Vaccination against Foot-and-Mouth Disease

Differentiating strategies and their epidemiological and economic consequences

Wageningen UR

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Jantien Backer	Central Veterinary Institute (CVI) of Wageningen UR
Ron Bergevoet	LEI Wageningen UR
Thomas Hagenaars	Central Veterinary Institute (CVI) of Wageningen UR
Nico Bondt	LEI Wageningen UR
Gonnie Nodelijk	Central Veterinary Institute (CVI) of Wageningen UR
Coen van Wagenberg	LEI Wageningen UR
Herman van Roermund	Central Veterinary Institute (CVI) of Wageningen UR

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Backer, J., R. Bergevoet, Th. Hagenaars, N. Bondt, G. Nodelijk,
C. van Wagenberg and H. van Roermund

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The effectiveness of different control strategies against Foot-and-Mouth Disease (FMD) were investigated using epidemiological and economic models. A quick and large-scale vaccination within a radius of at least 2km is as effective as preemptive 1-km ring culling to mitigate FMD epidemics. Control measures should primarily target cattle farms. After the epidemic, most seropositive animals are expected on sheep farms and vaccinated cattle farms. An effective end-screening strategy should focus on these farms. Market acceptance by trade partners of products of vaccinated animals can limit the economic consequences of outbreaks of FMD.

De effectiviteit van bestrijdingstrategieën tegen Mond-en-Klauwzeer (MKZ) is onderzocht met behulp van epidemiologische en economische modellen. Het blijkt dat snelle en op grote schaal toegepaste vaccinatie in een straal van 2 km rond geïnfecteerde bedrijven net zo effectief is als ruimen in een straal van 1 km rond geïnfecteerde bedrijven bij het bestrijden van MKZ-uitbraken. Controlemaatregelen moeten vooral worden gericht op rundveebedrijven. Na de epidemie zijn de meeste seropositieve dieren te verwachten. De eindscreening zal zich op schapenbedrijven en gevaccineerde rundveebedrijven moeten richten. Acceptatie door internationale handelspartners van producten van gevaccineerde dieren kan de economische gevolgen van een uitbraak van MKZ beperken.

Orders
+31.70-3358330
publicatie.lei@wur.nl

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Preface

Outbreaks of contagious animal disease have detrimental effects on the Dutch livestock sector as well as on Dutch society as a whole. In future outbreaks vaccination can be part of the control strategies. This has consequences for the system of diagnostics and sampling. Different control strategies differ in their epidemiological effects and have different economic consequences.

For the Dutch Ministry of Agriculture, Nature and Food Quality (LNV) this was reason to ask Wageningen UR to investigate the consequences of control strategies for epidemic contagious diseases. In 2007 the work on Classical Swine Fever was finished. This report shows the results of the research on Foot-and-Mouth Disease (FMD).

This report is the result of a close cooperation between two institutes of Wageningen UR: CVI and LEI. It shows that an effective multi-disciplinary approach can lead to better insights into complex problems.

We hope that the results of the research towards the epidemiological and economic consequences of different control and eradication strategies presented in this report can assist policy makers in choosing the optimal strategy in case of an outbreak of FMD.

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Andre Biachi	Prof.Dr R.B.M. Huirne
Director CVI	Director General LEI Wageningen UR

Summary

Outbreaks of Foot-and-Mouth Disease (FMD) in the Netherlands represent a major risk to the Dutch farming industry, as around 17 million cattle, pigs and sheep can be infected by the virus. In many countries around the world FMD is still endemic. This means that there is a continuous but low risk of introduction of the virus in the Netherlands. As previous outbreaks of FMD have shown, an FMD epidemic affects a substantial part of the Dutch farming industry, resulting in large economic losses and a major impact on animal welfare. Whereas in the past outbreaks of epidemic diseases in livestock were mainly of interest for the agri-business, now it involves the Dutch society as a whole. There is serious concern within the general public about the massive culling of animals in general and the culling of small ruminants that are kept as pets in particular.

In case of an outbreak the responsible authorities must act in a quick and adequate way. This task has recently become more complicated given the different and sometimes contradictory objectives from (international) society and the agricultural sector. To control an ensuing epidemic as quickly as possible, emergency vaccination is preferred in the Netherlands to preemptive culling (see Dutch contingency plan FMD, 2005). However, several concerns still exist. For instance, there is the question whether vaccination is as effective in controlling the epidemic as preemptive ring culling, because vaccinated animals are not instantaneously protected against infection. Another concern is that vaccination increases sub-clinical infections. These sub-clinically infected animals could escape clinical detection during the outbreak and need to be detected serologically in the end screening. If they also escape the end screening, they could pose a risk to a new outbreak and to the export of livestock and meat products from the Netherlands (if detected later). Finally there is concern about the cost-effectiveness and impact on animal welfare of these control strategies.

Problem definition

Since vaccination against FMD in case of an outbreak in which the animals are not culled after vaccination is relatively new for the Dutch situation insight is needed into the epidemiological and economic consequences of such a strategy.

Research questions

To evaluate the effectiveness of control strategies different control strategies were evaluated. Therefore the following questions were addressed:

1. What is the optimal control strategy in case of an outbreak of FMD from an epidemiological and economic perspective? Evaluated are the control strategy as required by the EU, culling within a 1-km ring, and vaccination within 2-km or 5-km rings around detected farms.
2. What are the consequences of alternative strategies?
   a. excluding pigs from vaccination;
   b. excluding animals on hobby farms from preemptive culling.
3. What are the consequences for screening and declaring freedom of infection when different control strategies that include vaccination are applied?
4. What is the distribution of costs between animal species and cost types?
5. What is the lost value of products of vaccinated animals?

Epidemiology of Foot-and-Mouth Disease

The project group has evaluated the effectiveness and safety of vaccination strategies in controlling an FMD epidemic, taking into account the differences between animal species and farm sectors. For this purpose a mathematical model was developed that describes the within-herd and between-herd dynamics at two distinct levels. Results of transmission experiments and data of the FMD outbreak that occurred in the Netherlands in 2001 (virus strain O/Net/2001) served to estimate the model parameters. The model has been applied to the farm density situation of 2006, involving 36,000 cattle farms, 18,000 sheep farms, 9,000 pig farms and 20,000 hobby farms (i.e. small sheep flocks held for recreational purposes). Location coordinates and number of animals of each of these farms has been taken into account. Differences in epidemiology between commercial herd/flock types of the same animal species have not been taken into account. This model was used to calculate the outbreak size and duration for hypothetical epidemics of FMD and to predict the number of infected farms and animals that escape clinical detection. Introduction of the virus was situated in different areas of the Netherlands on a cattle or pig farm. The results were used as input for a model that describes the serological testing in the end screening. Depending on the diagnostic test characteristics and the chosen end-screening strategy, it predicts the number of seropositive animals (i.e. infected but not infectious animals with a detectable anti-body response) that will remain when the country has been declared free of infection.

Model discussion
Models are frequently used to calculate the consequences of different control-strategy scenarios. They are based upon the most recent scientific insights into the spread of the disease and the effects of control strategies. Because the Netherlands only suffered incidental outbreaks of FMD, not all the required data for the used model were available. The input data are therefore partly based on reasoned assumptions. These models contain the most recent scientific insights into the spread of the disease and the effects of control strategies. However, some input data for the current situation in the Netherlands were not available, because the Netherlands only suffered incidental epidemics of FMD. These input data were based on reasoned assumptions. Furthermore, some input data (like the between-herd transmission) were only available for virus strain O/NET/2001. The overall results as shown in table 1.C should thus be seen as the best possible estimates of the effects of different control strategies, given these practical limitations. The resulting insight provides a basis for the discussion about the optimal control strategy for FMD in the Netherlands.

Control strategies
Several control strategies have been evaluated by simulating 1,000 hypothetical epidemics for each strategy. Table 1.A summarises the results of three control strategies, when the epidemic starts on a cattle farm in the Gelderse Vallei (i.e. a cattle- and pig-dense area of about 4 farms/km^2) and 10 farms have been infected by the source herd.

Freedom of infection
Before the country can be declared free of infection, the EU requires all animals on all vaccinated farms to be serologically tested, as well as samples of sheep on unvaccinated farms. Table 1.B summarises the results for this end-screening strategy for three basic control strategies (for epidemics that started on a cattle farm in the Gelderse Vallei).

Economic consequences of different control strategies
The different strategies were also evaluated from an economic perspective. To evaluate the economic consequences of the different control and eradication strategies a Partial Budget model was developed. In such a model only the costs and benefits that differ between the evaluated alternatives are included. The results of the calculations are summarised in table 1.C. The calculated costs of the evaluated strategies were lower than the reported costs of the last epidemic in the Netherlands, which only involved 26 detected farms. This is be-

cause the Partial Budget method used in this study only takes into account the costs that differ between the control strategies. For example, costs related to tourism and those that depend on an epidemic per se, irrespective of the control strategy, were not included in the costs calculated in this study.

It is difficult to predict the effect of a specific FMD introduction in the Netherlands. Chance plays an important role at the start and during an epidemic. In the epidemiological model probability is used to model this. Due to chance there is a wide variety of possible outcomes. Using multiple model runs provides insight into this variation. It is assumed that an actual epidemic (with a comparable virus strain) will fall within the simulated variation.

Table 1.A Results for different control strategies of epidemics that started in the Gelderse Vallei on a cattle farm: median values (between brackets 5%-95% interval)

Control strategy	Duration (days)		# Detected farms		# Preemptively culled farms		# Vaccinated farms	
minimal (EU) a)	259	(181-390)	1,640	(1,126-2,145)	0	(0-0)	0	(0-0)
1-km ring culling	67	(30-124)	45	(17-97)	974	(342-1,870)	0	(0-0)
2-km ring vaccination	76	(41-133)	72	(23-162)	165	(76-300)	2416	(706-4,400)
2-km vacc. except pig farms	85	(40-152)	85	(23-215)	165	(76-300)	2159	(574-4,624)
5-km ring vaccination	52	(34-91)	43	(19-89)	165	(76-300)	4,065	(1,935-7,469)
5-km vacc. except pig farms	55	(33-106)	45	(19-105)	165	(76-300)	3,509	(1,542-7,516)

a) The minimal control strategy as required by the EU: culling of detected infected herds, tracing of their dangerous contacts and regulation of transport.

Table 1.B Results for end screening as required by the EU for different control strategies: median values (between brackets 5%-95% interval)

Control strategy	# Farms tested		# Farms tested positive a)		# Seropositive animals before end screening		# Seropositive animals after end screening	
minimal (EU)	19,880	(16,101-22,759)	110	(68-149)	767	(466-1,090)	62	(33-94)
1-km ring culling	2,479	(1,028-4,916)	1.9	(0.3-5.8)	8	(0-42)	1.0	(0.0-9.2)
2-km ring vaccination	5,463	(2,122-10,420)	15.6	(2.6-42.9)	50	(7-148)	3.5	(0.3-14.8)
2-km vacc. except pig farms	5,520	(1,940-12,300)	17.9	(2.8-50.7)	58	(6-180)	4.7	(0.3-20.3)
5-km ring vaccination	5,973	(2,994-10,967)	12.7	(3.8-33.5)	35	(6-99)	2.1	(0.3-9.4)
5-km vacc. except pig farms	5,403	(2,478-11,669)	13.3	(3.3-37.1)	36	(5-109)	2.3	(0.3-11.0)

a) Both true and false positive farms.

Table 1.C **Summary table with the total costs of the different strategies**

	Number of culled farms			Last week of detection			Total cost in million €		
	percentile			percentile			percentile		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
Friesland start in cattle farm									
1-km ring culling	*56*	2	295	*3*	1	8	*61*	48	109
2-km ring vaccination	*30*	2	117	*3*	1	8	*61*	48	108
5-km ring vaccination	*30*	2	113	*3*	1	6	*65*	48	121
Gelderse Vallei start in cattle farm									
1-km ring culling	*971*	206	3,217	*9*	4	15	*236*	94	615
1-km ring culling except hobby animals	*821*	169	2,662	*9*	4	15	*229*	93	600
2-km ring vaccination	*260*	70	707	*10*	5	17	*227*	99	526
2-km vacc. except pig farms	*268*	71	791	*11*	5	20	*220*	95	571
2-km ring vaccination (no culling of hobby animals)	*236*	63	643	*10*	5	17	*230*	98	525
5-km ring vaccination	*230*	68	571	*6*	4	11	*228*	106	504
5-km vacc. except pig farms	*234*	68	598	*7*	4	13	*197*	98	467
5-km ring vaccination (no culling of hobby animals)	*206*	61	509	*6*	4	11	*230*	109	502

Table 1.C **Summary table with the total costs of the different strategies (continued)**

	Number of culled farms			Last week of detection			Total cost in million €		
	percentile			percentile			percentile		
	50%	5%	95%	50%	5%	95%	50%	5%	95%
Oost-Nederland start in cattle farm									
1-km ring culling	*393*	84	1,595	*6*	3	13	*110*	67	327
1-km ring culling except hobby animals	*319*	68	1,281	*6*	3	13	*110*	67	309
2-km ring vaccination	*136*	36	469	*7*	3	16	*119*	62	315
2-km vacc. except pig farms	*136*	36	473	*7*	3	16	*106*	60	239
2-km ring vaccination (no culling of hobby animals)	*116*	31	424	*7*	3	16	*119*	62	319
5-km ring vaccination	*132*	36	407	*6*	3	10	*146*	69	355
5-km vacc. except pig farms	*131*	37	406	*5*	3	10	*128*	68	271
5-km ring vaccination (no culling of hobby animals)	*112*	31	360	*6*	3	11	*146*	69	361

Table 1.C **Summary table with the total costs of the different strategies (continued)**

	Number of culled farms			Last week of detection			Total cost in million €		
	percentile			percentile			percentile		
	50%	5%	95%	50%	5%	95%	50%	5%	95%
Gelderse Vallei start in pig farm									
1-km ring culling	*1,656*	495	3,980	*9*	5	15	*334*	140	728
1-km ring culling except hobby animals	*1,383*	419	3,280	*9*	5	15	*331*	138	712
2-km ring vaccination	*506*	170	1,109	*10*	6	16	*302*	141	597
2-km vacc. except pig farms	*516*	170	1,175	*11*	6	19	*287*	132	615
2-km ring vaccination (no culling of hobby animals)	*455*	148	997	*10*	6	16	*305*	140	603
5-km ring vaccination	*464*	163	970	*7*	4	11	*325*	154	653
5-km vacc. except pig farms	*467*	163	998	*7*	5	13	*276*	138	586
5-km ring vaccination (no culling of hobby animals)	*409*	143	861	*7*	5	11	*323*	160	647

Table 1.C Summary table with the total costs of the different strategies (continued)

	Number of culled farms			**Last week of detection**			**Total cost in million €**		
	percentile			**percentile**			**percentile**		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
Noord-Brabant start in Pig farm									
1-km ring culling	*579*	166	2,030	*7*	4	14	*185*	98	483
1-km ring culling except hobby animals	*462*	132	1,704	*7*	4	15	*187*	97	497
2-km ring vaccination	*180*	61	499	*7*	4	16	*169*	95	452
2-km vacc. except pig farms	*181*	61	538	*7*	4	18	*150*	89	439
2-km ring vaccination (no culling of hobby animals)	*153*	53	450	*8*	4	16	*177*	94	462
5-km ring vaccination	*174*	60	415	*6*	3	10	*222*	108	505
5-km vacc. except pig farms	*173*	61	424	*6*	4	12	*171*	98	395
5-km ring vaccination (no culling of hobby animals)	*144*	52	355	*6*	3	11	*222*	109	514

Interpretation of the economic results

Interpretation of the economic results depends on the risk attitude of the decision maker. A risk-neutral decision maker is assumed to choose a strategy that on average has the lowest costs. A risk-averse decision maker is assumed to base the decision on minimising the chance of unpleasant outcomes.

To support the risk-neutral decision maker we present the 50% percentile of the costs. This means that 50% of the simulated epidemics have calculated costs that are less than or equal to the presented number. For the risk-avoiding decision maker the 95% percentile of the costs may be the better choice. This means that 95% of the simulated epidemics have calculated costs that are less than or equal to the presented number. Only in 5% of the simulated outcomes arethe costs higher. To represent the costs in a 'best case scenario' the 5% percentile of the costs were selected.

A specific feature of the used simulation method is that the decision maker is supposed to stick to the strategy on which he decided at the start of the epidemic. In reality, a process of monitoring and adapting the control strategy based on a series of decisions is more likely to occur. Or, as Ge (2008) puts it: 'The epidemic can only be understood backwards, but it must be controlled forward.'

The economic results suggest that several control measures themselves incur high costs. For example, vaccinating in a 5-km ring around a detected farm results in high numbers of vaccinated animals and large amounts of products of vaccinated animals that have to be processed separately. A decision maker can decide on a control strategy with relatively cheap measures at the start of an epidemic and additional, more costly measures during the epidemic to prevent an explosion. This can result in a more cost efficient control than a massive response at the start of an epidemic.

This means that measures which have an irreversible effect and a big impact, e.g. culling or vaccinating a large number of animals, should be taken cautiously but timely. To enable such dynamic decisions, it should be clear what information is needed at what moment in the decision process. This information need should of course be met with adequate data collection. Furthermore, control measures should be implemented in a 'smart' way. For example, when it is decided to vaccinate one could start with a 2-km circle and only expand this circle to a 5-km ring when needed.

Ripple and spill-over effects

In addition to the direct costs of the epidemic for farmers, ripple and spill-over effects are likely to occur. Ripple effects are the effects of an epidemic that are felt up- and downstream along the livestock value chain: breeding, feed production, input supply, slaughter, processing, final sale and consumption. For example, the stand-still measures in infected compartments prevent the slaughter of animals for at least six weeks. This can seriously affect the supply of slaughterhouses, especially when multiple compartments are affected. In previous epidemics of FMD in the Netherlands this caused a temporary production stop in slaughterhouses. This problem is especially prevalent for veal calves. For the pig industry it might be a somewhat different picture, because currently large numbers of slaughter pigs are exported alive. In case of an epidemic live export of slaughter animals will not be possible. The additional supply of pigs that now have to be slaughtered within the Netherlands might compensate the stagnating supply from infected compartments.

Due to an epidemic the market access for products of susceptible species is seriously restricted. An epidemic of FMD will result in trade restrictions that are related to the epidemic per se and do not depend on the specific characteristics of the chosen control strategy. After the last detection it takes time to remove all the restrictions in trade and the situation regarding export of animals and products is back to what it was before the epidemic. An epidemic of FMD can have serious consequences, especially for the Dutch pig sector, because of the export of large numbers of live pigs. These pigs must then be sold in the Netherlands. It can therefore be expected that prices in the areas affected by restrictions will fall.

Spill-over effects are the effects of an epidemic of FMD on non-agricultural sectors such as tourism and other services. Because non-agricultural production is increasingly important for the rural economy, spill-over effects are likely to have an increasing effect on the total costs of an epidemic. In the last outbreak of FMD in the Netherlands in 2001 the costs for the tourist sector alone were estimated at €275m.

Conclusions regarding control strategies

- Additional measures such as preemptive culling or vaccination are necessary to control the epidemic in densely populated livestock areas (DPLA) (>3 farms per km^2) such as in Gelderse Vallei and Noord-Brabant, whereas in sparsely populated livestock areas (SPLA) (of about 2 farms per km^2), such as in Friesland, the minimal (EU) control strategy is sufficient.

- In densely populated livestock areas 2-km ring vaccination is much more effective than the minimal strategy required by the EU, but less effective than 1-km ring culling in terms of epidemic size and duration.
- In densely populated livestock areas 5-km ring vaccination and 1-km ring culling are equally effective (when vaccination capacity is not limiting).
- In the first stages of controlling the epidemic, the required culling capacity is 18 (0-83) farms per day for the 1-km ring culling strategy. The required vaccination capacity is 53 (0-237) farms per day for the 2-km vaccination strategy and 149 (0-800) farms per day for the 5-km vaccination strategy.
- At least 75% of the infected farms are cattle farms, even in pig-dense areas, regardless of the control strategy.
- Excluding hobby farms (here small sheep flocks of 10 animals, physically separated from commercial farms) from preemptive culling has a negligible effect on epidemic control. In the ring culling strategy, it reduces the number of farms to be culled by 20% (and the number of animals to be culled by 3%).
- Excluding pig farms from vaccination causes a significant but limited increase of both epidemic size and duration (for the virus strain under study). The number of animals to be vaccinated is more than halved. Whether this strategy is economically beneficial despite the increased risk, is evaluated in the economic analysis.
- A fraction of the infected farms remains undetected during the epidemic (around 9% for the minimal strategy and around 5% for the culling strategy), consisting mainly of unvaccinated sheep farms. This percentage is between 11 and 20 for vaccination strategies, involving mainly vaccinated cattle and sheep farms.

Conclusions regarding end screening

- In non-vaccination strategies 1,000-5,000 farms need to be tested in the end screening, while vaccination strategies require twice as many farms (2,000-11,000) to be tested.
- About half of the tested farms must be retested to exclude or confirm infection (because of false positive test results).
- Before the end screening, vaccination yields approximately 5 times as many seropositive animals as ring culling (seropositive for non structural FMD proteins, as detected by an NS Elisa).
- After the end-screening according to the EU legislation, the number of seropositive animals is similar for 1-km ring culling and 5-km ring vaccination, and slightly higher for 2-km ring vaccination. The average numbers of sero-

positive animals vary between 1.0 and 3.5. If these numbers of seropositive animals are considered to represent an acceptable risk, emergency vaccination would be a safe alternative to preemptive culling.

- Compared to the screening required by the EU, screening strategies in which more effort is placed on unvaccinated cattle and pig farms (testing a sample instead of none), do not improve the detection of seropositive animals, so implementation of this alternative end-screening strategy does not add value.
- Compared to the screening required by the EU, screening strategies in which less effort is placed on vaccinated pig farms (testing a sample instead of all), do not worsen the detection of seropositive animals, so this alternative end screening can be safely implemented.

