,115

The combined total of holdings and animals in the region are 6,669 and 599,716 respectively.

3.5.1 Region 3 simulation results

The overall mean values after 80 iterations conclude that stamping-out in conjunction with emergency vaccination (SOEV) would appear to be more cost-effective than stamping-out alone (SO) in this case.

Adopting a campaign SO only, 406 units were on average, destroyed over the course of the outbreak (with a standard deviation of 206, 115 at the 5th percentile and 767 at the 95th percentile). This on average led to the destruction of 40,980 animals. Average outbreak length was found to be 45 days (with a standard deviation of 13 days, 23 at the 5th percentile and 66 at the 95th percentile). In terms of dissemination of the virus – on average 11 units were infected by airborne spread, 34 by direct spread and 5 by indirect spread. 17 units were destroyed on average because they were detected positive (standard deviation 13, 3 at the 5th percentile and 44 at the 95th percentile) and 389 because they were in the destruction ring (standard deviation 195, 112 at the 5th percentile and 747 at the 95th percentile). The total cost associated with destruction came to €39.6m on average (with a standard deviation of €19.6m, €11.3m at the 5th percentile and €72.5m at the 95th percentile).

On the other hand SOEV resulted, on average, in the destruction of 27 fewer herds, at 379 units (standard deviation 172, 145 at the 5th percentile and 668 at the 95th percentile) and 2,719 less animals (38,261). Vaccination (and subsequent slaughter) was carried out on 82 holdings on average over the course of the outbreak (with a standard deviation of 146, 0 at the 5th percentile and 391 at the 95th percentile) with 8,098 animals vaccinated. On average, 10 units were infected by airborne spread, 31 by direct spread and by 5 indirect spread. 15 units were destroyed because they were detected positive and 364 because they were in the destruction ring. The average outbreak length was found to be the same at 45 days (with a standard deviation of 12 days, 26 at the 5th percentile and 68 at the 95th percentile) with an overall saving on destruction and vaccination costs on average of €2.63m with total control costs amounting to €36.97m (standard deviation of €16.4m, €14.8m at the 5th percentile and €64.9m at the 95th percentile). On average €36.9m of this was associated with destruction and €58,000 with vaccination.

In this high-density region (unlike the previous high-density one) then a campaign of SOEV would appear to be more cost-effective (in terms of control) than one of SO alone. There was no difference in the duration of the outbreak

3.6 Region 4: Cavan



Fig. 5: Region 4 – County Cavan

This county bordering the North covers an area of 193,188 hectares. As pigs are important in the dissemination of FMD virus, analysing the impact of an outbreak in this region both with and without pigs is important. 156 pig herds are taken in to account in the second analysis. Again the area can be described as being of a fairly high herd density (150 animals per km²).

Table 6: Region 4 – Co. Cavan

Area (hectares)	193,188
Holdings	5,207
Sheep flocks	789
Total Sheep	55,839
Average flock size	71
Cattle herds	4,765
Total Cattle	242,284
Average herd size	51
Total herds/flocks	5,554
Total animals	289,123

Pig production has become highly specialised and dominated by a small number of very large producers. In 1973 the average size of a herd was 29 animals, by 1983 this had increased to 114 and by 1997 it was 846, indicating the ‘industrialisation’ associated with pig production (Lafferty et al., 1999:110). Of the 1,167 pig herds in the country 15% of these are in Co. Cavan; this numbers 780,225 pigs (61% of the country total).

3.6.1 Region 4 – Cavan (without pigs) simulation results

The combined total of holdings and animals in the region are 5,207 holdings and 289,123 respectively. The overall mean values after 80 iterations conclude that stamping-out alone (SO) would appear to be more cost-effective than stamping-out in conjunction with emergency-vaccination (SOEV) in this case.

Adopting a campaign SO only led to, on average, the destruction of 891 units (with a standard deviation of 568 units, 180 at the 5th percentile and 1,943 at the 95th percentile). This totalled 46,155 animals on average over the course of the outbreak. Average outbreak length was found to be 66 days (with a standard deviation of 25 days, 31 at the 5th percentile and 109 at the 95th percentile). In terms of dissemination of the virus – on average, 32 units were infected by airborne spread, 38 by direct spread and 8 by indirect spread. 45 units were destroyed because they were detected positive on average (standard deviation 49, 5 at the 5th percentile and 141 at the 95th percentile) and 846 because they were in the destruction ring (standard deviation 522, 175 at the 5th percentile and 1,806 at the 95th percentile). The total cost associated with destruction came to €64m on average (with a standard deviation of €40.7m, €13m at the 5th percentile and €137.9m at the 95th percentile).