Conclusions regarding economic consequences

- What is the optimal strategy: culling, 2-km or 5-km vaccination? Culling strategy is the economically preferred strategy in SPLAs. Vaccination is the economically preferred strategy in DPLAs.
- In DPLAs with vey high densities of livestock vaccination within a radius of 5km around detected farms results in the lowest costs whereas in other DPLAs vaccination of 2km around detected farms results in the lowest costs.
- Alternative strategies: excluding pigs from vaccination and excluding animals on hobby farms from preventive culling.
  When vaccination is chosen as strategy in DPLA regions, excluding pigs from vaccination should be seriously considered since there is a relevant reduction in costs.
- Abolishing preventive culling of animals on hobby farms (i.e. small sheep flocks with less than 10 sheep held for recreational purposes) should seriously be considered. Preventive culling of animals on hobby farms does not attribute much to a faster elimination of the epidemic but contributes a lot to the negative perception of the public towards the needed interventions. Excluding animals on hobby farms from preventive culling does not substantially affect the costs of an epidemic but it improves the societal acceptance of the eradication strategies.

Distribution of costs

The dairy industry, veal calve industry and the pig industry all suffer a lot from an FMD epidemic. Although vaccination can limit the costs of an epidemic it also introduces the potential problem of reduced market access for products from vaccinated animals.

For the dairy industry a large part of the costs originate from the inability to create value from side products of the processing of milk from vaccinated cows.

For the veal calve industry the highest costs originate from animals getting older than eight months at slaughter during an epidemic, so that their meat cannot be sold as white veal.

For the pig industry the highest costs originate from the reduced market acceptance of animals and their products from infected compartments by (international) trade partners.

Value loss due to vaccination

Market acceptance by the trade partners of products originating from vaccinated animals might cushion the economic effects of an epidemic. An integrated effort of the government and the livestock industry to limit the consequences of an epidemic of FMD to inform the trade partners about the Dutch approach to fight the disease is needed.

A coordinated action between the relevant stakeholders during an epidemic can reduce the value loss of milk from vaccinated dairy cows. Logistic cooperation between dairy companies can reduce the logistic costs and limit the number of locations where the milk from vaccinated animals has to be processed. Consultations need to be initiated with the trade partners on the market acceptance of products from vaccinated animals.

Insight into ways to reduce the value loss of products of vaccinated animals with a focus on cattle (dairy products and veal calves) is needed to decrease the potential costs of a vaccination strategy to eradicate a FMD epidemic.

In conclusion, vaccination is as effective as preemptive 1-km ring culling to mitigate FMD epidemics, provided it can be applied quickly and on a large scale, especially in densely populated livestock areas. Control measures should primarily target cattle farms, as these seem to play the largest role in the epidemic (for the virus strain under study). After the epidemic, most seropositive animals are expected on sheep farms and vaccinated cattle farms. An effective end-screening strategy should focus on these farms. Market acceptance by trade partners of products of vaccinated animals can limit the economic consequences of outbreaks of FMD.

Samenvatting

Vaccinatie tegen mond- en klauwzeer; Verschillende strategieën en hun epidemiologische en economische gevolgen

Uitbraken van Mond-en-Klauwzeer (MKZ) in Nederland zijn een bedreiging voor de Nederlandse veehouderij: ongeveer 17 miljoen koeien, varkens en schapen kunnen mogelijk worden geïnfecteerd met het virus. MKZ komt nog steeds endemisch voor in veel landen. Dit betekent dat er een continu maar klein risico is op de introductie van het virus in Nederland. Zoals voorgaande uitbraken van MKZ hebben laten zien, heeft een uitbraak voor de Nederlandse veehouderij grote gevolgen. Er zijn grote economische verliezen en grote gevolgen voor het dierenwelzijn. Was in het verleden een uitbraak van MKZ iets wat vooral van belang was voor de agrarische sector, nu wordt de gehele samenleving er door getroffen. Er is weerstand tegen het massale doden van dieren in het algemeen en het doden van kleine herhauwers die als huisdier worden gehouden in het bijzonder.

In het geval van een uitbraak wordt van de verantwoordelijke autoriteiten verwacht dat ze snel en adequaat handelen. Deze taak is er niet eenvoudiger op geworden in het licht van de soms tegenstrijdige belangen van de (internationale) samenleving en de agrarische sector. Bij de bestrijding van een uitbraak van MKZ heeft noodvaccinatie de voorkeur boven preventief ruimen (zie Beleidsdraaiboek MKZ 2005). Maar er blijven nog zorgen. Bijvoorbeeld de vraag of vaccinatie net zo effectief is bij het onder controle brengen van de epidemie als preventief ruimen; gevaccineerde dieren zijn immers niet onmiddellijk beschermd tegen infecties. Een andere zorg is dat vaccinatie mogelijk leidt tot subklinische infecties. Deze subklinisch geïnfecteerde dieren worden mogelijk niet opgemerkt bij klinische inspecties en moeten worden opgespoord met serologisch onderzoek bij de eindscreening. Als ze dan ook niet worden opgemerkt zouden ze mogelijk een risico vormen voor een nieuwe uitbraak of voor de export van dieren en hun producten (als ze later alsnog worden opgespoord). Als laatste is de kosteneffectiviteit en de invloed op dieren welzijn van belang.

Probleemstelling
Er is meer inzicht nodig in de epidemiologische en economische gevolgen van een aanpak waarbij vaccinatie tegen MKZ als bestrijdingstrategie wordt ingezet waarbij de dieren na de gevaccineerde dieren niet na de uitbraak alsnog geruimd worden. Dit omdat een dergelijke aanpak relatief nieuw is voor de Nederlandse situatie.

Onderzoeksvragen
Om meer inzicht te krijgen in de effectiviteit van de verschillende controlestrategieën tegen Mond-en-Klauwzeer zijn de volgende onderzoeksvragen gesteld:

1. Wat is de optimale controlestrategie in geval van een uitbraak van Mond-en-Klauwzeer? Hiervoor zijn conrolestrategieën waarbij gevaccineerd is in 2 of 5 km rond geïnfecteerde bedrijven vergeleken met de (minimale) EU-strategie of met ruimen in 1 km rond geïnfecteerde bedrijven.
2. Wat zijn de gevolgen van alternatieve controlestrategieën? Hiervoor zijn per vaccinatiestrategie de gevolgen van 2 alternatieve scenario's berekend:
   a. als tijdens de vaccinatiestrategie de varkensbedrijven niet worden gevaccineerd;
   b. als op de hobbybedrijven ruiming achterwege wordt gelaten.
3. Wat zijn de gevolgen voor screening en vrijverklaren van infectie bij verschillende vaccinatiestrategieën?
4. Wat is de verdeling van de kosten tussen de verschillende diersoorten en de omvang van deze kosten?
5. Wat is het waardeverlies van de producten van gevaccineerde dieren?

De epidemiologisch en economische gevolgen zijn beoordeeld aan de hand van modelberekeningen.

Epidemiologisch gevolgen van Mond-en-Klauwzeer
De effectiviteit en veiligheid van vaccinatiestrategieën voor de controle van een MKZ-epidemie zijn onderzocht. Hierbij is met verschillen tussen diersoorten en veehouderijsectoren rekening gehouden. Een wiskundig model is ontwikkeld dat MKZ-besmettingen binnen bedrijven en tussen bedrijven in kaart brengt. Hierbij is gebruik gemaakt van de gegevens die afkomstig zijn van recente experimenten en uitbraken in Nederland in 2001 (virus strain O/Net/2001). In het model is gebruik gemaakt van de bedrijfsgegevens van 2006, waarbij locatie en bedrijfsomvanggegevens van 36.000 rundvee-, 18.000 schapen- en 9.000 varkensbedrijven zijn opgenomen evenals 20.000 hobbybedrijven (schapenbedrijven van beperkte omvang die voor recreatie worden gehouden). Het model houdt geen

rekening met eventuele verschillen in epidemiologie binnen een bepaalde diersoort of een bepaald bedrijfstype. Het model is gebruikt om de omvang (aantal geïnfecteerde bedrijven) en de duur van een hypothetische uitbraak te berekenen. Ook berekent het model het aantal geïnfecteerde bedrijven en dieren die aan klinische inspectie ontsnappen. De hypothetische uitbraken in het model zijn gestart door introductie van het MKZ-virus op verschillende typen bedrijven in verschillende regio's in Nederland. De resultaten van de uitbraaksimulatie zijn gebruikt in een model dat de serologische testen en eindscreening modelleert. Afhankelijk van testeigenschappen en de gekozen eindscreeningsstrategie wordt het aantal seropositieve dieren voorspeld (geïnfecteerd maar niet infectieus met een waarneembare antilichaamrespons) die aanwezig blijven op het moment dat Nederland weer officieel is vrijverklaard na de uitbraak.

Modeldiscussie
Modellen worden vaak gebruikt om de gevolgen van bestrijdingstrategieën te berekenen. Zij zijn gebaseerd op de meest recente inzichten in de spreiding van de ziekte en de effecten van controlestrategieën. Omdat Nederland gelukkig maar incidenteel te maken heeft met uitbraken van MKZ zijn niet alle benodigde data voor het model op grond van gegevens van recente uitbraken beschikbaar. Hierdoor zijn de inputdata gedeeltelijk gebaseerd op beredeneerde aannames. Bovendien waren de data die beschikbar zijn over de transmissie alleen beschikbaar voor de virusstam O/NET/2001. De resultaten zoals weergegeven in tabel 1.A moeten daarom worden gezien als beste mogelijke schattingen binnen de gegeven beperkingen. De inzichten op basis van de modelberekeningen kunnen wel de basis vormen voor de optimale controlestrategie in Nederland.

Controlestrategieën
Verschillende mogelijke controlestrategieën zijn geëvalueerd door 1.000 hypothetische epidemieën te simuleren voor iedere onderzochte controlestrategie. Uitbraken met start in Friesland (start rundvee), Gelderse Vallei (start of rundvee of varkens), Oost-Nederland (start rundvee) of Noord-Brabant (start varkens) zijn gemodelleerd. Tabel 1.A vat de resultaten van drie controlestrategieën, die beginnen op een rundvee bedrijf in de Gelderse Vallei samen. De Gelderse Vallei is een rundvee en varkensdicht gebied met ongeveer 4 bedrijven per km^2 waarbij het eerste bedrijf al 10 bedrijven heeft besmet voordat de infectie wordt opgemerkt.

Vrij zijn van infectie
Voordat een land vrij van infectie verklaard kan worden verlangt de EU dat alle dieren op alle gevaccineerde bedrijven serologisch getest worden. Bovendien moeten steekproefsgewijs schapen op ongevaccineerde bedrijven getest worden. Tabel 1.B vat de resultaten van deze eindscreening van drie controle-strategieën, die beginnen op een rundveebedrijf in de Gelderse Vallei samen.
Economische gevolgen van verschillende controlestrategieën
Naast epidemiologisch zijn de verschillende strategieën ook gevaluteerd vanuit een economisch perspectief. Hiervoor is een Partial Budget-model gemaakt. In zo'n model worden alleen de kosten en baten die verschillen tussen de verschillende alternatieven meegenomen. De berekende kosten zijn samengevat in tabel 1.C.

De gecalculeerde kosten van de onderzochte strategieën zijn lager dan de kosten van de laatste uitbraak in 2001, die slechts 26 gedetecteerde bedrijven betrof. De reden is dat de kosten die voor alle strategieën gelijk blijven (bijvoorbeeld kosten voor toerisme en die kosten die te maken hebben met een uitbraak) per se onafhankelijk van de toegepaste bestrijdingsstrategie in de berekende kosten in deze studie *niet* zijn meegenomen. Het is moeilijk de gevolgen van een uitbraak in Nederland te voorspellen, toeval speelt een belangrijke rol bij het begin van een epidemie. In het epidemiologische model is gebruik gemaakt van kansen om dit te modelleren. Door deze kansen ontstaat een grote variatie in mogelijke uitkomsten. Door het model vele malen te laten rekenen kan er inzicht in deze variatie worden gekregen. We nemen aan dat uitkomst van een eventuele echte uitbraak (met een vergelijkbare virusstam) binnen deze berekende variatie valt.

Tabel 1.A **Resultaten voor verschillende controlestrategieën voor MKZ-uitbraken die beginnen in de Gelderse Vallei op een rundveebedrijf: mediaan (met tussen haakjes het 5%- en 95%-interval)**

Controlestrategie	Duur (dagen)		# Opgespoorde bedrijven		# Preventief geruimde bedrijven		# Gevaccineerde bedrijven	
minimaal (EU)	259	(181-390)	1.640	(1.126-2.145)	0	(0-0)	0	(0-0)
1-km-ringruimen	67	(30-124)	45	(17-97)	974	(342-1.870)	0	(0-0)
2-km-ringvaccinatie	76	(41-133)	72	(23-162)	165	(76-300)	2416	(706-4.400)
2-km-vacc. excl. varkensbedrjiven	85	(40-152)	85	(23-215)	165	(76-300)	2159	(574-4.624)
5-km-ringvaccinatie	52	(34-91)	43	(19-89)	165	(76-300)	4065	(1.935-7.469)
5-km-vacc. excl. varkensbedrjiven	55	(33-106)	45	(19-105)	165	(76-300)	3509	(1.542-7.516)

a) The minimal control strategy zoals verplicht door de EU: ruimen van gedetecteerde bedrijven, traceren van gevaarlijke contacten en transportbeperkingen; b) In deze strategie worden varkensbedrijven niet gevaccineerd.

Tabel 1.B **Mode uitkomsten voor de eindscreening volgens EU-eisen voor verschillende controlestrategieën: mediaan (met tussen haakjes het 5%- en 95%-interval)**

Controlestrategie	# Bedrijven getest		# Bedrijven positief getest a)		# Seropositieve dieren voor de eindscreeening		# Seropositieve dieren na de eind-screening	
minimaal (EU)	19.880	(16.101-22.759)	110	(68-149)	767	(466-1.090)	62	(33-94)
1-km-ringruimen	2.479	(1.028-4.916)	1.9	(0,3-5,8)	8	(0-42)	1.0	(0,0-9,2)
2-km-ringvaccinatie	5.463	(2.122-10.420)	15.6	(2,6-42,9)	50	(7-148)	3.5	(0,3-14,8)
2-km-vacc. excl. varkensbedrjiven	5.520	(1.940-12.300)	17.9	(2,8-50,7)	58	(6-180)	4.7	(0,3-20,3)
5-km-ringvaccinatie	5.973	(2.994-10.967)	12.7	(3,8-33,5)	35	(6-99)	2.1	(0,3-9,4)
5-km-vacc. excl. varkensbedrjiven	5.403	(2.478-11.669)	13.3	(3,3-37,1)	36	(5-109)	2.3	(0,3-11,0)

a) Zowel werkelijk als vals positieve bedrijven.

Tabel 1.C **Samenvattende tabel met de totale kosten van de verschillende strategieën: mediaan (met het 5%- en 95%-interval)**

	Aantal geruimde bedrijven			**Laatste week van detectie**			**Totale kosten in mil. €**		
	percentiel			**percentiel**			**percentiel**		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
Friesland start in rundveebedrijf									
1-km-ringruimen	*56*	2	295	*3*	1	8	*61*	48	109
2-km-ringvaccinatie	*30*	2	117	*3*	1	8	*61*	48	108
5-km-ringvaccinatie	*30*	2	113	*3*	1	6	*65*	48	121
Gelderse Vallei start in rundveebedrijf									
1-km-ringruimen	*971*	206	3.217	*9*	4	15	*236*	94	615
1-km-ringruimen excl. hobbydieren	*821*	169	2.662	*9*	4	15	*229*	93	600
2-km-ringvaccinatie	*260*	70	707	*10*	5	17	*227*	99	526
2-km-vacc. excl. varkens	*268*	71	791	*11*	5	20	*220*	95	571
2-km-ringvaccinatie (geen ruimen van hobbydieren)	*236*	63	643	*10*	5	17	*230*	98	525
5-km-ringvaccinatie	*230*	68	571	*6*	4	11	*228*	106	504
5-km-vacc. excl. varkensbedrijven	*234*	68	598	*7*	4	13	*197*	98	467
5-km-ringvaccinatie (geen ruimen van hobbydieren)	*206*	61	509	*6*	4	11	*230*	109	502

Tabel 1.C **Samenvattende tabel met de totale kosten van de verschillende strategieën: mediaan (met het 5%- en 95%-interval) (vervolg)**

	Aantal geruimde bedrijven			Laatste week van detectie			Totale kosten in mil. €		
	percentiel			percentiel			percentiel		
	50%	5%	95%	50%	5%	95%	50%	5%	95%
Oost-Nederland start in rundveebedrijf									
1-km-ringruimen	*393*	84	1.595	*6*	3	13	*110*	67	327
1-km-ringruimen excl. hobbydieren	*319*	68	1.281	*6*	3	13	*110*	67	309
2-km-ringvaccinatie	*136*	36	469	*7*	3	16	*119*	62	315
2-km-vacc. excl. varkens	*136*	36	473	*7*	3	16	*106*	60	239
2-km-ringvaccinatie (geen ruimen van hobbydieren)	*116*	31	424	*7*	3	16	*119*	62	319
5-km-ringvaccinatie	*132*	36	407	*6*	3	10	*146*	69	355
5-km-vacc. excl. varkensbedrijven	*131*	37	406	*5*	3	10	*128*	68	271
5-km-ringvaccinatie (geen ruimen van hobbydieren)	*112*	31	360	*6*	3	11	*146*	69	361

Tabel 1.C **Samenvattende tabel met de totale kosten van de verschillende strategieën: mediaan (met het 5%- en 95%-interval) (vervolg)**

	Aantal geruimde bedrijven			Laatste week van detectie			Totale kosten in mil. €		
	percentiel			percentiel			percentiel		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
Gelderse Vallei start in varkensbedrijf									
1-km-ringruimen	*1.656*	495	3.980	*9*	5	15	*334*	140	728
1-km-ringruimen excl. hobbydieren	*1.383*	419	3.280	*9*	5	15	*331*	138	712
2-km-ringvaccinatie	*506*	170	1.109	*10*	6	16	*302*	141	597
2-km-vacc. excl. varkens	*516*	170	1.175	*11*	6	19	*287*	132	615
2-km-ringvaccinatie (geen ruimen van hobbydieren)	*455*	148	997	*10*	6	16	*305*	140	603
5-km-ringvaccinatie	*464*	163	970	*7*	4	11	*325*	154	653
5-km-vacc. excl. varkensbedrjven	*467*	163	998	*7*	5	13	*276*	138	586
5-km-ringvaccinatie (geen ruimen van hobbydieren)	*409*	143	861	*7*	5	11	*323*	160	647

Tabel 1.C **Samenvattende tabel met de totale kosten van de verschillende strategieën: mediaan (met het 5%- en 95%-interval) (vervolg)**

	Aantal geruimde bedrijven			**Laatste week van detectie**			**TOTALE kosten in mil. €**		
	percentiel			**percentiel**			**percentiel**		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
Noord-Brabant start in varkensbedrijf									
1-km-ringruimen	*579*	166	2.030	*7*	4	14	*185*	98	483
1-km-ringruimen excl. hobbydieren	*462*	132	1.704	*7*	4	15	*187*	97	497
2-km-ring vaccination	*180*	61	499	*7*	4	16	*169*	95	452
2-km-vacc. excl. varkens	*181*	61	538	*7*	4	18	*150*	89	439
2-km-ringvaccinatie (geen ruimen van hobbydieren)	*153*	53	450	*8*	4	16	*177*	94	462
5-km-ringvaccinatie	*174*	60	415	*6*	3	10	*222*	108	505
5-km-vacc. excl. varkensbedrijven	*173*	61	424	*6*	4	12	*171*	98	395
5-km-ringvaccinatie (geen ruimen van hobbydieren))	*144*	52	355	*6*	3	11	*222*	109	514

Interpretatie van de economische resultaten

De interpretatie van de economische resultaten is afhankelijk van de risicohouding van de beslisser. Een risiconeutrale beslisser wordt verondersteld die strategie te kiezen die gemiddeld de laagste kosten geeft. Een risicomijdende beslisser wordt verondersteld te kiezen voor die strategie die de kleinste kans op ongunstige uitkomsten geeft. Om de risiconeutrale beslisser te ondersteunen worden de 50% percentiel of mediane waarde gegeven. Dit betekent dat 50% van de modeluitkomsten lager dan of gelijk aan de gepresenteerde waarde zijn. Voor de risicomijdende beslisser zal de 95% percentiel mogelijk een betere keuze zijn. Vijfennegentig procent van de uitkomsten is lager dan of gelijk aan de gegeven waarde, in 5% van de gevallen zal de uitkomst hoger zijn. Om inzicht te krijgen in het geval van een 'best case scenario' zijn de 5% percentielwaarden gegeven.

Een specifiek kenmerk van de gebruikte simulatiemethodes is dat de beslisser wordt geacht tijdens de hele epidemie vast te houden aan de keuze die aan het begin van de epidemie is gemaakt. In werkelijkheid zal een proces van monitoring en aanpassen van de controlestrategie optreden.

De resultaten van de economische berekeningen suggereren dat het instellen van de bestrijdingsstrategie al met hoge kosten gepaard gaat. Bijvoorbeeld vaccineren in een ring van 5 km rond geïnfecteerde bedrijven resulteert in grote aantallen gevaccineerde dieren waarvan de producten apart verwerkt moeten worden. Een beslisser kan daarom besluiten om relatief goedkope maatregelen aan het begin te nemen en eventueel duurdere maatregelen later om een grote uitbreiding van de epidemie te voorkomen. Een dergelijke aanpak kan een meer kosteneffectieve aanpak tot gevolg hebben dan een massale respons aan het begin van de uitbraak. Dit betekent dat maatregelen die onomkeerbaar zijn en grotere gevolgen hebben (bijvoorbeeld ruimen of vaccineren) voorzichtig maar tijdig genomen moeten worden. Om zulke dynamische beslissingen te kunnen nemen moet op voorhand bekend zijn welke informatie op welk moment van de besluitvorming aanwezig moet zijn. Deze informatiebehoefte moet ondersteund worden met adequate gegevensverzameling. Bovendien moeten maatregelen 'slim' geïmplementeerd worden. Bijvoorbeeld als gekozen wordt voor vaccinatie kan men beter kiezen om te beginnen met een cirkel van 2 km die indien nodig uitgebreid wordt naar 5 km.

Bijkomende gevolgen van een uitbraak

Naast de directe kosten van een epidemie voor veehouders zijn er ook bijkomende gevolgen verderop in de keten. Fokkerij, voerproductie, slachthuizen, retail en consumenten worden mogelijk met de gevolgen van een uitbraak geconfronteerd. Bijvoorbeeld de standstill-periode in besmette compartimenten maakt het voor 6 weken onmogelijk dieren uit deze gebieden te slachten. Zeker als er meerdere compartimenten zijn besmet kan dit grote gevolgen hebben voor de aanvoer van slachthuizen. Dit geldt vooral voor de blankkalfsvleessector. Voor de varkenssector is er mogelijk sprake van een iets ander beeld omdat op het ogenblik grote hoeveelheden Nederlandse vleesvarkens in het buitenland worden geslacht. Een verbod voor heel Nederland voor levende export kan een extra aanbod voor de Nederlandse slachthuizen betekenen. Dit extra aanbod kan de stagnerende aanvoer vanuit geïnfecteerde compartimenten compenseren.

Een uitbraak van MKZ zal exportrestricties tot gevolg hebben die gedeeltelijk gerelateerd zullen zijn aan een uitbraak van MKZ en niet zozeer aan de keuze van de bestrijdingsstrategie. Na het einde van de een uitbraak en als alle beperkingen zijn opgeheven gaat er geruime tijd overheen voordat de situatie weer die is van voor de epidemie. Vooral voor de varkenssector kunnen de gevolgen groot zijn vanwege de grote export van levende biggen en vleesvarkens. Deze varkens zullen nu tijdelijk in Nederland verkocht moeten worden. De verwachting is dat de prijzen in gebieden met exportrestricties sterk zullen dalen.

Naast de effecten in de keten zijn er ook mogelijke gevolgen voor andere sectoren als toerisme en andere diensten. Omdat niet-agrarische economische activiteiten in belang toenemen voor het landelijk gebied zullen deze effecten in belang toenemen. Bij de laatste uitbraak van MKZ in Nederland zijn de kosten voor de toeristensector geschat op 275 miljoen euro.

Conclusies met betrekking tot de controlestrategieën

- Op basis van de modelberekeningen kan worden geconcludeerd dat aanvullende maatregelen op de minimale EU-strategie zoals extra ruimen of vaccineren nodig zijn om een uitbraak van MKZ te kunnen controleren in gebieden met hoge bedrijfsdichtheid (DPLA) (>3 bedrijven/km^2) zoals de Gelderse Vallei en Noord-Brabant. Echter, in gebieden met een lage dichtheid (SPLA)(<3 bedrijven/km^2), zoals in Friesland, lijkt de minimale EU-strategie afdoende.
- Als wordt gekeken naar omvang van de epidemie en uitbraakduur dan is in gebieden met een hoge bedrijfsdichtheid (DPLA): (a) vaccineren in een straal van 2 km rond geïnfecteerde bedrijven effectiever dan het minimale EU-scenario, maar minder effectief dan 1 km ruimen en (b) vaccineren in een straal van 5 km rond geïnfecteerde bedrijven even effectief als ruimen in een straal van 1 km.
- In de beginfase van het controleren van de epidemie is de benodigde ruimingscapaciteit 18 (0-83) bedrijven per dag voor ruimen in 1 km. De beno-

digde vaccinatiecapaciteit is 53 (0-237) bedrijven per dag voor de 2-km-vaccinatiestrategie en 149 (0-800) bedrijven voor de 5-km-vaccinatie-strategie.
- Vijfenzeventig procent van alle geïnfecteerde bedrijven zijn rundveebedrijven (onafhankelijk van de varkensdichtheid in een bepaald gebied).
- Uitsluiten van hobbybedrijven (in dit onderzoek bedrijven met 10 schapen die gescheiden zijn van commerciële bedrijven) van preventief ruimen heeft een verwaarloosbaar effect op de controle van de epidemie. In de strategie ruimen in een straal van 1 km reduceert dit het aantal te ruimen bedrijven met 20% (en het aantal te ruimen dieren met 3%).
- Het uitsluiten van varkensbedrijven van vaccinatie geeft een beperkte toename van omvang en duur van de epidemie (voor het onderzochte virus). Bovendien halveert het aantal te vaccineren dieren.
- Een aantal geïnfecteerde bedrijven wordt niet gedetecteerd tijdens de uitbraak. Deze bedrijven zullen tijdens de screeningsfase op het einde van de uitbraak opgespoord moeten worden. Het percentage bedrijven dat niet wordt opgespoord is ongeveer 9 bij de EU-strategie en 5 bij de ruimingstrategie (dit zijn vooral schapenbedrijven). Bij de vaccinatiestrategieën varieert dit percentage tussen 11 en 20 (dit zijn vooral gevaccineerde rundvee- en schapenbedrijven).

Conclusies met betrekking tot eindscreening
- In non-vaccinatiestrategieën moeten 1.000 tot 5.000 bedrijven worden getest in de eindscreening, terwijl een dubbel aantal bedrijven (2.000-11.000) moet worden onderzocht bij vaccinatiestrategieën.
- Ongeveer de helft van de onderzochte bedrijven moet worden hertest om infectie te bevestigen of uit te sluiten (vals-positieve testuitkomsten).
- Vaccinatie geeft 5 maal zo veel positieve dieren (in een NS-ELISA voor non-structural MKZ-eiwitten) voor de eindscreening als ruimen in een cirkel van 1 km.
- Na de eindscreening, zoals voorgeschreven door de EU, is het verwachte aantal positieve dieren gelijk voor de '1-km ruimen' en de '5-km vaccineren' strategie en gering hoger voor de '2-km-vaccinatiestrategie'.
- Screeningstrategieën, waarbij meer dan in de door de EU voorgeschreven strategie aandacht wordt gegeven aan het testen van niet-gevaccineerde rundvee- en varkensbedrijven (testen van steekproef in plaats van niet testen), verbeteren het opsporen van seropositieve dieren niet en heeft geen toegevoegde waarde.

- Screeningstrategieën, waarbij minder dan in de door de EU voorgeschreven strategie aandacht wordt gegeven aan het testen van gevaccineerde varkensbedrijven (een steekproef in plaats van alle dieren), hebben geen nadelige invloed op de detectie van seropositeve dieren en kan veilig worden geïmplementeerd.

Conclusies met betrekking tot de economische gevolgen
Met betrekking tot de reguliere bestrijdingsstrategieën, waarbij varkens ook worden gevaccineerd en gevoelige dieren op hobbybedrijven worden geruimd, kan worden geconcludeerd dat:
- in SPLA-gebieden ruimen in 1 km rond geïnfecteerde bedrijven de voorkeur heeft boven vaccineren. In DPLA-gebieden heeft vaccineren de voorkeur;
- in DPLA-gebieden met een hoge veedichtheid vaccinatie in een ring van 5 km lagere kosten heeft dan vaccinatie in een ring van 2 km.

Met betrekking tot alternatieve bestrijdingsstrategieën, waarbij varkens niet worden gevaccineerd of gevoelige dieren op hobbybedrijven niet worden geruimd, kan worden geconcludeerd dat:
- als gekozen wordt om gevoelige dieren te gaan vaccineren als bestrijdingsstrategie in DPLA-gebieden, het niet vaccineren van varkens serieus overwogen moet worden gezien de hiermee gepaard gaande substantiële reductie in kosten;
- afzien van preventief ruimen op hobbybedrijven moet worden overwogen. Preventief ruimen van de dieren op deze bedrijven draagt slechts in geringe mate bij aan de snellere eliminatie van de epidemie. Maar het draagt wel in belangrijke mate bij aan de negatieve perceptie van het publiek met betrekking tot de benodigde interventiemaatregelen. Het niet preventief ruimen van dieren op hobbybedrijven heeft geen substantiële invloed op de kosten van de uitbraak, maar bevordert de acceptatie van de samenleving voor de bestrijdingsstrategieën.

Met betrekking tot de verdeling van kosten kan worden geconcludeerd dat:
- de zuivelsector, de vleeskalversector en de varkenssector alle grote schade ondervinden bij een uitbraak van MKZ. Hoewel vaccinatie de kosten van de epidemie kan beperken, brengt vaccinatie ook het mogelijke probleem met zich mee van verminderde markttoegang van producten van gevaccineerde dieren;

- voor de zuivelsector een groot deel van de kosten ontstaat bij vaccinatie doordat het niet mogelijk is een aantal bijproducten van de zuivelverwerking van melk van gevaccineerde koeien optimaal te verwaarden;
- voor de vleeskalverindustrie de hoogste kosten ontstaan bij dieren die tijdens de uitbraak ouder worden dan acht maanden worden. Hun vlees kan niet meer als blank kalfsvlees worden afgezet;
- voor de varkenssector de hoogste kosten voortkomen uit de verminderde acceptatie van dieren en hun producten van de geïnfecteerde compartimenten door (internationale) handelspartners.

Met betrekking tot waardeverlies ten gevolge van vaccinatie kan worden geconcludeerd dat:
- acceptatie door internationale handelspartners van producten van gevaccineerde dieren de economische gevolgen van een uitbraak kan beperken. Een gezamenlijke inspanning van de overheid en de veehouderijsectoren om handelspartners over de Nederlandse aanpak te informeren is nodig;
- een gecoördineerde actie van de relevante stakeholders gedurende een epidemie het waardeverlies van producten van gevaccineerde dieren kan beperken. Logistieke samenwerking kan de kosten beperken en verminderd het aantal locaties waar producten moeten worden verwerkt;
- inzicht in de wijze waarop het waardeverlies van producten van gevaccineerde dieren (zuivel en vleeskalveren) kan worden beperkt, nodig is om de potentiële schade van een vaccinatiestrategie te verminderen.

Samenvattend
Vaccinatie is zeker zo effectief als ruimen in een straal van 1 km rond geïnfecteerde bedrijven bij het bestrijden van MKZ-uitbraken. Voorwaarde is wel dat de vaccinatie snel en op grote schaal kan worden toegepast, vooral in veedichte gebieden. Controle maatregelen moeten vooral worden gericht op rundveebedrijven, omdat zij de belangrijkste rol spelen in de epidemie (in ieder geval voor de in dit onderzoek aangenomen eigenschappen van de virusstam). Na de epidemie zijn de meeste seropositieve dieren zijn te verwachten op schapenbedrijven en gevaccineerde rundveebedrijven. Een effectieve strategie voor de eindscreening zal zich dan ook op deze bedrijven moeten richten. Acceptatie door internationale handelspartners van producten van gevaccineerde dieren kan de economische gevolgen van een uitbraak beperken.

1 Introduction

In the Netherlands around 17m. farm animals are at risk of being infected by Foot-and-Mouth Disease (FMD), as all even-toed ungulates (artiodactyls), such as cattle, sheep, goats and pigs, are susceptible to the virus. In many countries around the world FMD is still endemic. This means that there is a continuous but low risk of introduction of the virus in the Netherlands. As previous outbreaks of FMD have shown, an FMD epidemic affects a substantial part of the Dutch farming industry, resulting in large economic losses and a major impact on animal welfare. Where in the past outbreaks of epidemic diseases in livestock were mainly of interest to the agri-sector, now it involves the Dutch society as a whole. For example, during the 2001 outbreak in the UK and the Netherlands the tourist sector in infected areas suffered heavily. There also was serious concern within the general public about the massive culling of animals in general and the culling of small ruminants that were kept as pets in particular.

It is the task of the responsible authorities in case of an outbreak to act in a quick and adequate way. This task has become more complicated recently given the different and sometimes contrary objectives that (international) society and agricultural sector have. Different options for the most effective strategies have to be evaluated. The results of the research towards the epidemiological and economic consequences of different control and eradication strategies presented in this report can assist policy makers in choosing the optimal strategy in case of an outbreak of FMD.

FMD outbreaks and their control

When an outbreak of FMD is first detected measures need to be taken to control the outbreak. This detection occurs after a period of 'silent spread' (or High Risk Period (HRP)) since the introduction in the Netherlands. EU regulations demand the culling of detected infection sources, regulation of transport and tracing (and possibly culling) of dangerous contacts. When these measures are insufficient to stop FMD spread, additional measures such as preemptive culling or vaccination are necessary to halt the epidemic in a minimal time span. This happened during the FMD epidemic in the Netherlands in 2001, when about 270,000 animals were preemptively culled. Destroying so many (healthy) animals caused the public opinion to demand the adoption of alternative control strategies. The Dutch contingency plan for FMD therefore now specifies the use of vaccination or marker vaccination in a radius of 2km around a source herd

(Ministry of Agriculture, Nature and Food quality, 2005). While it was necessary to cull the vaccinated animals in 2001, this is no longer necessary in future outbreaks in which animals are vaccinated. Vaccination, however, is expected to be less effective than preemptive culling and to increase the number of minor (i.e. not detected) farm outbreaks during the epidemic. For the latter reason vaccinated farms need to be more thoroughly screened at the end of the epidemic to substantiate freedom of infection before export trading can resume. The EU requires that all animals on all vaccinated farms, are serologically tested, while for unvaccinated animals only a sample of the sheep suffices.

The Dutch contingency plan as well as the EU-screening regulations for vaccinated animals does not make a distinction between animal species or farm sectors. However, virus transmission and the effect of vaccination differ considerably between species. Cattle are highly susceptible to infection, and they can become carriers of the disease, Infected sheep can also become carriers and show little clinical symptoms, even when they are unvaccinated. Infected pigs excrete large amounts of virus, but they are not easily infected. Vaccination does not work as effectively on them as on cattle or sheep. Furthermore, the socio-economic impact of an FMD epidemic can vary for different farm sectors. Dairy, veal and pig farmers will most probably encounter difficulties in marketing products of vaccinated animals, once the epidemic is under control. Hobby farmers (i.e. small herds held for recreational purposes) on the other hand are largely unknown due to incomplete registration, but the social impact of the control measures such as culling in case of an epidemic can be considerable here as well.

A control strategy might be feasible that is cost-effective, while minimising the impact on animal welfare and society. Also for the end-screening strategy it is of paramount importance to minimise the risk of missing infected animals without wasting screening capacity. Understanding the role of different species and farm sectors in the epidemic is of key importance for the design of both control and end-screening strategies.

Problem statement

Since vaccination against FMD in case of an outbreak in which the animals are not culled after vaccination is relatively new for the Dutch situation, insight is needed into the epidemiological and economic consequences of such a strategy.

Research questions

To evaluate the effectiveness of control strategies different control strategies were evaluated. Therefore the following questions were addressed:

1. What is the optimal control strategy in case of an outbreak of FMD from an epidemiological and economic perspective? Evaluated are the control strategy as required by the EU, culling within a 1-km ring, and vaccination within 2 or 5-km rings around detected farms.
2. What are the consequences of alternative strategies?
   a. excluding pigs from vaccination;
   b. excluding animals on hobby farms from preemptive culling.
3. What are the consequences for screening and declaring freedom of infection when different control strategies that include vaccination are applied?
4. What is the distribution of costs between animal species and cost types?
5. What is the lost value of products of vaccinated animals?

The outline of the rest of the report

In this report we will evaluate the effectiveness of control strategies that differentiate between species and sectors. In particular, we will examine the control strategy as required by the EU as well as control strategies involving additional measures (preemptive culling within a 1-km radius and vaccination within a 2 and 5-km radius) and compare them to alternative strategies that exclude hobby farms from preemptive culling, or pig farms from vaccination. For this purpose a mathematical model has been developed that takes the differences between species (cattle, sheep and pigs) and between sectors (commercial or recreational) into account. With this model, epidemics are simulated applying one of the control strategies under consideration. The results of these hypothetical epidemics give an idea of the relative effectiveness and the proportion of minor outbreaks for each control strategy. Based on these results the epidemiological consequences of the different control strategies are calculated. Both the epidemiologic model development and results are described in chapter 2.

In chapter 3, the epidemic results are used as input for the end screening. In accordance with EU legislation, we model that all vaccinated animals are serologically tested. With this screening model the probability of missing infected animals during the end screening is calculated. Missing infected animals poses a risk to new outbreaks and to the export position of the country. Two alternative screening strategies are also evaluated: (1) a less stringent strategy in which a smaller number of the vaccinated pigs are sampled and (2) a more stringent strategy in which also non-vaccinated cattle and pigs are sampled. Comparing the outcomes of the different end-screening strategies gives an idea of the expected risk of missing infected animals after an FMD epidemic and the required sampling effort.

In chapter 4 an economic evaluation of the different control strategies is made based on the results of the simulated epidemics. With a Partial Budget model the economic consequences of the strategies are compared and the economic impact for the different species and sectors is evaluated.

Chapter 5 finalises this report with discussion and conclusions.

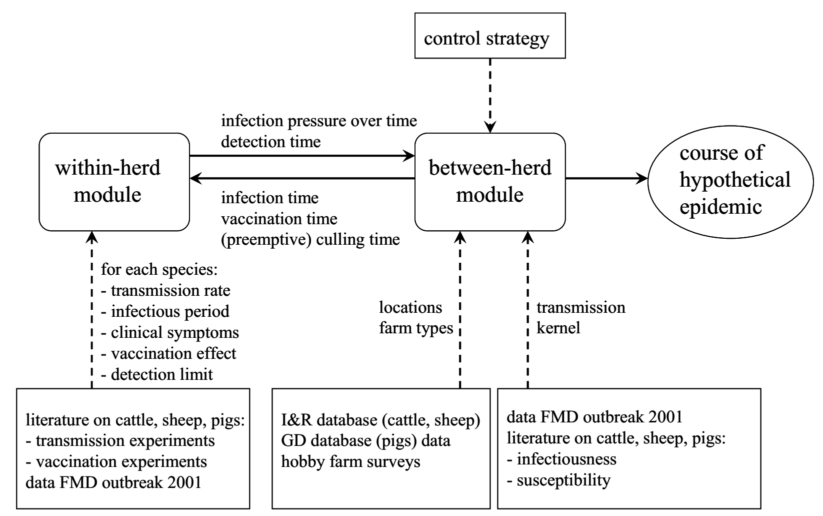
2 Epidemiology of Foot-and-Mouth Disease

Authors: Jantien Backer, Thomas Hagenaars, Gonnie Nodelijk, Herman van Roermund

2.1 Introduction: epidemiology

In this chapter we develop and apply a mathematical model that captures the key differences in the epidemiology of the different animal species and farm sectors. It consists of two modules that describe the within-herd and between-herd transmission dynamics of FMD, as shown schematically in figure 2.1. For the within-herd model that is formulated in terms of individual animals, parameters are estimated for each species from literature on transmission and vaccination experiments. In the between-herd model the farm itself is the smallest unit. The transmission at this level is modelled by distant-dependent probabilities, calibrated by the outbreak data of 2001 in the Netherlands (virus strain O/Net/2001). Information on interspecies transmission at this scale or relative importance is not available and must be estimated from other available sources. To apply the model to the 2006 farm density situation, it needs the locations and type of all farms in the Netherlands, which are available in databases. The within-herd module simulates a farm outbreak and sends the profile of the infection pressure (i.e. number of infectious animals as a function of time) to the between-herd module that determines which herds are infected by the source herd. The within-herd module also sends the detection time of the within-herd outbreak (if applicable), at which the between-herd module determines which herds need to be culled or vaccinated, depending on the control strategy. This information on infection, vaccination and culling times is sent back to the within-herd module that simulates the outbreak on the next infected farm. The result - after the last infected farm-outbreak is simulated - is the total course of the hypothetical epidemic. This model structure allows for the extrapolation of the effects of vaccinating individual animals to the level of an area with many farms.

Figure 2.1 **Schematic representation of two-level transmission model for FMD**



2.2 Within-herd model

The within-herd transmission of FMD between animals can be described by a simple SEIR model: when a susceptible (S) animal is infected, it will be exposed (E) for a latent period, after which it becomes infectious (I) to other animals, until it stops shedding virus and is removed (R) from the infection process. The rate of infection r_{inf} at time t is expressed as:

$$r_{\inf}(t) = \beta\,\sigma(t - t_{vac})\frac{S(t)I(t)}{N} \qquad [2.1]$$

where β is the transmission rate, σ the relative susceptibility (depending on the time since vaccination t_{vac}) and S, I and N denote the number of susceptible, infectious and all animals. As the number N of animals in a farm can be small, it is important to take variation occurring due to chance into account. Therefore, we consider a stochastic infection process with the rate given by Eq. 2.1. This is implemented numerically by giving each animal an individual infection threshold (Sellke, 1983). The latent and infectious periods are both modelled by a gamma distribution, making the model non-Markovian (i.e. each individual animal and its history needs to be modelled separately).

Parallel to the course of the FMD infection, are the clinical symptoms associated with it, such as lameness and vesicles on tongue and feet. An infected animal will show clinical symptoms after an incubation period, until it recovers. This is described by a model for clinical disease that determines whether and when an infected animal will show clinical symptoms. Both the incubation and clinical period are modelled by a gamma distribution.

The durations of all these periods (latent, infectious, incubation, clinical) for cattle, sheep/goats and pigs can be estimated from experiments with the different animal types, as well as the effect of vaccination on the susceptibility of animals. Data of the 2001 epidemic in the Netherlands provide information on the reproduction number within an infected herd and on the time between infection and (clinical) detection of the herd.

Below, the estimations for the parameters are discussed for the three animal types: cattle, pigs and sheep. For goats data were hardly available, and goats and goat farms were included as if sheep and sheep farms. In the model all periods (latent, infectious, incubation, clinical) are modelled by a gamma distribution, of which the 95% interval is denoted between brackets. They are summarised in table 2.1. The course of infection within the infected individuals and the build-up of protection for vaccinated individuals are shown in figure 2.2.