On the other hand SOEV resulted in the destruction of 372 more herds on average at 1,263 (with a standard deviation of 704, 361 at the 5th percentile and 2,912 at the 95th percentile) and 18,750 more animals on average at 64,905. Vaccination (and subsequent slaughter) was carried out on 733 holdings (standard deviation 758, 0 at the 5th percentile and 2,487 at the 95th percentile) with 37,819 animals vaccinated on average. 25 units were infected by airborne spread, 28 by direct spread and 6 by indirect spread. 40 units were destroyed on average because they were detected positive (standard deviation 42, 4 at the 5th percentile and 141 at the 95th percentile) and 1,222 because they were in the destruction ring. The average outbreak length was found to be longer at 74 days (with a standard deviation of 30 days, 37 at the 5th percentile and 142 at the 95th percentile). This option proved more costly with an overall increase on destruction and vaccination costs of €27m, with total control costs amounting to €91.4m on average (with a standard deviation of €51m, €26.7m at the 5th percentile and €209.1m at the 95th percentile). €90.9m corresponded, on average to destruction costs and €487,123 to vaccination.

In this high-density region then as in region 1 a campaign of SO would appear to be more cost-effective (in terms of control) than that of SOEV. The employment of emergency vaccination in this case did not as the theory would suggest shorten the duration of the outbreak. It should be pointed out that the vaccination costs are relatively small (when compared to those of destruction) however its employment does not have the desired effect of closing-in on the disease as perhaps expected.

3.6.2 Region 4 – Cavan (with pigs) simulation results

The addition of 175 pig herds (780,225 animals) brings the combined total of holdings and animals in the region to 5,382 and 1,069,348 respectively. The overall mean values after 80 iterations conclude that SO would again appear to be more cost-effective in this region even when pigs are added in to the animal population.

In adopting a campaign of SO only, 1,986 units on average were destroyed (standard deviation 1,262, 209 at the 5th percentile and 4,104 at the 95th percentile). This involved the destruction of 353,847 animals over the course of the outbreak. Average outbreak length was 100 days (with a standard deviation of 50 days, 28 at the 5th percentile and 185 at the 95th percentile). In terms of dissemination of the virus - on average 77 units were infected by airborne spread, 63 by direct spread and 36 by indirect spread. 133 units were destroyed because they were detected positive (standard deviation 130, 4 at the 5th percentile and 381 at the 95th percentile) and 1,852 (standard deviation 1,142, 206 at the 5th percentile and 3,739 at the 95th percentile) because they were in the destruction ring. The total cost associated with destruction came to €188m on average (standard deviation €139m, €16.5m at the 5th percentile and €440m at the 95th percentile).

On the other hand SOEV resulted in the destruction of 262 more herds (2,248) with a standard deviation of 1,315 (401 at the 5th percentile and 4,224 at the 95th percentile). This involved the destruction of 49,004 more animals (402,851) on average. Vaccination (and subsequent slaughter) was carried out on 1,605 holdings (standard deviation 1,343, 0

at the 5th percentile and 3,663 at the 95th percentile) with 84,203 animals vaccinated. In terms of dissemination of virus; 49 units were infected by airborne spread, 47 by direct spread and 26 by indirect spread. 94 units were destroyed on average, because they were detected positive (standard deviation 96, 3 at the 5th percentile and 271 at the 95th percentile) with 2,154 units culled because they were in the destruction ring. The average outbreak length was found to be seven days longer at 107 days (standard deviation 55, 28 at the 5th percentile and 190 at the 95th percentile). Destruction and vaccination costs were found to be €27m higher at €215 (with a standard deviation of €149.8m, €30.8m at the 5th percentile and €453.6m at the 95th percentile). Of this €214m related to destruction costs and €1m to vaccination.

Again SO was found to be the more cost-effective control option when pigs are taken into account.

3.7 Discussion of results

This section seeks to draw general conclusions from the simulation results. It would appear from this analysis that a policy of SOEV is most appropriate for use in the event of an outbreak in the low-density region 2 (Cork), when direct costs only are taken into account. An overall cost-saving of €14m and a reduction in the duration of the outbreak of on average of nine days is made here. Although the strategic use of vaccination in the high-density region 1 (Galway, Roscommon) also led to an overall reduction in the duration of the outbreak of twelve days, the total (direct) costs of control associated with vaccination and destruction in this case were found to be €5m higher when this policy was adopted. A relevant question in both of these cases is whether the subsequent trade and general economy-wide implications of using emergency vaccination add further to the costs or does the shortening of the outbreak lead to a quicker re-opening of markets and lower economy-wide costs? As in this case vaccinates are subsequently slaughtered there are no additional penalties in terms of officially getting back in to markets when vaccination is used but as costs are found to be higher when vaccination is employed in region 1 and lower in region 2 therefore stamping-out alone is the preferred option in the former and stamping-out in conjunction with emergency vaccination in the latter. While the strategic use of emergency vaccination should in theory help to dampen an outbreak and thus lessen its magnitude, this does not seem to be the case in region 1. Because a larger radius (around all IP's and DCP's) is taken into account when modelling the use of emergency vaccination, it is not surprising that more are culled in this high-density area; however the hypothesis that vaccination would lead to fewer occurrences of the disease and hence less destruction does not seem to be the case, with the destruction of, on average 118 more herds.