2.2.1 Latent period

The time between infection and becoming infectious is very short for FMD. We choose 2 (1.0-3.3) days for cattle (Orsel et al., 2007) and sheep/goats (Alexandersen et al., 2002; Gibson and Donaldson 1986). The latent period for pigs is even shorter: 1 (0.50-1.7) day (Eblé et al., 2004).

2.2.2 Infectious period

In the model the infectious periods represent only the acute stage of the infection; carriers (which for FMD occur in cattle only) with a long infectious period and low virus excretion are not modelled as they do not contribute to a within-herd outbreak (Moonen et al., 2004). By assuming short infectious periods, all secondary infections are concentrated during the first, highly infectious period of an infected animal. We choose 4 (2.0-6.7) days for both cattle (Orsel et al., 2007) and pigs (Eblé et al., 2004; Orsel et al., 2007c), whereas sheep and goats have a longer (highly) infectious period of 7 (5.0-9.3) days (Alexandersen et al., 2002; McVicar and Sutmolle, 1972).

2.2.3 Clinical disease

The reported incubation periods for FMD range from 2 to 14 days (Kitching, 2002; Kitching and Hughes, 2002; Kitching and Alexandersen, 2002), depending on challenge dose, virus strain and susceptibility. Based on experimental results, we assume a narrower incubation period of 5 (3.0-7.5) days for both cattle (Cox et al., 2005) and sheep/goats (Gibson and Donaldson, 1986; Orsel et al., 2007b). Pigs are assumed to show clinical signs a day earlier (i.e. 4 (2.0-6.7) days after infection), as they also become infectious a day earlier. In experimental settings 25% of the infected sheep and goats do not show any clinical signs (Kitching and Hughes, 2002; Orsel et al., 2007b), but in the field this percentage is expected to be higher, as these animals are not as well observed or examined by the farmer. Therefore, we assume subclinical infection for 50% of the infected sheep. All (unvaccinated) infected cattle and pigs will show clinical signs.

The animals recover in 1 or 2 weeks after the onset of the symptoms (website OIE), so the clinical period for all animal types is modelled as a broad gamma distribution around the average of 10.5 (7.0-14.7) days. This choice is not very relevant for unvaccinated cattle and pigs as most of the within-herd outbreaks are already detected before animals start to recover. Vaccinated animals (see paragraph 2.2.d) and unvaccinated sheep/goats however, may recover without the disease ever being noticed by the farmer or practitioner.

2.2.4 Vaccination

Vaccination reduces the susceptibility of vaccinated non-infected animals and when they are infected - it reduces the infectious period and the infectiousness. For Classical Swine Fever the effect of vaccination on these three parameters could be estimated (Backer et al., 2008). For FMD this was not possible as the available vaccination transmission experiments were less detailed. Therefore, we only model the decrease of susceptibility of non-infected animals as a function of the time since vaccination. So, when a vaccinated animal does get infected it will excrete virus as much and as long as if it were unvaccinated. The decrease in susceptibility is chosen so that it describes the results observed in transmission experiments. In this way the full effect of vaccination is described by the decrease in susceptibility alone.

Many vaccination-challenge and vaccination-transmission experiments have shown that vaccinated cattle (Orsel et al., 2007; Cox et al., 2005; Orsel et al., 2005; Doel et al., 1994; Golde et al., 2005), sheep (Orsel et al., 2007b) and pigs (Eblé et al., 2004; Eblé et al., 2008; Salt et al., 1998) are protected against infection from 14 days post vaccination onwards. Experiments with a shorter vaccination-challenge period of 7 days are less common and indicate that cattle (Doel et al., 1994; Golde et al., 2005) and sheep (Cox et al., 1999) are already fully protected against infection, but in those experiments the challenge and vaccination strains were identical. Therefore, a more conservative choice for immunity is appropriate. In the model the susceptibility decreases linearly from 1 at 4 dpv (days post vaccination) to 0 at 11 dpv for cattle and sheep/goats. Pigs are not protected against infection after a vaccination-challenge period of 7 days (Eblé et al., 2004). For pigs the susceptibility starts decreasing three days later than for cattle: from 1 at 7 dpv, until 0 at 14 dpv. Although vaccinated pigs can even be infected by unvaccinated seeders after 14 dpv (Orsel et al., 2007c), it is assumed that this situation will not occur when all animal transports are prohibited (after HRP) and that earlier infected vaccinated animals will not be sufficiently infectious to maintain the epidemic (because of pen barriers that prevent direct contact). Recent experiments by Van Roermund et al. (in preparation) indeed showed that between-pen transmission of vaccinated pigs (14 dpv) is too low for a within-herd outbreak to occur.

Vaccination also protects infected animals against clinical disease. We assume this protection mirrors the susceptibility for cattle and sheep/goats, starting at 4 dpv and linearly increasing to full protection at 11 dpv. Remember that only 50% of the infected unvaccinated sheep and goats show clinical disease. Pigs only achieve a maximum of 50% protection against clinical disease (Orsel et al., 2007c). The protection against clinical disease is an important aspect of the model, as the detection of an infected farm is based on the number of observed clinical cases. When this number does not exceed a certain detection limit, the outbreak will die out unnoticed, affecting only a small number of animals that need to be detected during the end screening.

2.2.5 Reproduction of FMD within a herd

For the virus transmission within a herd, we can use the results of transmission experiments and the clinical and laboratory reports of real outbreaks.

Transmission experiments provide information on the spread of the infection through a relatively small population. They can often only determine whether the reproduction number R_0 is significantly above unity. Moreover, in experiments all animals are in direct contact, which is not true for most farm situations. On the other hand, real outbreaks are often less well documented. Usually the herd prevalence is known at the time of detection and the time of infection of the farm is estimated. Here, we use clinical reports and estimated infection dates of a number of cattle herds that were infected during the 2001 epidemic in the Netherlands and literature findings, to estimate the reproduction number for each animal type.

From the Dutch 2001 outbreak we obtained 21 data points for cattle farms. A reproduction number of 6 seems to fit the data reasonably well (see figure 2.3). Estimating the best fit is probably too rigorous for these data, due to the lack of data points and because the infection dates are only rough estimates. Moreover, the period when the virus survives outside the host is not taken into account. For pigs we assume an identical reproduction number of 6. This is much lower than found in transmission experiments (Eblé et al., 2008), but the clustering in pens and stables will most probably lower the overall reproduction number within a pig herd (Eblé et al., 2006). Virus transmission amongst sheep is observed to be very gradual, indicating a reproduction number just above unity; in the model it is assumed to be 1.5, agreeing with the value of 1.1 reported by Orsel et al. (2007b).

The reproduction rate is the reproduction number divided by the average infectious period.

2.2.6 Clinical detection

The detection of infection during the epidemic is based on the number of clinical cases that a visiting practitioner notices. The detection threshold of clinical cases in the model is set to 3 cases for cattle, 6 for sheep and goats and 7 for pigs, all derived from the estimated period between infection and suspicion. The first (3 clinical cases for cattle) corresponds to an average period between infection and suspicion of 8 days, as was observed in the 2001 outbreak in the Netherlands. For sheep this type of information is lacking, and we assume a double detection limit, i.e. 6 clinical cases. Due to the higher detection limit, the high percentage of subclinical disease and the smaller reproduction number in sheep, it may take a considerable period of time before suspicion arises, typically around three weeks.

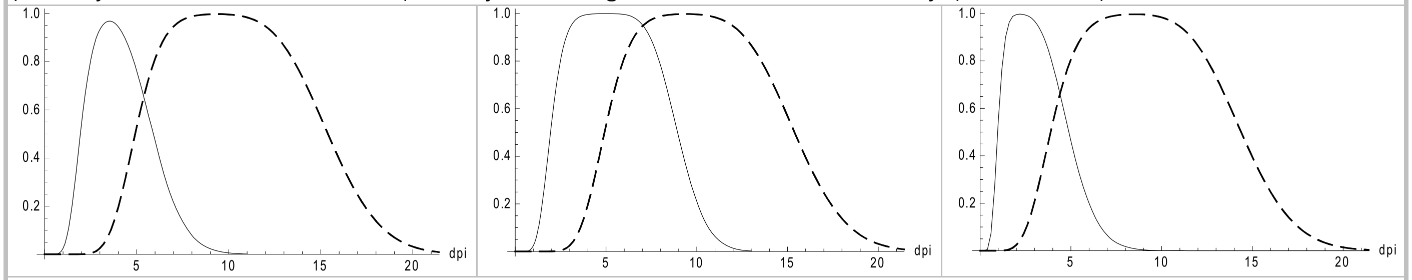
For pigs we assume that clinical detection will on average take place a day earlier than for cattle (as the latent period is one day shorter), resulting in a detection time of 7 days and a corresponding detection limit of 7 clinical cases. The detection limit for sheep on a hobby farm is set to 3 clinical cases (instead of 6 clinical cases on a commercial sheep farm), because hobby farms consist of fewer animals.

These detection limits are fixed, ensuring that the detection time can vary. One day after the suspicion the disease is confirmed and the farm culled.
To illustrate the within-herd model, outbreaks are simulated at different infection-vaccination intervals for three model farms that consist of 100 cattle, 100 sheep and 1,000 pigs. The results of these simulations, including the fraction of detected outbreaks, the detection time and the number of affected animals at the end of a detected or undetected outbreak, are described in detail in Appendix 1.

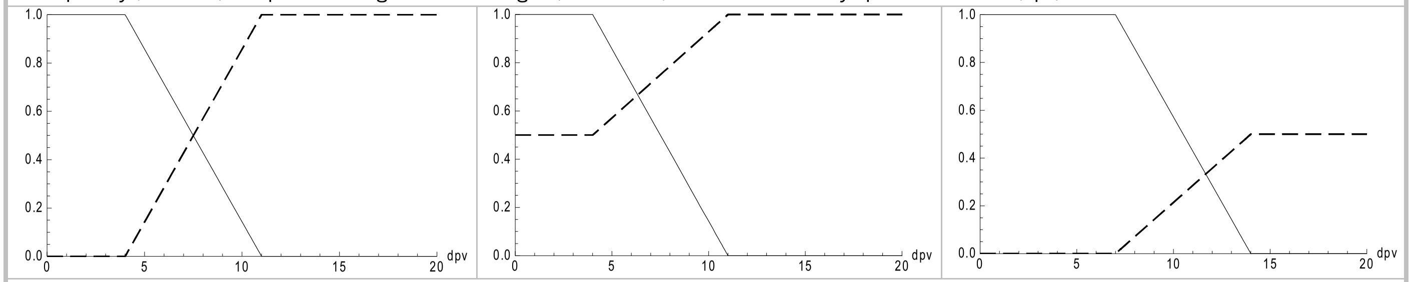
Figure 2.2 **Individual parameters for infected and vaccinated animals a)**

Cattle	Sheep/goats	Pigs

probability of infectiousness (solid line) and probability of clinical signs (dashed line) as a function of days post infection (dpi)



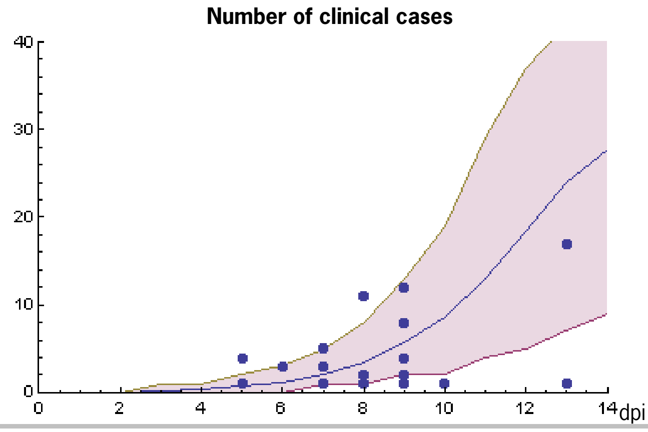
susceptibility (solid line) and protection against clinical signs (dashed line) as a function of days post vaccination (dpv)



a) 50% of infected sheep do not show any clinical symptoms at all, and that only 50% of vaccinated pigs (from 14 dpv onwards) are protected against clinical signs.

Table 2.1	FMD parameters for within-herd model		
Parameter	**Cattle**	**Sheep/goats**	**Pigs**
latent period (days)	2 (1.0-3.3)	2 (1.0-3.3)	1 (0.50-1.7)
infectious period (days)	4 (2.0-6.7)	7 (5.0-9.3)	4 (2.0-6.7)
clinical disease			
onset (dpi)	5 (3.0-7.5)	5 (3.0-7.5)	4 (2.0-6.7)
duration (days)	10.5 (7.0-14.7)	10.5 (7.0-14.7)	10.5 (7.0-14.7)
subclinical (%)	0%	50%	0
vaccination			
- protection against infection:			
onset (dpv)	4	4	7
full protection (dpv)	11	11	14
- protection against			
- clinical disease:			
onset (dpv)	4	4	7
full protection (dpv)	11	11	14 (max. 50%)
reproduction within a herd			
reproduction number (R0)	6	1.5	6
reproduction rate (day-1)	1.5	0.21	1.5
Clinical detection of infected farm			
- average period between infection and suspicion of farm (days)	8	22	7
- corresponding number of clinical cases at which farm is suspect	3	6 (3 for hobby farms)	7

Figure 2.3 **Clinical cases as a function of days post infection (dpi), observed in the 2001 outbreak for 21 farms (large dots) and simulated with R_0=6 (solid line with shaded 95% interval) for cattle farms**



2.3 Between-herd model

The transmission between herds depends on the distance between source and destination herd, the infection pressure generated at source herd and the type of animals at source and destination herd. The hazard λ_{ij} at time t that an infectious farm i infects a susceptible farm j at that time, is described by:

$$\lambda_{ij}(t) = I_i S_j k(r_{ij}) q_i(t) \quad [2.2]$$

where I_i is the relative infectivity of the infectious farm, S_j the relative susceptibility of the susceptible farm, q_i the time-dependent infection pressure at the infectious farm and $k(r_{ij})$ the transmission kernel that depends on the distance r_{ij} between farms i and j. The probability that a farm i will infect farm j during its entire infectious period T_i is:

$$p_{ij} = 1 - \exp\left[-I_i S_j k(r_{ij}) \int_0^{T_i} q_i(t)\,dt\right]. \quad [2.3]$$

This formulation describes a heterogeneous model that relates the transmission probability to distance between farms (via $k(r_{ij})$), that allows a varying infection pressure (via $q_i(t)$) and infectious period (via T_i) per infectious herd, and that discerns different herd types (via I_i and S_j). Herd-size differences within a herd type are directly related to the infection pressure, while differences between herd types are captured in the relative infectivity and susceptibility. Below we will discuss the separate elements of Eq. 2.3 in more detail.

2.3.1 Transmission kernel

The transmission kernel follows a power law relation:

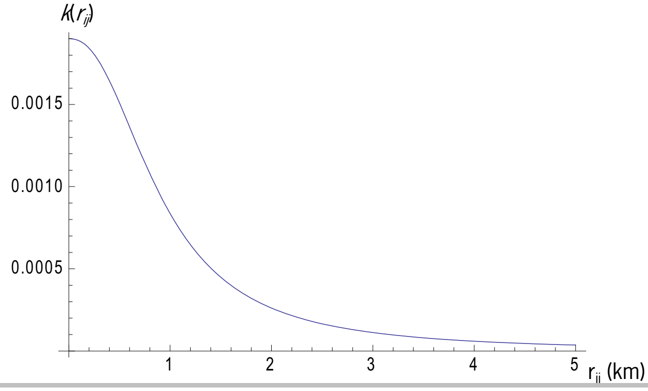
$$k(r_{ij}) = \frac{k_0}{1+\left(\frac{r_{ij}}{r_0}\right)^{\alpha}} \qquad [2.4]$$

,

where the parameters k_0, r_0 and α determine the height and the shape of the transmission kernel. These were estimated for the 2001 FMD epidemic in the Netherlands in a previous project (virus strain O/NET/2001, Boender et al., 2006), assuming all farms are equal (no distinction between farm types, i.e. $I_i = 1 \ \forall$ i and $S_j = 1 \ \forall$ j) and all infectious farms generate a fixed infection pressure ($q_i = 1$ day^{-1} $\forall$ i) for a fixed infectious period ($T_i = 7$ days $\forall$ i). This resulted in $r_0 = 0.9$km, $\alpha = 2.3$, and $k_0 = 0.0019$ day^{-1} (see figure 2.4).

We will use the estimations for the shape parameters r_0 and α in our model; the height of the kernel k_0 however depends on the heterogeneous properties of the transmission and will therefore be estimated for the new model in section 2.3.3.

Figure 2.4	Between-herd transmission kernel: probability of infection during the entire infectious period as a function of distance between source and destination herd (Eq. 2.4)



2.3.2 Infection pressure

A within-herd simulation for an infected herd provides the infection pressure as a function of time, which is proportional to the number of infectious animals at that time. When an outbreak on a farm affects a large number of animals, it will present a large infectivity to other herds. In this way, the difference between large and small farms (of the same herd type!) is captured, because large farms can host potentially larger outbreaks.

The infection pressure is normalised for each herd type (cattle, sheep, pigs and hobby farms) and multiplied by the fixed total infection pressure of 7 that was used for the kernel estimation. Using the same average total infection pressure means that the probabilities p_{ij} in Eq. 2.3 are on average also the same as during the kernel estimation (assuming that the exponential argument in Eq. 2.3 is much smaller than unity so that $1-e^{-x} \approx x$ applies), which allows for the use of the same kernel (shape) parameters.

2.3.3 Heterogeneous transmission

For the transmission kernel estimation the relative infectivity and susceptibility for all farm types were chosen to be unity (Boender et al., 2006). This means for instance that a susceptible hobby farm and a susceptible cattle farm have an equal chance to be infected by a source herd (at the same between-herd distance). We can use the observations from the 2001 epidemic to determine the probability of this 'homogeneous transmission assumption'. During this epidemic (with virus strain O/NET/2001) only cattle farms were infected, or - in other words - all sheep, pigs and hobby farms escaped infection despite the infection pressure posed by the infectious cattle farms. The probability that this would occur can be calculated with the estimated infection and removal dates of infected herds, the location data of all herds and the estimated parameters for the transmission kernel (Eq. 2.4). When all farms are equally susceptible the probability that none of the sheep farms is infected is 0.005, that none of the pig farms is infected is 0.09 and that none of the hobby farms is infected is 1·10-5. This is a strong indication that the equal susceptibility assumption should be rejected, at least for sheep and hobby farms. A similar check for the equal infectivity assumption is not possible, as only cattle herds were infected.

Relative transmission properties for different herd types have been estimated for the 2001 UK epidemic in two studies. Ferguson et al. (2001) classified the herd type by the most affluent species present on the farm, regardless of the species infected. Chis Ster et al. (2007) assume the infectivity and susceptibility of a farm to be directly proportional to the number of animals present, which is explicitly not assumed in our model. These different model assumptions and differences in herd size and contact structure makes a direct adoption of their estimated transmission properties invalid. Instead, we will use a combination of experimental results, literature and expert opinion to derive best guesses for the relative infectivity and susceptibility for each herd type. We will consider four herd types: cattle, sheep, pig and hobby farms. This means that different commercial herd types of the same species (such as dairy and beef cattle) are identical in the model.

To assess the relative infectivity of each herd type, we need to consider the amount of virus present on an infected farm and the various ways for a virus particle to leave an infected farm. The amount of virus present on an infected farm depends on the virus excretion per animal and the number of infectious animals. Infected cattle and sheep excrete similar quantities of virus (Alexandersen et al., 2002), while aerosol production for pigs can be 100 times as high (Kitching and Alexandersen, 2002). Figure A1.2 shows that the number of affected animals on pig farms is 4 to 5 times higher than on sheep or cattle farms. The number of affected animals on hobby farms is lower than on commercial sheep farms, due to their limited size. For the virus transmission from an infected farm, we can consider airborne spread and spread via contacts. The role of airborne spread is closely related to the housing of the animals; cattle and sheep generally graze on pastures that might border neighbouring premises, while pigs are kept in closed buildings, which may also constrain virus particles. The transmission via contacts depends on the contact frequency with animals, vehicles and people. The transports of live animals can be neglected for this model, because it is only valid for the epidemic time after the HRP. Cattle (especially on dairy farms) are probably more intensively handled than pigs or sheep, and the frequency of contacts is expected to be lowest for hobby farms. We choose cattle farms as a reference (with a relative infectivity of unity) and based on the considerations above, the relative infectivity of sheep farms as 0.5, of pig farms as 10 and of hobby farms as 0.1.

To assess the relative susceptibility of each herd type, we need to consider the amount of virus needed to infect at least one animal on a farm and the various ways in which a virus particle can arrive at a non-infected farm. Based on the minimal infection dose and the respiratory volume of an animal, Donaldson et al. (2001) estimated the minimum concentration of virus particles in air to infect an animal. His results suggest that cattle are 10 times more susceptible for airborne infection than sheep and at least 200 times more susceptible than pigs. The susceptibility of an entire farm also depends on the number of animals at risk, i.e. the herd size. Pig farms are on average 10 times larger than cattle or sheep farms, but due to the low susceptibility per pig it is expected that pig farms have a lower susceptibility. Hobby farms are the smallest in size and therefore expected to be less susceptible. Concerning the different transmission routes, the same considerations apply as described above: closed housing could protect pigs against infection through airborne spread, handling and contact frequencies are expected to be highest for cattle farms, et cetera. We choose cattle farms as a reference (with a relative susceptibility of unity) and based on the considerations above, the relative susceptibility of sheep farms as 0.5, of pig farms as 0.1 and of hobby farms as 0.1.

The left-hand side of figure 2.5 shows a matrix with the estimated relative transmission properties and their multiplication. This assumes random mixing of the interherd contacts. However, Chis Ster et al. (2007) showed that it is more probable that cattle and sheep farms have more within-species contacts than between-species contacts (assortative mixing). Although their model is not directly comparable to ours, we will adopt their degree of mixing (an assortative mixing factor of 2) for the commercial farms. Contacts with hobby farms mix randomly; professional contacts are assumed to be less common in this group. The right-hand side of figure 2.5 shows the resulting transmission matrix.

Finally, we need to relate the kernel height k_0 for heterogeneous transmission to the outbreak data of 2001. The average reproduction ratio between herds R_h was estimated to be 1.25 with the homogeneous transmission kernel.

By multiplying the original kernel height with a correction factor of 1.15, the same average reproduction ratio is reproduced.

Figure 2.5 **Transmission matrix for each herd type a)**

infectious farm / susceptible farm

		cattle	sheep	pigs	hobby
		1	0.5	10	0.1
cattle	1	1	0.5	10	0.1
sheep	0.5	0.5	0.25	5	0.05
pigs	0.1	0.1	0.05	1	0.01
hobby	0.1	0.1	0.05	1	0.01

x

assortative mixing

2	1	1	1
1	2	1	1
1	1	2	1
1	1	1	1

=

infectious farm / susceptible farm

	cattle	sheep	pigs	hobby
cattle	2	0.5	10	0.1
sheep	0.5	0.5	5	0.05
pigs	0.1	0.05	2	0.01
hobby	0.1	0.05	1	0.01

a) The relative susceptibility and infectivity (during its entire infectious period) for each herd type are shown in gray; their multiplication (left) is multiplied by an assortative mixing matrix (middle), resulting in the overall transmission matrix (right).

2.4 Farm data

Two databases containing farm data are available (one from the Ministry of LNV and another for pig farms only from the Animal Health Service (GD)). The I&R database of LNV contains 92,333 records with farm location and the number of cattle, sheep, goats and pigs present in August 2007. As the information on pigs in this database is incomplete, the other database is used that solely contains pig farm data. This GD database contains 16,412 records with farm location and the number of finishers, gilts and sows plus boars present in 2005. The number of piglets on a farm is not given, but can be estimated from the number of sows present. Assuming a sow produces 2.4 litters per year of 10.5 piglets on average, and the piglets stay on the multiplier farm for 9 weeks, the number of piglets is calculated as $2.4 \cdot 10.5 \cdot 63/365 = 4.3$ times the number of sows. As the records in both databases also contain 'empty' and 'historic' holdings, we need extra information to select the 'active' farms. We will match the databases to the number of commercial farms in 2006, as reported in the *Land- en tuinbouwcijfers 2007* survey, and to an estimation of the number of hobby farms. We will not make a distinction between different commercial herd types of the same species; a cattle farm can consist of dairy cattle or beef cattle and a pig farm can be a finishing or multiplier farm, et cetera.

The agricultural survey (*Land- en tuinbouwcijfers 2007*) reports all holdings with a minimum size of 3 nge ('Nederlandse grootte-eenheid', measure of the economic value of agricultural activities, see table 2.2). Although the smaller farms are too small to be economically profitable, we will consider all farms reported in the agricultural survey as commercial, because small animal sections can be part of a larger holding (that will be considered commercial). From an epidemiological point of view, the most important parameter is the number of farms (and thus the relative farm densities). That is why the number of farms in the two databases are matched to the number of farms in the survey data, by omitting the farms that are smallest in size. The resulting lower limits for the farm size are 5 for cattle, 11 for sheep/goats and 190 for pigs. Comparing the average farm size and the total number of animals (table 2.2), the survey and model farms are also in agreement. Farms that are less than 20 meters apart, are considered to be mixed holdings.

A survey of the hobby farm sector is less straightforward. The definition of a hobby farm is not always clear and not all hobby farms are reported, but the extent of underreporting is unknown. Treep et al. (2004) use an economic point of view that a hobby farm is by definition not for profit. They estimate 15,000-30,000 hobby sheep farms with in total 450,000 sheep and 10,000-20,000 hobby goat farms with in total 112,000 goats. However, in times of an epidemic crisis, the definition of a hobby farm will most probably be based on its contacts. For instance, when a not-for-profit farm is part of a larger commercial holding or is embedded in professional contact structures, it is more likely to be treated as a commercial holding. Therefore, we choose the number of hobby farms lower than the hobby farm survey: 20,000 hobby sheep farms with 10 sheep each, so 200,000 hobby sheep in total. These hobby farms are never part of a mixed holding for the reasons above. Other types of hobby farms (cattle, pigs) are less common and not taken into account in the model. For the locations of the hobby sheep farms, we use 17,711 locations of the small sheep and goats farms in the I&R database (from 1 to 10 sheep/goats per farm), that were not used for the commercial holdings. For the remaining 2,289 farm locations (to add up to 20,000) we use empty holdings where sheep and/or goats can be held. This group of farms is randomly scattered over the Netherlands.

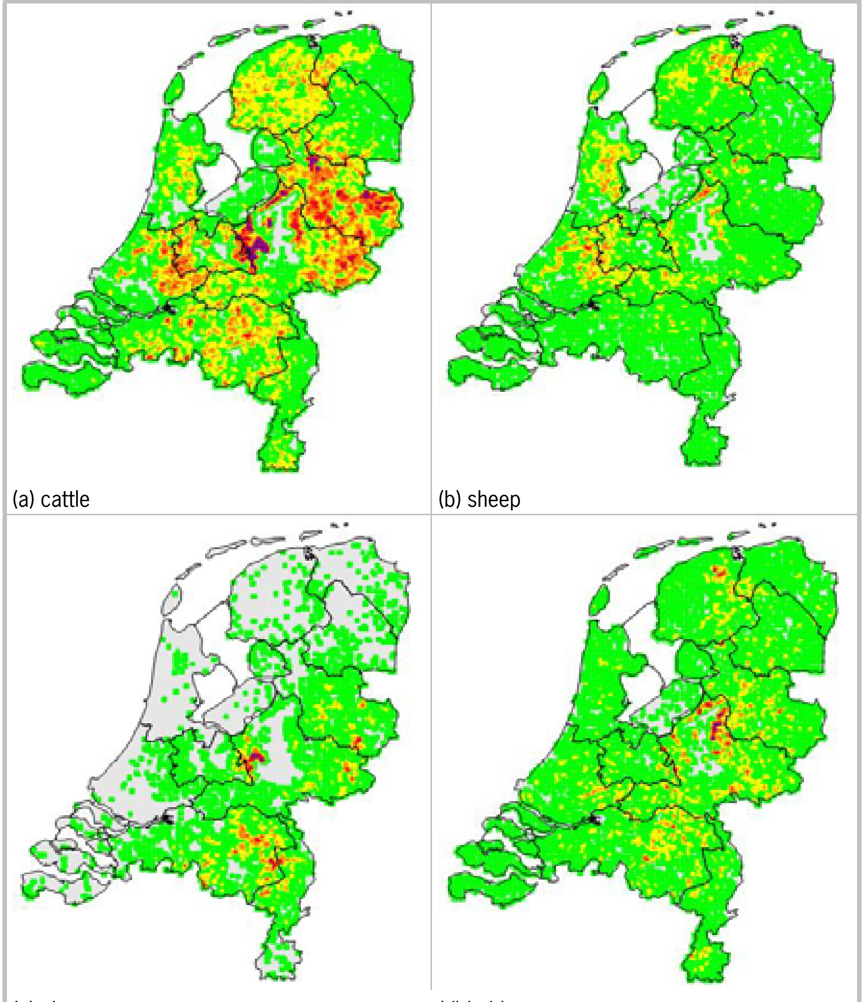
Table 2.2 Farm data for 2006 in the Netherlands, as taken from the agricultural survey (LEI Wageningen UR and Statistics Netherlands, 2007) and as used in the model

	Agricultural survey	Model
	cattle a)	cattle c)
number of farms	36,246	36,567
average farm size (min-max)	103	101 (5-3,229)
total number of animals (x 1,000)	3,745	3 695
	sheep/goats a)	sheep/goats c)
number of farms	18,305	18,648
average farm size (min-max)	92	78 (11-4,781)
total number of animals (x 1,000)	1,686	1,456
	pigs a)	pigs d)
number of farms	9,041	9,021
average farm size (min-max)	1,256	1,228 (190-35,366)
total number of animals (x 1,000)	11,356	11,075
	hobby b)	hobby e)
number of farms	25,000-50,000	20,000
average farm size (min-max)	11-22	10 (10-10)
total number of animals (x 1,000)	562	200

a) Land- en tuinbouwcijfers (2007); b) Treep et al. (2004); c) I&R database (LNV, August 2007); d) GD database (2005); e) Estimation (see text).

Livestock farms are not evenly distributed over the Netherlands, which is also reflected by the farms used in the model (see figure 2.6).

Figure 2.6 **Farm densities in the model for (a) cattle, (b) sheep, (c) pigs and (d) hobby farms; 0 (grey), 0-1 (green), 1-2 (yellow), 2-3 (orange), 3-4 (red) and >4 (purple) farms/km^2**



(a) cattle (b) sheep (c) pigs (d) hobby

2.5 Control strategies

The model described in sections 2.2 and 2.3 is applied to the farm structure of 2006 in the Netherlands (section 2.4) to compare different control strategies (see table 2.3). The minimal control strategy *(min)* consists of the EU-required measures of culling detected infection sources, regulating transport and tracing dangerous contacts. The delay between confirmation of the infection and culling of the detected farm is assumed to be one day throughout the epidemic. Often additional control measures are required to curb the epidemic. Here we will study preemptive ring culling and ring vaccination in various conformations.

Preemptive ring culling is always applied within a radius of 1km around a detected infection source, and is applied either to all farms *(cul1)* or only to commercial farms *(cul1h)*. In the first week after the first detection the delay between culling the infection source and preemptive culling of the neighbouring farms is one day, but it increases to two days after the first week to account for potentially limited culling capacity. Ring vaccination strategies cannot be applied instantaneously following the first detection, but permission needs to be obtained from the EU first. We assume this takes 7 days, in which period the starting epidemic is controlled by preemptive ring culling within 1-km radius with a 1 day delay between culling of the infection source and neighbouring farms. After the first week the delay between culling of the infection source and vaccination of the neighbouring farms is also one day, regardless of the vaccination radius. Two control strategies apply ring vaccination to all farms, i.e. within 2-km and 5-km radius around a detected source farm *(vac2 and vac5).* For DPLAs the 5-km ring vaccination strategy will in practice be comparable to area-wide vaccination. Two alternative vaccination strategies make a distinction between commercial and non-commercial farms, by excluding hobby farms from preemptive culling in the week after the first detection *(vac2h and vac5h),* after which they are vaccinated like the commercial farms. Similarly, in two alternative vaccination strategies pig farms are excluded from vaccination *(vac2p and vac5p)*, but not from preemptive culling in the first week. In total nine control strategies are evaluated. Table 2.3 summarises them and shows their abbreviations.

Table 2.3	Different evaluated control strategies
Abbreviation	**Control strategy**
min	EU measures, no additional measures
cul1	1-km preemptive ring culling
cul1h	1-km preemptive ring culling, except hobby farms
vac2	2-km ring vaccination
vac2h	2-km ring vaccination, no culling of hobby farms in 1st week
vac2p	2-km ring vaccination except pig farms
vac5	5-km ring vaccination
vac5h	5-km ring vaccination, no culling of hobby farms in 1st week

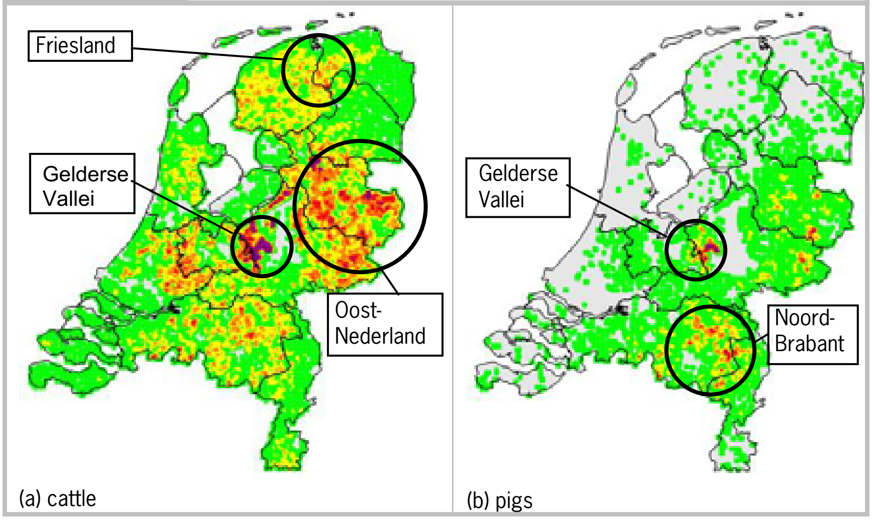
For each control strategy the initial state is identical, i.e. the number of infected farms and their locations at the time of the first detection. To construct such an initial state, we use the model described in sections 2.2 and 2.3, even though it is only valid in the period after the first detection. One farm (either a cattle or pig farm) is randomly picked as infection source that with a high hypothetical infection pressure transmits the infection to ten other farms during 14 days. These second-generation farms can in their turn infect other farms. The situation at the moment the first farm is detected, is used as initial state for simulating the different control scenarios. Four 'worst case' scenarios are chosen to start the epidemic in a densely populated livestock area (DPLA) with either many pig farms (as in Noord-Brabant), many cattle farms (as in Oost-Nederland) or both (as in the Gelderse Vallei). As a comparison also a sparsely populated livestock area is chosen in Friesland, where the infection will start on a cattle farm that infects five other farms (instead of ten). Table 2.4 summarises the different scenarios and figure 2.7 shows the different areas.

Table 2.4	**Simulated scenarios in different areas with different infection source**			
	Farm density (farms/km^2)		**Infection source**	**Number of farms infected by source farm (during HRP)**
	commercial holdings	**hobby farms**		
Gelderse Vallei a)	4.3	0.94	cattle farm	10
Gelderse Vallei a)	4.3	0.94	pig farm	10
Noord-Brabant a)	3.0	0.99	pig farm	10
Oost-Nederland a)	2.9	0.92	cattle farm	10
Friesland b)	2.2	0.76	cattle farm	5

a) Densely populated livestock area; b) Sparsely populated livestock area.

Finally, the different control strategies are also evaluated with a homogeneous transmission kernel (only for the Gelderse Vallei with a cattle farm as infection source). This means that all infected farms (cattle, pigs and sheep/goats) are on average equally infectious, and all non-infected farms are equally susceptible (in other words, all terms in figure 2.5 are unity). Although this is not a realistic scenario, it serves to assess the effect of the assumptions made for the heterogeneous transmission model.

Figure 2.7	Different areas for initialisation of the simulated epidemics, starting on (a) a cattle farm or (b) a pig farm



2.6 Results and discussion: epidemiology of FMD

For each control strategy and starting situation, 1,000 hypothetical epidemics are simulated. Each realisation can be characterised by the duration of the epidemic, the number of infected farms (that are either detected, not detected or preemptively culled) and the number of preemptively culled and/or vaccinated farms. These characteristics are summarised in table 2.5 for the heterogeneous transmission model and in table 2.6 the composition of infected and not detected farms (before the end screening) is given. Below, the results and the course of the epidemics are discussed in more detail.

2.6.1 Results for the minimal control strategy

The minimal control strategy (*min*) comprises culling of detected infection sources, set up of transport regulations and tracing of dangerous contacts. No additional measures regarding the neighbouring farms of detected infected herds are taken. In DPLAs this can lead to a severe epidemic lasting up to one year and reaching outbreak sizes up to 2,000 farms (table 2.5). The largest part of the infected farms comprises cattle farms, even in the pig-dense areas (table 2.6). Around 8% of the infected farms are not detected during the epidemic, which are mainly sheep farms (table 2.6).

In the Gelderse Vallei the farm densities are higher than in the other two DPLAs (Oost-Nederland and Noord-Brabant), leading to a larger median outbreak size and duration, and thus a larger epidemic curve (see figure 2.8). In fact, the 95% epidemic curves of Oost-Nederland and Noord-Brabant in figure 2.8 are caused by epidemics that also affect the Gelderse Vallei. When the epidemic starts on a pig farm instead of a cattle farm, the peak of the epidemic curve is higher and earlier, because of the high infectivity of an infected pig farm and the relative ease to infect other pig farms. These differences between the starting situations are similar for all control strategies and will not be discussed further in the following sections. The results of the minimal control strategy suggest that in DPLAs additional control is always required, to curb the epidemic as soon as possible. For SPLAs, results are shown and discussed in section 2.6.5.

2.6.2 Results for basic control strategies

The basic control strategies are applied to all farms, regardless of species or commercial purposes. They include preemptive ring culling within 1-km radius around a detected infection source *(cul1)* and ring vaccination within 2-km and 5-km radius *(vac2 and vac5)*. The results in table 2.5 show that the outbreak sizes of 1-km culling and 5-km vaccination are comparable, but the outbreak duration is shorter for 5-km vaccination. The 2-km vaccination strategy is less effective than 1-km culling in terms of both outbreak size and duration. The number of preemptively culled farms using the culling strategy is large compared to the outbreak size (around a factor of 20 in the Gelderse Vallei), due to the high farm densities. Interestingly, the number of preemptively culled farms is comparable to the number of detected and culled farms in the minimal strategy, meaning that either strategy will lead to large numbers of culled farms. In the vaccination strategies the number of culled farms is much smaller, even though large numbers of farms are affected by the control measures (ratio of vaccinated farms and outbreak size is 30 for 2-km vaccination and 100 for 5-km vaccination). Figure 2.9 shows the required culling and vaccination capacities for the basic control strategies. In the first week all strategies require a considerable culling capacity of around 10 (0-63) farms to be culled per day. When permission for vaccination is obtained, the required culling and vaccination capacities are highest in the first week of the vaccination campaign (i.e. the second week after the first detection): for the 1-km culling strategy 18 (0-83) farms need to be culled per day, for the 2-km vaccination strategy 53 (0-237) farms need to be vaccinated per day, and for the 5-km vaccination strategy 149 (0-800) farms need to be vaccinated per day. Table 2.7 specifies these numbers for the different types of animals and lists the number of animals to be vaccinated per day. From this table it is clear that the largest amounts of animals to be vaccinated are pigs. Comparing these outcomes with the estimated available vaccination capacity of 120 farms per day or 10,000 animals per day (personal communication, Aldo Dekker, Wim Pelgrim), we conclude that the vaccination capacity is sufficient for 5-km vaccination for almost 50% of the simulated epidemics. When pig farms are excluded from vaccination the vaccination capacity is sufficient for larger epidemics and/or larger vaccination circles.

The number of infected farms that is not detected during the epidemic (before the end screening) differs largely: for 1-km culling 4%-7% of the infected farms is not detected, while this percentage is 11%-18% for 2-km vaccination and 12%-20% for 5-km vaccination (see table 2.6). For the culling strategy these undetected farms are mostly sheep farms (just like the minimal strategy), but for the vaccination strategies they are mostly (vaccinated) cattle farms.

The epidemic curves in figure 2.10 provide insight into the effectiveness of the control strategies during the epidemic. The curves are identical for all three strategies in the first week, because in this period preemptive culling within a 1-km circle around detected herds is applied. From day 7 onwards, the epidemic curves diverge: for the culling strategy the curve is already decreasing, while for the vaccination strategies they start to increase again, as vaccination needs more time to take effect. The peak of the epidemic curves indicates the time at which the between-herd reproduction number is lowered below unity, while at the start of the epidemic the between-herd reproduction number is above unity. Figure 2.10 shows that for at least 50% of the epidemics for all basic control strategies in all DPLA starting areas, the between-herd reproduction number at the time of the first detection is above unity, which agrees with the findings in our previous study (Boender et al., 2006). The peak of the epidemic curve for the 5-km vaccination strategy is lower and earlier than for the 2-km vaccination strategy, indicating more effective control of the epidemic. The 5-km vaccination strategy even curbs the epidemic so effectively that it halts the epidemic earlier than the culling strategy, thus explaining the comparable outbreak size, but the shorter outbreak duration. It must be noted though that the differences between the basic control strategies are smaller for the 'less dense' DPLAs (Oost-Nederland and Noord-Brabant), suggesting that the relative performances of the basic control strategies strongly depend on the local farm density.

2.6.3 Results for strategies excluding hobby farms from preemptive culling

For non-commercial farms three alternative strategies are evaluated that all involve the exception of hobby farms from preemptive culling. For the culling strategy *(cul1h)* this means that the minimal strategy applies to hobby farms, i.e. a hobby farm is only culled when an infection is detected in the herd. For the vaccination strategies *(vac2h and vac5h),* the hobby farms are not preemptively culled in the first week after the first detection, but after this period they are vaccinated like the commercial farms. Table 2.5 and figures 2.11, 2.12 and 2.13 show that these alternative measures do not affect the outbreak size or duration. Statistical analysis (Wilcoxon signed-rank test) reveals that the alternative strategies are not significantly different from the basic control strategies. The alternative strategies have little effect, because from all infected farms only a small percentage (not more than 4%) are hobby farms. A more important reason however that is once a hobby farm is infected, the infectivity for other farms is so low that the probability of secondary infections is very small (making a hobby farm a 'dead end host').

Hobby farms can be excluded from preemptive culling without altering the effect of control measures. The total number of farms that need to be preemptively culled reduces by about 20%, and the number of animals to be culled by 3%.

2.6.4 Results for strategies excluding pig farms from vaccination

For pig farms an alternative strategy is evaluated, by excluding pig farms from vaccination in the 2-km and 5-km vaccination strategy *(vac2p and vac5p).* The most important advantages of this alternative are the smaller vaccination capacity that is needed (as an average pig farm is ten times larger than an average cattle farm) and an assured pig export position (as vaccinated meat is not automatically permitted on international markets). Compared to the basic control strategies of 2-km and 5-km vaccination where all farms are vaccinated, excluding the pig farms from vaccination leads to larger and longer epidemics (table 2.5 and figures 2.14 and 2.15). The median epidemic length is increased by 0-9 days and the median outbreak size by 0-13 detected farms. Although the differences are significant (except for the results of Oost-Nederland), they are not very large (for the virus strain under study). Before drawing conclusions we need to falsify the possible explanation that most pig farms are already preemptively culled in the first week after the first detection. For this reason we repeated the vaccination strategies *(vac2p, vac2p, vac5 and vac5p)* with only two days (instead of seven) of preemptive culling before vaccination starts. As expected, all strategies yielded larger and longer epidemics, but the relative differences between including and excluding pig farms in the vaccination campaign are the same. From this we can conclude that pig farms play a significant but limited role in the transmission process (again, for the virus strain under study). Although excluding pig farms from vaccination does increase the risk of large epidemics, it reduces the required vaccination capacity considerably (the number of animals to be vaccinated more than halves). Whether this strategy is economically beneficial despite the increased risk, will be evaluated in the second part of this report.