In region 3 (Laois, Offaly), another high herd density region the average length of outbreak was found to be 45 days in both cases. However, a cost-saving of €2.63m was made when SOEV was applied. 27 fewer herds were destroyed when SOEV was applied. In this high-density region (unlike the previous high-density one), a campaign of SOEV would appear to be more cost-effective (in terms of control) than one of SO alone. There

was no difference in the duration of the outbreak here. As to why SOEV was found to be marginally more suitable in this high-density region as opposed to the previous one; a point to note here is that there are relatively fewer sheep than cattle in this region (165,539 as compared to 434,576) than in region 1 (694,420 sheep, 673,677 cattle) and perhaps this has some implications in terms of disease spread (with clinical signs being generally more noticeable at an earlier stage with cattle).

In the final high-density region (Region 4 – Cavan) SO was again found to be the more cost-effective option both with and without the pig population being taken into account. The very high costs associated with slaughter when pigs are added should be noted – around 20% of herds were slaughtered in this case. Cost-savings of €27m were made in both the ‘without pigs’ and ‘with pigs’ scenarios when SO was used. Before taking pigs into account in comparing SO and SOEV, 374 more herds were destroyed when SOEV was adopted and the outbreak was found to increase by eight days (up from 66 days with SO only to 74 days with SOEV). Costs were found to increase from €64m to €91m respectively. With pigs, 262 more herds were destroyed when SOEV was applied and the average length of outbreak was found to be seven days longer at 107 days. Control costs were found to be €188m and €215m when SO and SOEV were compared when pigs were taken into account.

4. Conclusion

In terms of a general conclusion, holding constant all modelling parameters, stamping-out alone was found to be more cost-effective in two out of the three high-density regions examined here and stamping-out in conjunction with emergency vaccination was preferred otherwise. Overall, this underlines the fact that there is no common ‘best’ policy in terms of FMD control in the face of an outbreak – differences across regions in terms of area size and structural differences in the composition of herds indicate that any decision taken in determining the most appropriate control strategy must be taken at a regional level. It should be noted that direct costs (of control) only have been taken into account in this analysis and exploring and the indirect economic effects of adopting either strategy may point to a different overall conclusion.¹⁸

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¹⁸ The analysis is further extended to include an overview of the wider economic costs of control in a forthcoming publication.

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Appendix A

Criteria for the decision to apply protective vaccination* (Annex X)

Criteria	Decision	
	For vaccination	Against vaccination
Population density of susceptible animals	High	Low
Predominant species clinically affected	Pigs	Ruminants
Movement of potentially infected animals or products out of the protection zone	Evidence	No evidence
Predicted airborne spread of virus from infected holdings	High	Low or absent
Suitable vaccine	Available	Not available
Origin of outbreaks (tractability)	Unknown	Known
Incidence slope of outbreaks	Rising rapidly	Shallow or slow rise
Distribution of outbreaks	Widespread	Restricted
Public reaction to total stamping out policy	Strong	Weak
Acceptance of regionalisation after vaccination	Yes	No

* = In accordance with the report of the Scientific Committee on Animal Health 1999

Additional criteria for the decision to introduce emergency vaccination

Criteria	Decision	
	For vaccination	Against vaccination
Acceptance of regionalisation by third countries	Known	Unknown
Economic assessment of competing control strategies	If it is foreseeable that a control strategy without emergency vaccination would lead to significantly higher economic losses in the agricultural and non agricultural sectors	If it is foreseeable that a control strategy with emergency vaccination would lead to significantly higher economic losses in the agricultural and non agricultural sectors
It is foreseeable that the 24/48 hours rule cannot be implemented effectively for two consecutive days ⁽¹⁾	Yes	No
Significant social and psychological impact of total stamping out policy	Yes	No
Existence of large holdings of intensive livestock production	Yes	No

(1) 24/48 hours rule means: (a) Infected herds on holdings referred to in Article 10 cannot be stamped out within 24 hours after the confirmation of the disease, and (b) The pre-emptive killing of animals likely to be infected or contaminated cannot be safely carried out within less than 48 hours.