2.6.5 Results for a sparsely populated livestock area

One starting situation has been evaluated that involves a sparsely populated livestock area (SPLA) in Friesland, where the hypothetical epidemics start in a cattle farm. Four control strategies, i.e. the minimal strategy *(min)* and the three basic strategies *(cul1, vac2 and vac5),* are compared in table 2.5 and 2.6. Epidemics are much smaller, in terms of both outbreak size and duration. Due to the smaller epidemics, the differences between the basic control strategies disappear. The minimal control strategy leads to slightly larger outbreaks, but this is only caused by a small number of simulated epidemics that jump to denser areas, such as Oost-Nederland. As long as the epidemic stays in an SPLA, the minimal control strategy is sufficient to control the epidemic and additional control measures do not provide any added value. When the epidemic also starts affecting denser areas, additional control is needed as shown in the previous sections. This conclusion is in agreement with a previous study (Boender et al., 2006) that compared the basic control strategies using risk maps of the Netherlands.

2.6.6 Sensitivity to between-species differences

The epidemics in the previous sections were simulated using a heterogeneous transmission kernel (figure 2.5), that is based on literature and expert opinion. To assess the effect of these assumptions, the results (table 2.5) are compared with simulations using a homogeneous transmission kernel (table 2.8). This means that an average cattle farm is equally infectious as average pigs, sheep/goats or hobby farm during their infectious period (differences in number of infectious animals on a farm is still accounted for) and all susceptible herds are equally susceptible, regardless of size or species. Seven of nine control strategies are evaluated, all except the alternative vaccination strategies for hobby farms. Table 2.8 shows that the homogeneous epidemics have smaller outbreak sizes and shorter durations. They are less severe (compare for instance the results for the minimal control strategy), because they lack the effect of 'super spreaders' such as infected pig farms in the heterogeneous model. This effect of heterogeneity between species is mathematically described by Diekmann and Heesterbeek (2000). The effect of spatial heterogeneity (i.e. non-Poisson distributed farm densities) also leads to higher disease persistence (Hagenaars et al., 2004). Because of the smaller epidemics, the differences between the basic control strategies *(cul1, vac2 and vac5)* diminish, as was also observed in the SPLA simulations (previous section). Interestingly, the differences between the basic vaccination strategies *(vac2 and vac5)* and the vaccination strategies that exclude pig farms (*vac2p* and *vac5p*), vanish completely. The degree of vaccination in the latter strategies is apparently sufficiently high to halt the epidemic. This is not the case for the alternative culling strategy for hobby farms *(cul1h)* that leads to larger outbreaks than the basic culling strategy *(cul1)*. Here the degree of preemptive culling does not seem sufficient, due to the higher hobby farm densities. As hobby farms are now infectious to other farms (in contrast to the 'dead end hosts' they were with the heterogeneous transmission kernel), they can serve as 'stepping stones' in propagating the epidemic. The assumption of a fully homogeneous transmission kernel will obviously not hold in practice; different species and herd types will also differ in infectivity and susceptibility. It should be kept in mind though, that the relative performances of the evaluated control strategies depend on the degree of heterogeneity used in the model (see figure 2.5).

Table 2.5 Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval)

Control strategy	Duration in days		# Detected farms		# Not detected farms (before end screening)		# Infected preemptively culled farms	
Gelderse Vallei, start in cattle farm								
min	259	(181-390)	1,640	(1,126-2,145)	146	(93-197)	0	(0-0)
cul1	67	(30-124)	45	(17-97)	3	(0-8)	22	(8-53)
cul1h	66	(30-119)	45	(17-97)	3	(0-8)	21	(8-53)
vac2	76	(41-133)	72	(23-162)	17	(2-47)	6	(2-14)
vac2h	77	(40-128)	75	(23-160)	16	(3-47)	6	(2-14)
vac2p	85	(40-152)	85	(23-215)	19	(3-55)	6	(2-14)
vac5	52	(34-91)	43	(19-89)	12	(3-34)	6	(2-14)
vac5h	53	(33-88)	44	(19-88)	12	(2-35)	6	(2-14)
vac5p	55	(33-106)	45	(19-105)	13	(2-37)	6	(2-14)
Oost-Nederland, start in cattle farm								
min	167	(54-392)	302	(37-2,083)	25	(2-186)	0	(0-0)
cul1	51	(22-103)	26	(12-62)	2	(0-5)	11	(5-26)
cul1h	50	(22-101)	26	(12-64)	2	(0-5)	12	(4-25)
vac2	59	(26-120)	36	(15-104)	5	(0-20)	5	(1-15)
vac2h	58	(28-127)	36	(14-116)	5	(1-22)	5	(1-15)
vac2p	59	(25-119)	36	(15-106)	5	(0-20)	5	(1-15)
vac5	45	(25-84)	29	(13-60)	5	(1-16)	5	(1-15)
vac5h	47	(28-90)	30	(13-61)	5	(1-17)	5	(1-15)
vac5p	46	(27-87)	29	(13-60)	5	(1-15)	5	(1-15)

Table 2.5 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) (continued)**

Control strategy	Duration in days		# Detected farms		# Not detected farms (before end screening)		# Infected preemptively culled farms	
Friesland, start in cattle farm								
min	34	(9-100)	9	(4-28)	1	(0-5)	0	(0-0)
cul1	26	(9-71)	7	(3-16)	1	(0-3)	1	(0-4)
vac2	30	(8-72)	7	(3-19)	1	(0-4)	0	(0-2)
vac5	29	(8-60)	7	(3-16)	1	(0-4)	0	(0-2)
Gelderse Vallei, start in pig farm								
min	243	(168-377)	1,722	(1,232-2,254)	155	(107-208)	0	(0-0)
cul1	70	(41-118)	78	(36-126)	6	(1-11)	49	(20-90)
cul1h	72	(40-122)	76	(35-127)	5	(1-11)	48	(18-91)
vac2	77	(51-128)	118	(50-210)	27	(8-59)	19	(6-46)
vac2h	78	(51-125)	120	(48-212)	27	(9-58)	19	(5-46)
vac2p	86	(52-147)	130	(56-248)	30	(8-67)	19	(6-46)
vac5	58	(39-94)	80	(39-142)	24	(8-50)	19	(6-46)
vac5h	57	(38-94)	80	(38-145)	23	(7-52)	19	(5-46)
vac5p	62	(39-106)	87	(39-156)	25	(7-51)	19	(6-46)

Table 2.5 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) (continued)**

Control strategy	Duration in days		# Detected farms		# Not detected farms (before end screening)		# Infected preemptively culled farms	
Noord-Brabant, start in pig farm								
min	112	(53-402)	138	(43-2,111)	16	(4-195)	0	(0-0)
cul1	58	(31-110)	41	(20-87)	4	(1-10)	14	(6-37)
cul1h	59	(30-116)	42	(20-95)	4	(1-10)	14	(5-36)
vac2	63	(34-130)	52	(23-147)	9	(2-33)	6	(2-13)
vac2h	66	(35-131)	54	(23-149)	9	(2-35)	6	(1-13)
vac2p	65	(34-139)	54	(23-182)	9	(2-41)	6	(2-13)
vac5	50	(31-88)	44	(21-88)	9	(3-26)	6	(2-13)
vac5h	52	(32-90)	44	(22-89)	10	(2-25)	6	(1-13)
vac5p	52	(32-101)	44	(21-92)	9	(3-26)	6	(2-13)

Table 2.5	Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) (continued)							
Control strategy	# Preemptively culled farms		# Vaccinated farms		# Preemptively culled animals (x 1,000)		# Vaccinated animals (x 1,000)	
Gelderse Vallei, start in cattle farm								
min	0	(0-0)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	974	(342-1870)	0	(0-0)	275	(93-514)	0	(0-0)
cul1h	784	(292-1501)	0	(0-0)	268	(95-498)	0	(0-0)
vac2	165	(76-300)	2,416	(706-4,400)	49	(18-90)	630	(180-1,129)
vac2h	137	(60-250)	2,474	(724-4,429)	49	(18-89)	631	(175-1,079)
vac2p	165	(76-300)	2,159	(574-4,624)	49	(18-90)	246	(66-454)
vac5	165	(76-300)	4,065	(1,935-7,469)	49	(18-90)	955	(480-1,765)
vac5h	137	(60-250)	4,196	(1,953-7,709)	49	(18-89)	980	(467-1,785)
vac5p	165	(76-300)	3,509	(1,542-7,516)	49	(18-90)	362	(173-673)
Oost-Nederland, start in cattle farm								
min	0	(0-0)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	405	(212-1,003)	0	(0-0)	60	(18-217)	0	(0-0)
cul1h	332	(168-747)	0	(0-0)	58	(18-204)	0	(0-0)
vac2	111	(45-213)	992	(273-3,529)	12	(5-34)	168	(32-804)
vac2h	87	(36-181)	1023	(283-3,586)	12	(4-33)	174	(32-802)
vac2p	111	(45-213)	888	(263-2,878)	12	(5-34)	61	(18-252)
vac5	111	(45-213)	2962	(955-6,888)	12	(5-34)	506	(114-1,479)
vac5h	87	(36-181)	3010	(1,064-7,175)	12	(4-33)	520	(123-1,497)
vac5p	111	(45-213)	2600	(869-5,774)	12	(5-34)	184	(60-442)

Table 2.5 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) (continued)**

Control strategy	# Preemptively culled farms		# Vaccinated farms		# Preemptively culled animals (x 1,000)		# Vaccinated animals (x 1,000)	
Friesland, start in cattle farm								
min	0	(0-0)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	60	(18-177)	0	(0-0)	6	(2-21)	0	(0-0)
vac2	24	(4-60)	117	(0-477)	2	(0-8)	12	(0-61)
vac5	24	(4-60)	547	(0-1,629)	2	(0-8)	59	(0-205)
Gelderse Vallei, start in pig farm								
min	0	(0-0)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	1538	(714-2,300)	0	(0-0)	423	(183-613)	0	(0-0)
cul1h	1219	(577-1,832)	0	(0-0)	408	(184-612)	0	(0-0)
vac2	328	(142-574)	3,168	(1,558-5,315)	94	(36-172)	798	(418-1,316)
vac2h	271	(116-481)	3,296	(1,588-5,244)	93	(36-171)	810	(393-1,295)
vac2p	328	(142-574)	2,839	(1,300-5,064)	94	(36-172)	300	(152-474)
vac5	328	(142-574)	5,980	(3,350-10,116)	94	(36-172)	1366	(794-2,348)
vac5h	271	(116-481)	6023	(3384-10279)	93	(36-171)	1340	(777-2368)
vac5p	328	(142-574)	5420	(2,689-9,867)	94	(36-172)	506	(278-834)

Table 2.5 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) (continued)**

Control strategy	# Preemptively culled farms		# Vaccinated farms		# Preemptively culled animals (x 1,000)		# Vaccinated animals (x 1,000)	
Noord-Brabant, start in pig farm								
min	0	(0-0)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	575	(273-1,438)	0	(0-0)	276	(124-588)	0	(0-0)
cul1h	442	(206-1,241)	0	(0-0)	274	(119-602)	0	(0-0)
vac2	128	(66-219)	1467	(566-4,411)	69	(29-124)	645	(248-1,517)
vac2h	99	(50-168)	1560	(546-4,607)	69	(30-124)	668	(232-1,592)
vac2p	128	(66-219)	1098	(394-4,179)	69	(29-124)	92	(33-414)
vac5	128	(66-219)	4364	(1,920-9,042)	69	(29-124)	1786	(789-3,162)
vac5h	99	(50-168)	4401	(2,039-9,021)	69	(30-124)	1751	(791-3,227)
vac5p	128	(66-219)	3432	(1,440-7,254)	69	(29-124)	280	(117-627)

Table 2.6 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) of number of infected (i.e. detected + not detected) and number of not detected farms and average species composition**

Control	Infected farms						Not detected farms (before end screening)					
strategy	total number		% cattle	% sheep	% pigs	% hobby	total number		% cattle	% sheep	% pigs	% hobby
Gelderse Vallei, start in cattle farm												
min	1,788	(1,232-2,336)	84	9	4	3	146	(93-197)	12	86	0	1
cul1	70	(28-154)	89	7	2	2	3	(0-8)	15	84	0	1
cul1h	70	(27-152)	89	7	2	2	3	(0-8)	15	83	0	1
vac2	96	(32-216)	88	7	3	2	17	(2-47)	60	38	1	1
vac2h	98	(31-213)	88	7	3	2	16	(3-47)	59	38	2	2
vac2p	112	(32-282)	87	7	4	2	19	(3-55)	59	39	0	2
vac5	61	(29-133)	89	7	3	2	12	(3-34)	67	30	2	2
vac5h	63	(28-128)	89	7	3	2	12	(2-35)	66	31	2	2
vac5p	66	(28-150)	87	7	4	2	13	(2-37)	67	32	0	2

Table 2.6 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) of number of infected (i.e. detected + not detected) and number of not detected farms and average species composition (continued)**

Control	Infected farms						Not detected farms (before end screening)					
strategy	total number		% cattle	% sheep	% pigs	% hobby	total number		% cattle	% sheep	% pigs	% hobby
Oost-Nederland, start in cattle farm												
min	326	(40-2,262)	88	8	2	2	25	(2-186)	14	85	0	1
cul1	40	(21-90)	90	7	1	2	2	(0-5)	15	83	0	2
cul1h	40	(22-85)	90	7	1	2	2	(0-5)	14	84	0	2
vac2	47	(22-126)	90	7	1	2	5	(0-20)	45	53	0	2
vac2h	48	(22-134)	90	7	1	2	5	(1-22)	46	52	0	1
vac2p	48	(23-132)	90	7	1	2	5	(0-20)	46	53	0	1
vac5	41	(22-79)	90	7	1	2	5	(1-16)	55	43	0	2
vac5h	41	(21-82)	90	7	1	2	5	(1-17)	56	42	0	2
vac5p	41	(22-79)	90	7	1	2	5	(1-15)	55	43	0	2
Friesland, start in cattle farm												
min	10	(5-31)	81	16	0	2	1	(0-5)	7	92	0	0
cul1	9	(5-19)	82	16	0	2	1	(0-3)	8	92	0	1
vac2	9	(5-23)	82	16	0	2	1	(0-4)	13	86	0	1
vac5	9	(5-19)	82	16	0	2	1	(0-4)	17	82	0	1

Table 2.6 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) of number of infected (i.e. detected + not detected) and number of not detected farms and average species composition (continued)**

Control	Infected farms							Not detected farms (before end screening)					
strategy	total number		% cattle	% sheep	% pigs	% hobby		total number		% cattle	% sheep	% pigs	% hobby
Gelderse Vallei, start in pig farm													
min	1,878	(1,354-2,457)	84	9	4	3		155	(107-208)	12	87	0	1
cul1	133	(62-218)	85	8	5	2		6	(1-11)	13	86	1	1
cul1h	129	(60-221)	85	8	5	2		5	(1-11)	13	85	0	2
vac2	168	(75-294)	85	8	4	2		27	(8-59)	58	39	2	1
vac2h	170	(71-298)	85	8	4	2		27	(9-58)	58	39	2	2
vac2p	183	(81-335)	84	8	6	2		30	(8-67)	57	41	0	2
vac5	126	(60-223)	84	8	5	2		24	(8-50)	63	34	2	2
vac5h	124	(62-225)	84	8	5	2		23	(7-52)	63	34	2	2
vac5p	134	(61-232)	83	8	6	2		25	(7-51)	63	35	0	2

Table 2.6 **Simulation results for heterogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) of number of infected (i.e. detected + not detected) and number of not detected farms and average species composition (continued)**

Control	Infected farms							Not detected farms (before end screening)					
strategy	total number		% cattle	% sheep	% pigs	% hobby		total number		% cattle	% sheep	% pigs	% hobby
Noord-Brabant, start in pig farm													
min	155	(49-2305)	79	11	7	3		16	(4-195)	10	88	1	1
cul1	58	(31-132)	74	12	11	4		4	(1-10)	9	89	1	1
cul1h	60	(31-140)	74	11	11	4		4	(1-10)	8	90	1	1
vac2	67	(33-187)	75	11	10	4		9	(2-33)	30	67	1	2
vac2h	70	(32-191)	75	11	10	4		9	(2-35)	31	66	1	2
vac2p	69	(32-229)	75	11	10	4		9	(2-41)	31	67	0	2
vac5	59	(30-122)	73	12	11	4		9	(3-26)	38	58	2	2
vac5h	59	(31-119)	73	12	11	4		10	(2-25)	38	58	2	2
vac5p	60	(31-123)	73	11	11	4		9	(3-26)	39	58	0	2

Table 2.7 **Required culling and vaccination capacities in second week after the first detection: median values (and 90% interval between brackets)**

	# Farms/day		# Animals/day	
	required culling capacity for 1-km ring culling			
cattle	11	(0-49)	1358	(0-8,233)
sheep	2	(0-11)	55	(0-1,080)
pigs	4	(0-25)	2410	(0-16,802)
hobby	2	(0-16)	20	(0-160)
	required vaccination capacity for 2-km ring vaccination			
cattle	30	(0-141)	3779	(0-22,843)
sheep	7	(0-34)	280	(0-2,408)
pigs	12	(0-72)	7965	(0-47,463)
hobby	9	(0-46)	90	(0-4,60)
	required vaccination capacity for 5-km ring vaccination			
cattle	69	(0-473)	8643	(0-75,673)
sheep	19	(0-130)	920	(0-8,397)
pigs	20	(0-229)	14355	(0-15,2647)
hobby	25	(0-161)	250	(0-1,610)

Table 2.8 **Simulation results for homogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval)**

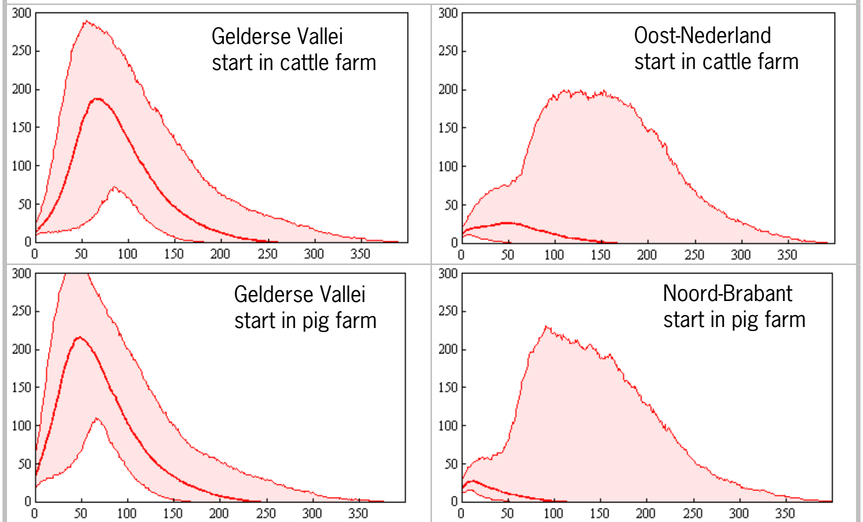
Control strategy	Duration in days		# Detected farms		# Not detected farms (before end screening)		# Infected preemptively culled farms		# Preemptively culled farms		# Vaccinated farms	
Gelderse Vallei, start in cattle farm												
min	188	(63-350)	237	(34-535)	28	(5-67)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	37	(20-73)	18	(11-28)	2	(0-5)	9	(4-17)	438	(230-682)	0	(0-0)
cul1h	54	(24-102)	27	(13-47)	3	(0-7)	9	(4-18)	478	(206-824)	0	(0-0)
vac2	38	(23-69)	21	(12-33)	3	(0-8)	5	(1-10)	150	(67-257)	756	(296-1,242)
vac2p	39	(23-69)	22	(12-35)	3	(0-7)	5	(1-10)	150	(67-257)	581	(231-962)
vac5	35	(21-60)	19	(11-31)	3	(1-7)	5	(1-10)	150	(67-257)	2058	(884-3,114)
vac5p	35	(22-60)	20	(11-32)	3	(0-7)	5	(1-10)	150	(67-257)	1637	(726-2,542)
Oost-Nederland, start in cattle farm												
min	84	(38-186)	40	(20-116)	7	(2-22)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	37	(18-75)	14	(7-23)	2	(0-5)	7	(3-13)	252	(146-378)	0	(0-0)
cul1h	45	(20-94)	18	(9-33)	2	(0-6)	6	(2-12)	226	(124-389)	0	(0-0)
vac2	38	(20-72)	16	(8-25)	3	(0-7)	4	(0-10)	91	(35-178)	407	(129-804)
vac2p	37	(20-72)	16	(8-25)	3	(0-7)	4	(0-10)	91	(35-178)	370	(124-691)
vac5	33	(19-62)	15	(7-23)	3	(0-7)	4	(0-10)	91	(35-178)	1,429	(465-2,866)
vac5p	33	(20-63)	15	(7-23)	3	(0-7)	4	(0-10)	91	(35-178)	1,308	(451-2,502)

Table 2.8 **Simulation results for homogeneous transmission for different control strategies and starting scenarios; median values (between brackets two-sided 90% interval) (continued)**

Control strategy	Duration in days		# Detected farms		# Not detected farms (before end screening)		# Infected preemptively culled farms		# Preemptively culled farms		# Vaccinated farms	
Gelderse Vallei, start in pig farm												
min	186	(64-358)	222	(34-544)	27	(4-69)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	43	(21-99)	20	(11-36)	2	(0-6)	10	(4-19)	479	(236-851)	0	(0-0)
cul1h	54	(24-103)	25	(13-46)	2	(0-6)	10	(4-17)	459	(207-805)	0	(0-0)
vac2	45	(25-88)	24	(12-49)	4	(1-13)	5	(1-10)	148	(64-254)	888	(345-1,905)
vac2p	45	(25-91)	25	(12-56)	4	(1-12)	5	(1-10)	148	(64-254)	683	(274-1,512)
vac5	38	(24-73)	21	(12-37)	4	(1-11)	5	(1-10)	148	(64-254)	2278	(1,108-3,937)
vac5p	38	(24-76)	22	(12-42)	4	(1-11)	5	(1-10)	148	(64-254)	1,806	(885-3,283)
Noord-Brabant, start in pig farm												
min	68	(35-146)	33	(19-68)	5	(1-12)	0	(0-0)	0	(0-0)	0	(0-0)
cul1	46	(22-87)	18	(10-30)	2	(0-6)	6	(2-10)	262	(145-471)	0	(0-0)
cul1h	47	(23-94)	20	(11-34)	2	(0-5)	5	(2-9)	211	(114-371)	0	(0-0)
vac2	47	(23-89)	20	(10-35)	4	(1-8)	3	(0-6)	79	(32-133)	579	(222-1,160)
vac2p	50	(25-92)	21	(11-38)	4	(1-9)	3	(0-6)	79	(32-133)	430	(165-930)
vac5	40	(24-73)	18	(10-31)	4	(1-9)	3	(0-6)	79	(32-133)	2040	(896-3,767)
vac5p	39	(24-76)	19	(10-34)	4	(1-8)	3	(0-6)	79	(32-133)	1506	(631-2,891)

Figure 2.8 **Epidemic curves for minimal control strategy: median values of number of infectious farms (solid line) and 90% interval (shaded area) for four different starting situations**

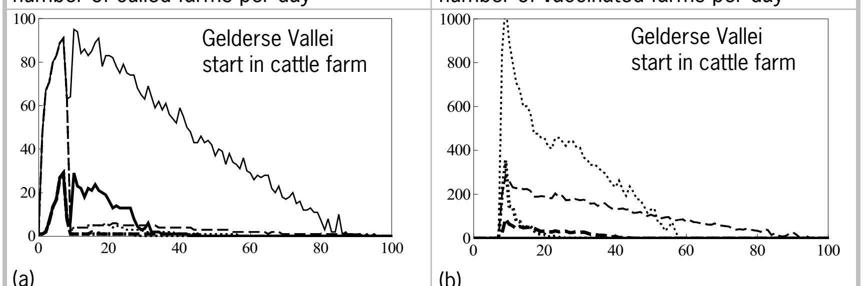
number of infectious farms (5%-50%-95%)



time since first detection (days)

Figure 2.9 **Required capacity for of (a) culling and (b) vaccination for the basic control strategies: median values (thick lines) and 95% quantiles (thin lines) for preemptive ring culling (solid) and ring vaccination within 2-km radius (dashed) and 5-km radius (dotted) in the Gelderse Vallei, start in cattle farm**

number of culled farms per day | number of vaccinated farms per day



time since first detection (days) | time since first detection (days)

Figure 2.10 **Epidemic curves for the basic control strategies: preemptive ring culling (solid black) and ring vaccination within 2-km radius (dotted blue) and 5-km radius (dashed magenta); median values of number of infectious farms (thick line) and 95% percentile (thin line) for four different starting situations**

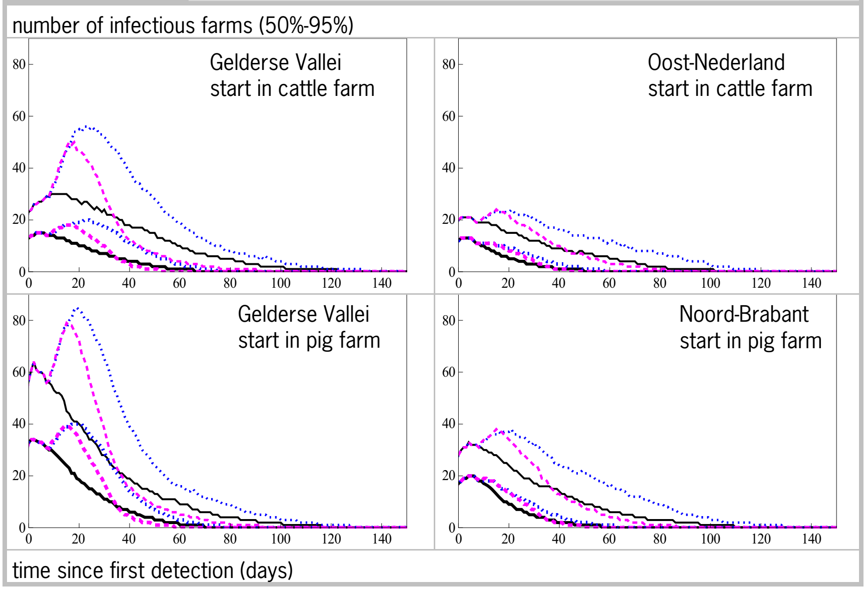


Figure 2.11 **Epidemic curves for preemptive ring culling (solid black) and preemptive ring culling except hobby farms (dashed green); median values of number of infectious farms (thick line) and 90% interval (shaded area) for four different starting situations**

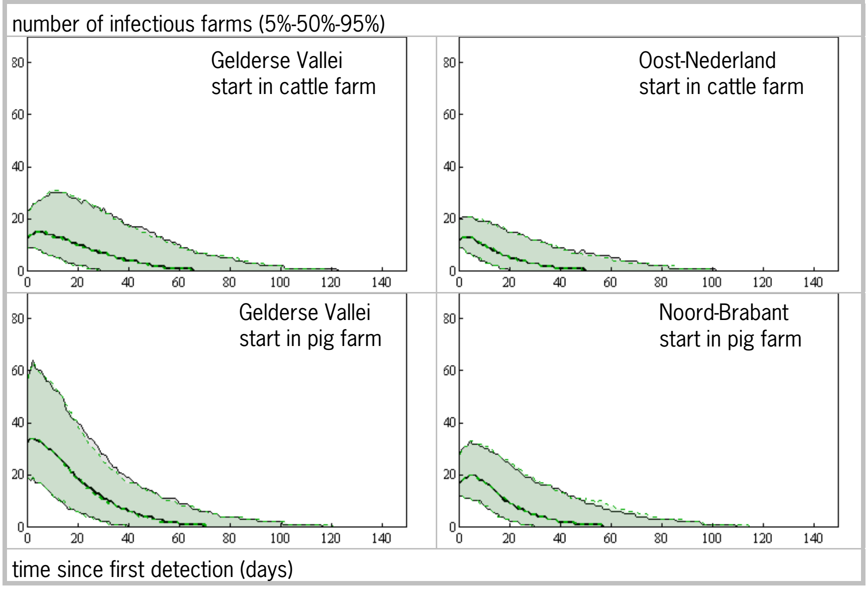
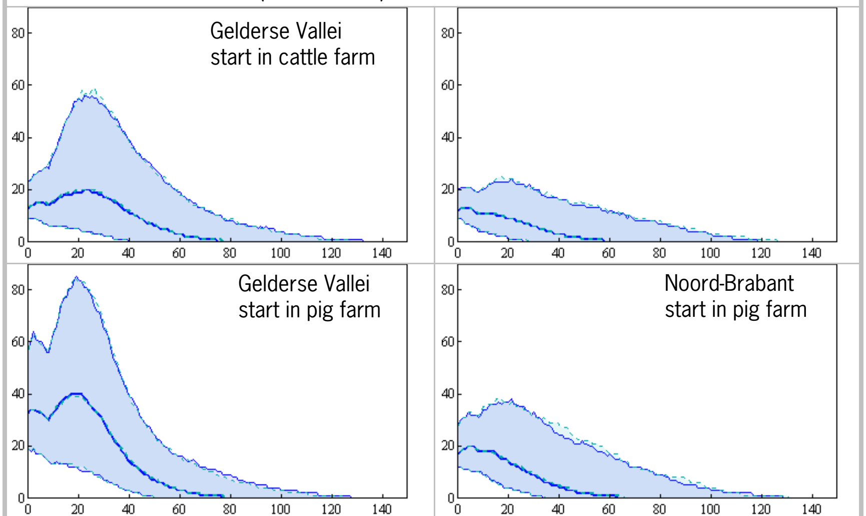


Figure 2.12 **Epidemic curves for preemptive ring culling (solid black) and preemptive ring culling except hobby farms (dashed green); median values of number of infectious farms (thick line) and 90% interval (shaded area) for four different starting situations**

number of infectious farms (5%-50%-95%)



time since first detection (days)

Figure 2.13	Epidemic curves for ring vaccination within 5-km radius (solid magenta) and ring vaccination within 5-km radius except culling hobby farms in first week (dashed purple); median values of number of infectious farms (thick line) and 90% interval (shaded area) for four different starting situations

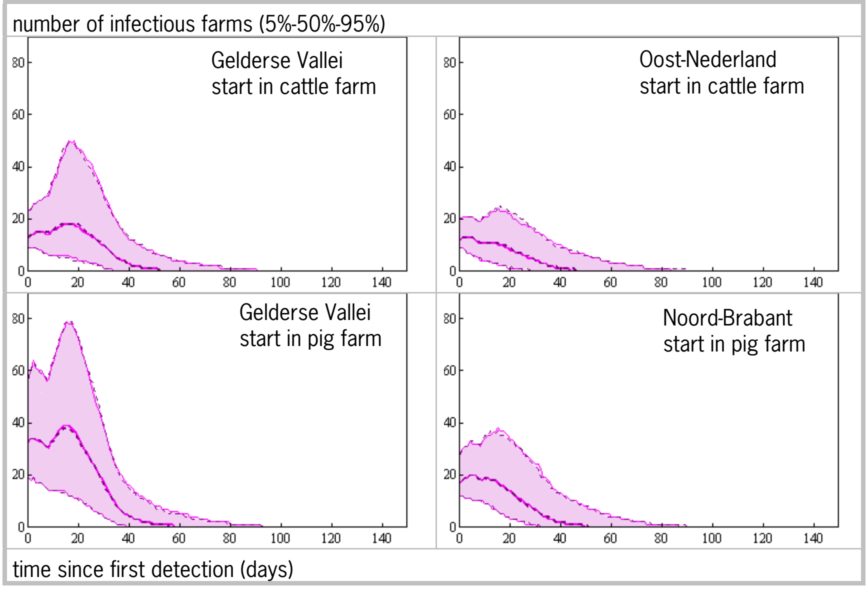


Figure 2.14	Epidemic curves for ring vaccination within 2-km radius (solid blue) and ring vaccination within 2-km radius except pig farms (dashed cyan); median values of number of infectious farms (thick line) and 90% interval (shaded area) for four different starting situations

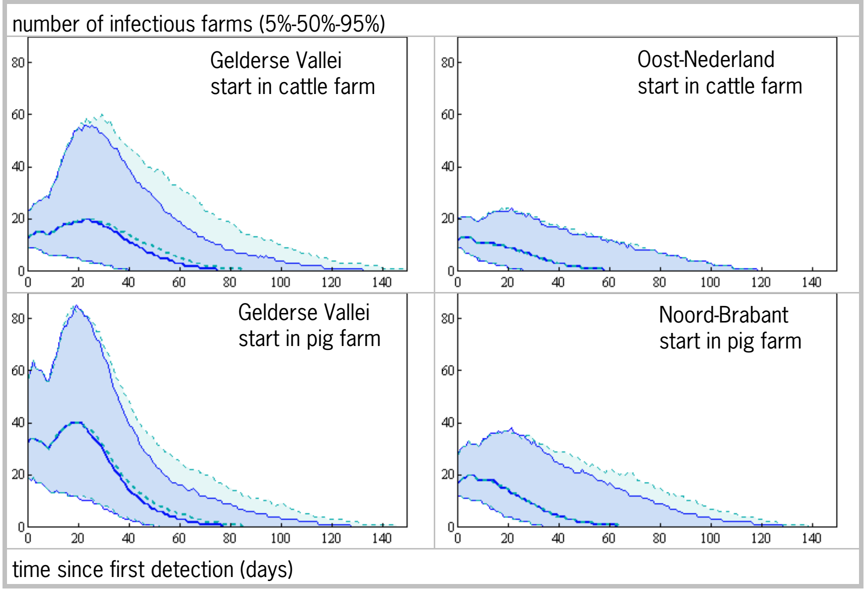
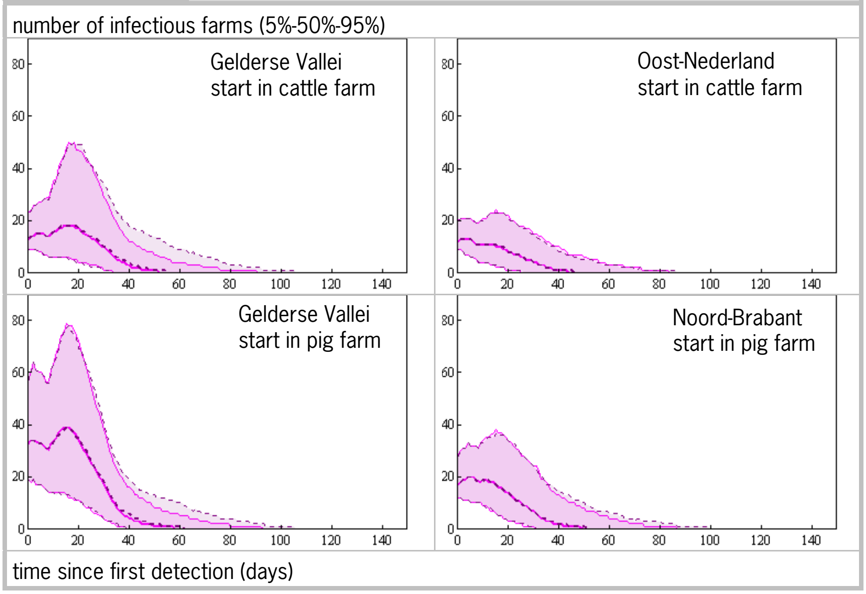


Figure 2.15 **Epidemic curves for ring vaccination within 5-km radius (solid magenta) and ring vaccination within 5-km radius except pig farms (dashed purple); median values of number of infectious farms (thick line) and 90% interval (shaded area) for four different starting situations**



3 Freedom of infection

Authors: Jantien Backer, Thomas Hagenaars, Gonnie Nodelijk, Herman van Roermund

3.1 Introduction: freedom of infection

The country is divided into 20 compartments with clear boundaries, such as rivers, highways, et cetera (Ministry of Agriculture, Nature and Food Quality, 2003). During an epidemic, strict regulations apply in the compartments with infected farms. Around every confirmed infected and subsequently culled herd a 3-km protection zone ('beschermingsgebied') and a 10-km surveillance zone ('toezichtsgebied') are set up. Depending on the control strategy a 2-km or 5-km vaccination zone may apply around a detected herd. These vaccination zones do not influence the outer radius of the protection or surveillance zones. This means that with the 2-km vaccination strategy the vaccination zone stretches from 0 to 2km around an infected herd, the protection zone from 2 to 3km and the surveillance zone from 3 to 10km. With the 5-km vaccination strategy, the vaccination zone stretches from 0 to 5km around an infected herd and the surveillance zone from 5 to 10km (effectively cancelling the protection zone).

All farms in these zones are closed and strict transport regulations apply. To lift these constraints after the epidemic, EU regulation requires that the affected areas are without outbreak for at least 30 days before an end screening may take place to substantiate freedom of infection. When the survey has been concluded with negative results, the country can be declared free to resume international trade.

The end screening consists of clinical inspection and serological testing. All animals of susceptible species on all farms within the surveillance zones of 10km, which include the protection zone and - if applicable - the vaccination zone, must be clinically examined. Depending on the zone (vaccination, protection or surveillance) and the end-screening strategy applied, blood samples are taken from a number of animals for serological testing.

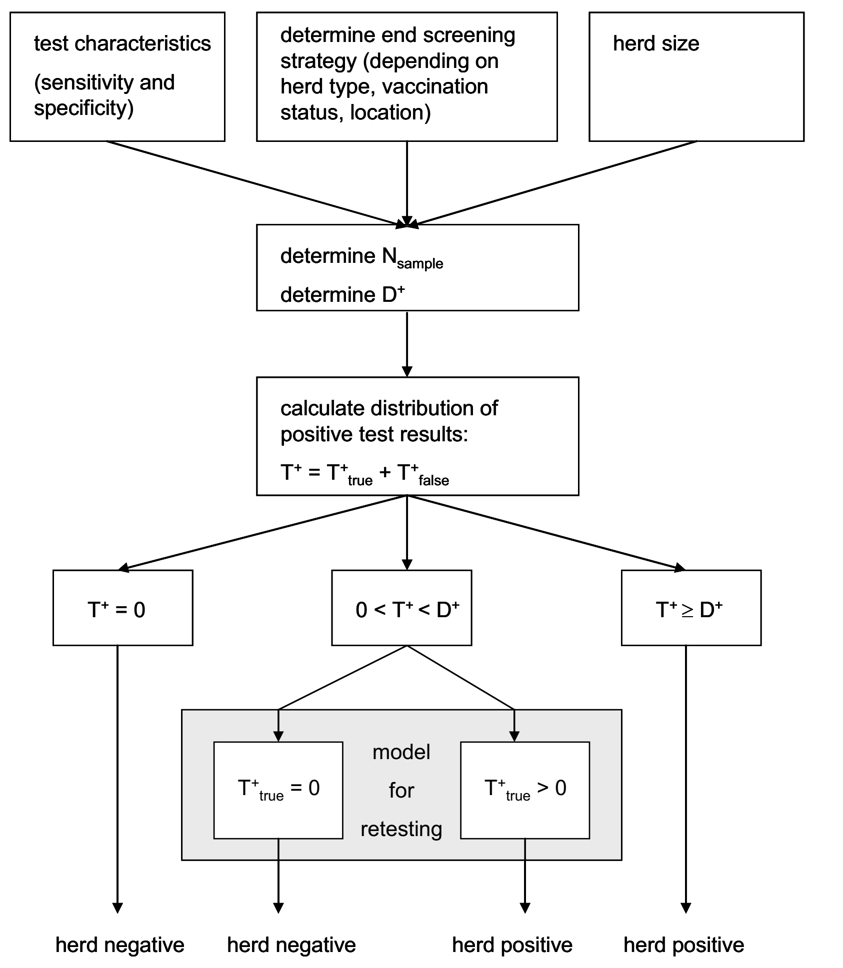
Even though the end screening can take place at day 30 after the last outbreak in a surveillance area, in practice the decision to start the end screening also depends on the number of cases, expert opinion, et cetera. In the model analyses we will perform the end screening at the end of each simulated epidemic, and we will only consider the serological screening. Clinical inspection would not yield any positive results, as at the end of a simulated epidemic all infected animals have either been detected or have recovered. It is assumed that all recovered animals have seroconverted (justified by the fact that the seroconversion rate is also reflected in the test sensitivity) and could be detected in the serological survey. In this way the end screening is focused on detecting seropositive non-infectious animals that were missed during the epidemic, and that might pose a risk to the export position of the country.

For our analyses the end screening is described by a model. Depending on the end screening strategy, the test characteristics, the herd size and the number of seropositive animals on the farm, we calculate the probabilities of the herd to be declared positive or negative, with or without retesting (retesting of a farm means using the same test again for a new blood sample of the positively tested animal(s) and animals that are in close contact with them). This end-screening model is applied to each farm that needs to be screened at the end of an epidemic, depending on the end-screening strategy. The EU-required strategy serves as a starting point and we will examine a less stringent and a more stringent alternative, as well as the combination. We will use the results of the simulated epidemics (chapter 2) to evaluate the performance of the different end-screening strategies, when different control strategies have been applied during the epidemic.

3.2 End-screening model

When a herd is subjected to a serological screening, several steps need to be taken, both in practice and in the model. The flow diagram shown in figure 3.1 represents this process for the model schematically. The flow diagram largely follows the procedure as will most probably be used in a real outbreak situation, but for the model situation we can make some shortcuts as the true disease status of each animal in the model is known. First, the test characteristics of the test used for serological screening must be known. Both the sensitivity and specificity can differ for different animal types and vaccination status (see section 3.2.1). Next, the end-screening strategy for the herd must be determined, depending on the animal species, vaccination status and whether the farm is located in the protection or surveillance zone. For the most part the end-screening strategy is specified in EU council directive 2003/85/EC (see section 3.3). We will examine this strategy, as well as some less and more stringent alternatives. With the test sensitivity and the end-screening strategy, we can determine the number of animals that must be sampled (see section 3.2.2; here we will find that some farms are so small that the specified level of certainty cannot be achieved). When we set the herd specificity to 99.99% and with the sample size and the test specificity known, we can determine a threshold value D^+ for the number of false positives in the sample (see section 3.2.3). We will use this threshold later on to compare with the actual number of positive test results. Next, we will calculate the distribution of the number of positive test results T^+, that is a combination of the distribution of the number of true positive test results T^+_{true}, and the distribution of the number of false positive test results, T^+_{false} (see section 3.2.4). Depending on the total number of positive results T^+ (= T^+_{true} + T^+_{false}) three situations can occur. When all results are negative ($T^+ = 0$), the herd is immediately declared negative. When the number of positive test results is equal to or higher than the upper limit for false positives ($T^+ \geq D^+$), the chance that these are all false positives is 0.01% or less. Retesting of the herd seems unnecessary; instead, the herd is immediately declared positive and subsequently culled. When the number of positive test results is in between these extremes ($0 < T^+ < D^+$), the herd needs to be retested. In practice, new samples will be taken from the previously sampled animals (in the first test round) and animals around them. When the animals are tested positive again and evidence of clustering is found (i.e. animals around the positive animal are also tested positive), the herd is declared positive. When no evidence of clustering is found, only the positive animals are culled and the farm is declared negative. In the model, the herd will not actually be tested again, but we use a model representation for retesting of the herd instead. This shortcut is allowed, as we know the distribution of true and false positive test results. The follow-up is assumed to be infallible, meaning that when the positive test results contain true positives ($T^+_{true} > 0$), the farm will be declared positive and when the positive test results do not contain any true positives ($T^+_{true} = 0$), the farm is declared negative.

Figure 3.1 **Flow diagram of end-screening model a)**



a) N_{sample} is the number of animals in the sample, D^+ is the 99.99% threshold value of false positives, T^+ is the number of positive test results (of which T^+_{true} are true positives and T^+_{false} are false positives)

3.2.1 Test characteristics

For the serological end screening the Ceditest will be used. This is an ELISA test that detects antibodies against non-structural (NS) proteins of the FMD virus. As these NS proteins are only present in animals that are infected by a (replicating) wild type virus (and not in vaccinated animals), the test can be used to distinguish between vaccinated non-infected and vaccinated infected animals. Two recent studies have examined the performance of this test. Brocchi et al. (2006) examined several species of susceptible animals, but the testing numbers for sheep and pigs are small. Engel et al. (2008) have analysed the data for cattle in a Bayesian framework.

Brocchi et al. (2006) estimated the test sensitivity for non-vaccinated cattle as 100% (94.6-100), meaning all infected unvaccinated animals are detected. The confidence interval is reasonably broad, because of the relatively small number of animals tested (n=54). In the Bayesian analysis the sensitivity is estimated as 97% (90.8-99.4) (Engel et al., 2008). This might be an underestimation as the model assumes that all animals have seroconverted before 21 days post infection. In the model calculations we assume a test sensitivity for non-vaccinated cattle of 98%.

The test sensitivity for vaccinated cattle increases with the time since infection; measured detection rates range from 48.6% to 74.5% (Brocchi et al., 2006). The Bayesian analysis however estimates a higher sensitivity of 85% (78.9-89.7). The discrepancy is partly explained by the fact that the former results are for experimentally infected vaccinated cattle only, and the latter for both experimental and field data. In the model calculations we assume a conservative test sensitivity for vaccinated cattle of 70%.

The test specificity for non-vaccinated cattle is estimated as 97.2% (Brocchi et al., 2006) and in the Bayesian analysis as 97% (95.8-98.2) (Engel et al., 2008). For vaccinated cattle the specificity is estimated to be higher: 99.5% (Brocchi et al., 2006) and 99% (97.9-99.5) (Engel et al., 2008). Even though retesting the positive samples would increase the specificity (especially for non-vaccinated animals, Brocchi et al., 2006), it is probable that the farm will also be revisited to take extra samples. For the model we choose a test specificity for non-vaccinated cattle of 99% and for vaccinated cattle of 97%.

Brocchi et al. (2006) report on only a small number of sheep and pigs (9 non-vaccinated sheep, 6 vaccinated sheep, 12 non-vaccinated pigs and 18 vaccinated pigs). As a consequence, the confidence intervals for the test sensitivity and specificity are very broad and include the values for cattle. Therefore, we assume that the test characteristics for sheep and pigs are the same as forCcattle. Table 3.1 summarises all test sensitivities and specificities used in the model. The values were discussed with and agreed by FMD virologists (CVI).

Table 3.1	**Test characteristics in the model**			
	Sensitivity		**Specificity**	
	non-vaccinated	**vaccinated**	**non-vaccinated**	**vaccinated**
Cattle	0.98	0.70	0.97	0.99
Sheep	0.98	0.70	0.97	0.99
Pigs	0.98	0.70	0.97	0.99

3.2.2 Determination of sample sizes

To determine the required sample size (to detect the design prevalence with a prescribed certainty), the probability *P* not to detect any true positive animal in the sample is calculated. This probability is related to the total number of animals *N*, the sample size *n* and the test sensitivity *se*. When *S* out of *N* animals are seropositive, we calculate the probability that none of the *S* seropositive animals is detected ($P(T^+_{true}=0)$) by considering all possibilities that *i* seropositive animals are present in the sample. For each of these possibilities the probability is calculated that none of the *i* seropositive animals are detected (with a probability of *(1-se)* each) and all of these probabilities are summed:

$$P(T^+_{true} = 0) = \sum_{i=0}^{\min[n,S]} \frac{\binom{S}{i}\binom{N-S}{n-i}}{\binom{N}{n}} (1-se)^i \qquad [3.1]^{1}$$

An end-screening scenario denoted by 5/95 in table 3.2, means that for an assumed true within-herd prevalence of 5%, the required sample size is such that probability *1-P* is larger than or equal to 95% (i.e. at least one true positive animal is detected with 95% certainty). By setting *S* to *0.05 N* in Eq. 3.1 the

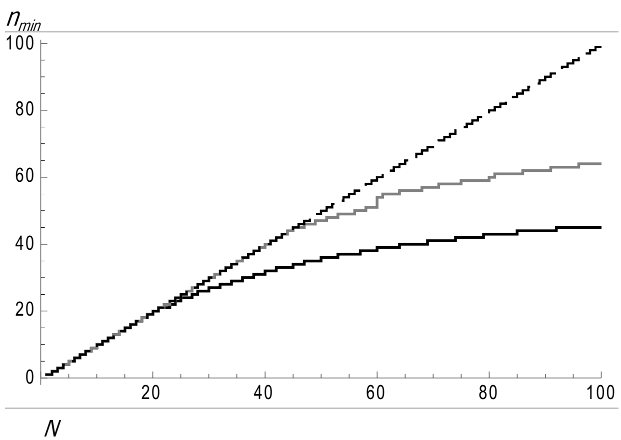
[1] When the non-perfect specificity is taken into account, instead of Eq. 3.1

$$P(T^+_{true} = 0) = \sum_{t=0}^{D^+-1} P(T^+ = t \mid T^+_{true} = 0) \qquad [3.1.b]$$

should be used, where $P(T^+=t/T^+_{true}=0)$ is defined by Eq. 3.5 and D^+ is a threshold value determined by the herd specificity (see section 3.2.4). When the herd specificity is sufficiently high, the difference between Eq. 3.1 and 3.1.2 is negligible.

minimal sample size n_{min} is calculated by solving the inequality $1\text{-}P(T^{+}_{true} = 0) \geq 0.95$. Figure 3.2 shows the calculated minimal sample sizes as a function of herd size, for the three possible situations in the end-screening scenario. When the discrete nature of the number of seropositive animals is taken into account (i.e. by setting S to $\lfloor 0.05\ N \rfloor$), the lines in figure 3.2 become tooth saws. This is done in the analyses, but omitted in the figure because of clarity reasons. As an illustration, the 5/95 sample size for a non-vaccinated cattle farm of 100 animals is 46 animals (test sensitivity of 98%), for a non-vaccinated pig farm of 1,000 animals 58 animals (test sensitivity of 98%) and for a vaccinated sheep farm of 100 animals 64 animals (test sensitivity of 70%).

Figure 3.2 **Minimal sample size n_{min} as a function of total number of animals N, when at least one seropositive animal is detected with at least 95% certainty at a design seroprevalence of 5% with a test sensitivity of 98% (solid black line) or 70% (solid gray line) or when all animals are tested ($n_{min} = N$, dashed line)**



For small farms the seroprevalence cannot be as low as required (5%) because of the limited number of animals and/or the certainty level cannot be as high as required (95%) because of the low sensitivity. The safest option, despite the fact that the requirements are not met, is to test all animals. This is the case for non-vaccinated farms up to 22 animals and vaccinated farms up to 45 animals (where the solid black and gray lines start to deviate from the dashed line in figure 3.2).

3.2.3 Determination of threshold value of false positives in sample

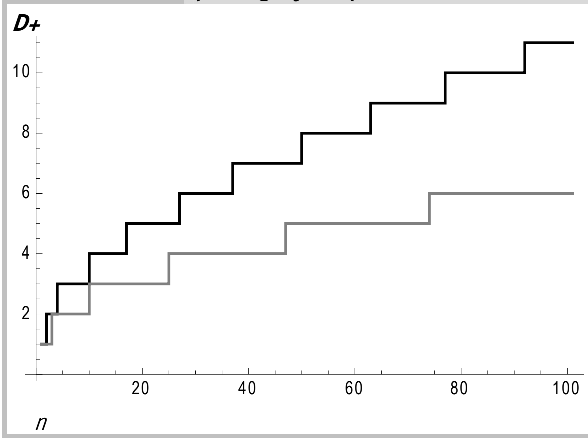
Suppose that all animals in a sample of size n are truly seronegative. The number of false positives T^{+}_{false} in this sample, i.e. the animals that test positive, follows a binomial distribution:

$$P(T^{+}{}_{false} = t) = \binom{n}{t}(1-sp)^{t}\, sp^{n-t} \quad [3.2]$$

Setting the herd specificity to 99.99%, the threshold value D^{+} is determined by calculating the upper 99.99% percentile of this distribution, i.e. finding the minimal value of T that satisfies:

$$\sum_{t=0}^{T} P(T^{+}{}_{false} = t) \geq 0.9999 \quad [3.3]$$

Figure 3.3 **Threshold value of false positives D^{+} as a function of sample size n with a test specificity 97% (solid black line) or 99% (solid gray line)**



Obviously, this threshold value increases with increasing sample size (see figure 3.3). It serves as a decision tool whether the herd is retested or not. When the number of positive test results exceeds the threshold D^{+}, the probability that all positive test results are false positives is less than 0.01%. The herd is not retested and is declared positive.

3.2.4 Probability distribution of true and false positives in sample

In a herd of N animals, S animals are seropositive (and so N-S animals are sero-negative) and a sample of n animals is taken to be tested. To derive the probability distribution of T^+, i.e. the number of animals that test positive in the sample, all combinations of seropositive animals in the sample and true and false positive results need to be considered. The probability for i truly positive animals in the sample follows from a Hypergeometric distribution with parameters n, S and N. The probability that k of these i true positives in the sample indeed test (truly) positive follows from a Binomial distribution with parameters i and se. The probability that $(t\text{-}k)$ of the remaining $(n\text{-}i)$ true negatives in the sample test (falsely) positive follows from a Binomial distribution with parameters $(n\text{-}i)$ and $(1\text{-}sp)$. Together, this yields the probability for $T^+ = T^+_{true} + T^+_{false}$ animals that test positive in the sample:

$$P(T^+ = t) = \sum_{i=0}^{\min[n,S]} \frac{\binom{S}{i}\binom{N-S}{n-i}}{\binom{N}{n}} \left[\sum_{k=0}^{\min[i,t]} \binom{i}{k}\binom{n-i}{t-k} se^k (1-se)^{i-k} (1-sp)^{t-k} sp^{n-i-t+k} \right] \qquad [3.4]$$

The variables in this equation are schematically represented by:

- n animals in the sample
  - i true positives
    - k test (truly) positive (= T^+_{true})
    - i-k test (falsely) negative (= T^-_{false})
  - n-i true negatives
    - t-k test (falsely) positive (= T^+_{false})
    - $(n\text{-}i)\text{-}(t\text{-}k)$ test (truly) negative (= T^-_{true})

and

$T^+ = T^+_{true} + T^+_{false} = k + (t\text{-}k) = t$

$T^- = T^-_{true} + T^-_{false} = (i\text{-}k) + (n\text{-}i\text{-}t\text{+}k) = n\text{-}t$

Note that Eq. 3.1 is recovered when *t=0* and *sp=1* and Eq. 3.2 when *S=0*. For our retesting model we will also need the probability of finding zero true positives in a sample (so all seropositive animals test negative):

$$P(T^{+}=t\,|\,T^{+}{}_{true}=0)=\sum_{i=0}^{\min[n,S]}\frac{\binom{S}{i}\binom{N-S}{n-i}}{\binom{N}{n}}\binom{n-i}{t}(1-se)^{i}(1-sp)^{t}\,sp^{n-i-t} \qquad [3.5]$$

which is derived from Eq. 3.4 by setting *k=0*. With Eq. 3.4 and 3.5 we can calculate the probability that a herd is declared positive or negative, with or without retesting (retesting here means that when a seropositive animal is present in the first sample, it will be detected), i.e. the probability of each of the four routes in figure 3.1:

$$\mathrm{Prob}_{\text{herd negative, without retesting}} = P(T^{+}=0)$$

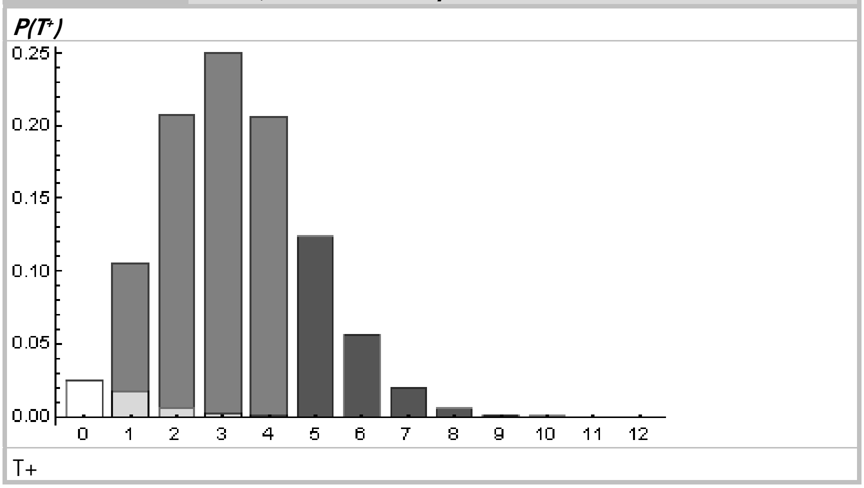
$$\mathrm{Prob}_{\text{herd negative, with retesting}} = \sum_{t=1}^{D^{+}-1} P(T^{+}=t\,|\,T^{+}{}_{true}=0)$$

$$\mathrm{Prob}_{\text{herd positive, with retesting}} = \sum_{t=1}^{D^{+}-1} P(T^{+}=t) - \sum_{t=1}^{D^{+}-1} P(T^{+}=t\,|\,T^{+}{}_{true}=0)$$

$$\mathrm{Prob}_{\text{herd positive, without retesting}} = \sum_{t=D^{+}}^{n} P(T^{+}=t)$$

As an illustration the probability distribution is calculated for a vaccinated pig farm of N = 200 animals with a seroprevalence of 5%, i.e. the number of seropositive animals is 0.05 N=10. With a test sensitivity of 70% the sample size required for the 5/95 strategy, is 73 animals (Eq. 3.1). With a test specificity of 99% the threshold value D^{+} is calculated to be 5 animals (Eq. 3.3). Figure 3.4 shows the corresponding probability distribution of positive test results. The probability that the herd is tested negative without retesting (T^{+} = 0) is 2.4% (and not 100-95=5%, due to the contribution of false positive test results), shown by the white bar in figure 3.4. All positive test results equal to or higher than the threshold value ($T^{+} \geq D^{+}$) leads to declaring the herd positive without retesting (cumulative probability of 20.7%, dark gray bars in figure 3.4). The probability to retest the herd ($0 < T^{+} < D^{+}$) is 76.9%, of which 2.6% does not contain a true positive animal (and the herd is declared negative, light gray bars in figure 3.4) and of which the remaining 74.3% is the probability that the herd is declared positive after retesting (gray bars in figure 3.4). The probability to falsely declare the herd positive is 5%, which is in agreement with the 5% (100-95) certainty level required for a herd with a 5% seroprevalence. In practice the seroprevalence of a herd is unknown, and it is therefore unknown whether a farm is truly or falsely declared positive.

Figure 3.4 **Probability distribution for number of positive test results T^+, consisting of probabilities to declare a herd negative without retesting (white bar) and with retesting (light gray bars) and to declare a herd positive with retesting (gray bars) and without retesting (dark gray bars) for N = 200, n = 73, S = 10, D^+ = 5, se = 0.70 and sp = 0.9**



3.3 End-screening strategies

The end screening that must take place to declare a country free of infection, involves a clinical examination and a serological surveillance. While all animals in the vaccination, protection and surveillance zones need to be clinically examined, only a part of the animals need to be sampled for serological screening. Here we will only focus on the serological surveillance.

The EU-council directive 2003/85/EC specifies guidelines for the serological end screening. It states that on all vaccinated farms (without distinguishing between commercial and hobby farms), all animals must be serologically tested, regardless of animal species. In the protection (3km) and surveillance (10km) zones, the non-vaccinated cattle and pig herds do not need to be sampled (reasoning that an infection would not have escaped clinical detection during the epidemic, as the clinical signs are very apparent). In non-vaccinated sheep farms it is more likely that an infection has escaped clinical detection. In the protection zone all non-vaccinated sheep herds must be examined, by taking a sample size that would detect at least 5% seroprevalence with at least 95% certainty. In the surveillance zone not all non-vaccinated sheep farms are tested, but only so many to detect a between-herd prevalence of at least 2% (with 95% certainty), while the design within-herd prevalence is still 5% (with 95% certainty). This end-screening scenario is marked as 'EU' in table 3.2.

We will study the strategy of the EU directive in our model calculations, but we will also study a more relaxed and a more stringent alternative, as well as the combination of both. Serological testing of all animals on a vaccinated farm, is especially cumbersome for pig farms that are usually much larger than cattle or sheep farms. Therefore, we will also implement the recommendation of the Epizone workshop (held in Tervuren, Belgium in January 2007), to test only a sample of the vaccinated pigs that would detect a seroprevalence of at least 5% with at least 95% certainty. In this end-screening scenario, called 'EU-' less effort is put into the sampling than strictly required by the EU. In the 'EU+' scenario more effort is put into the end screening by also sampling non-vaccinated cattle and pig farms, in the same way as non-vaccinated sheep farms. Finally, the 'EU+-' scenario combines both alternatives, i.e. sampling less vaccinated pigs and more non-vaccinated cattle and pigs. Table 3.2 summarises the four end-screening strategies studied in our analyses.

The sample sizes are determined for and taken from one epidemiological unit. For small farms (such as cattle and sheep farms) the epidemiological unit is the farm itself, but larger farms (such as pig farms) are divided in epidemiological units of a maximum of 1,000 animals each.

Table 3.2	Strategies for serological end screening in the model; 5/95 means a sample size of animals on a farm that would detect at least 5% seroprevalence with at least 95% certainty; 2/95 means a sample size of farms that would detect at least 2% of the farms (with at least 5% seroprevalence) with at least 95% certainty						
		Vaccination zone (2 or 5km) vacc. herds		Protection zone (3km) non-vacc. herds		Surveillance zone (10km) non-vacc. herds	
strategy		**herds**	**animals**	**herds**	**animals**	**herds**	**animals**
EU	cattle	all	all	none	none	none	none
	sheep	all	all	all	5/95	2/95 b)	5/95
	pigs	all	all	none	none	none	none
EU-	cattle	all	all	none	none	none	none
	sheep	all	all	all	5/95	2/95 b)	5/95
	pigs	all	5/95	none	none	none	none
EU+	cattle	all	all	all	5/95	2/95 a)	5/95
	sheep	all	all	all	5/95	2/95 b)	5/95
	pigs	all	all	all	5/95	2/95 c)	5/95
EU+-	cattle	all	all	all	5/95	2/95 a)	5/95
	sheep	all	all	all	5/95	2/95 b)	5/95
	pigs	all	5/95	all	5/95	2/95 c)	5/95

a) Equivalent to 56% of the cattle farms; b) Equivalent to 55% of the commercial sheep farms (and 66% of hobby sheep farms); c) Equivalent to 66% of the pig farms.

For the end-screening strategies that involve only a part of the herds (i.e. the 2/95 scenarios in the surveillance zones), we need to determine the number of herds to be tested. It can be calculated for each surveillance zone separately using Eq. 3.1, but the large overlaps between the zones make an exact calculation difficult. Instead, we calculate the average fraction of herds that need to be tested in a surveillance zone (i.e. between 3 and 10km around a detected herd, and between 5 and 10km for the 5-km vaccination strategy) for each species. These fractions are 0.56 for cattle, 0.55 for sheep, 0.66 for pigs and 0.66 for hobby farms. The probability of detection is multiplied by the appropriate fraction to account for the possibility that the herd is not included in the serological survey.

The probability that a herd is tested negative (with or without retesting) is multiplied by the number of seropositive animals on the farm that are missed during the epidemic. This gives the average number of seropositive animals that remain after the end screening that will be used in comparing the results of the different end-screening scenarios.

3.4 Results and discussion: freedom of infection

At the end of each hypothetical epidemic the end screening is simulated. Around each detected herd a 3-km protection zone and a 10-km surveillance zone is set up (the vaccination zone was of course already determined during the simulation of the epidemic). All herds in these zones are identified and depending on the species and end-screening strategy, it is determined whether a herd needs to be tested and if so, which sampling protocol to follow. Depending on the farm size, the required sample size is calculated. From the results of the epidemic it is known how many seropositive animals are still present on the farm. With the end-screening model that was outlined in section 3.2 the probability of detecting the herd is calculated. One minus is the probability of declaring the herd negative. Multiplied with the number of seropositive animals on the farm after the epidemic, it gives the number of seropositive animals remaining on the farm after the end screening. The total number of seropositive animals after the end screening is obtained by summing the number of seropositive animals per farm over all tested farms. This is a measure for the risk that seropositive animals pose, when we assume that each seropositive animal contributes equally to the total risk.

Due to the large amount of herds to be tested, the end-screening strategies are only evaluated for the minimal strategy (*min*), the three basic control strategies *(cul1, vac2 and vac5)* and the two alternative strategies for pig farms *(vac2p and vac5p)* and only for the situation where epidemics are seeded on a cattle farm in the Gelderse Vallei. The results for other strategies and starting situations are not expected to be fundamentally different.

3.4.1 Results for numbers of (re)tested farms and animals

In the end screening, the number of farms that needs to be tested differs largely, depending on the epidemic, the control strategy and the end-screening strategy (see table 3.3). The minimal strategy requires a large number of farms to be tested (around 20,000), because of the large outbreak sizes. The culling strategy always requires fewer herds to be tested (around 2,500) than any vaccination strategy, since all vaccinated herds must be screened. In the basic EU-screening strategy, the median of the number of tested herds for the 2-km and 5-km vaccination strategies is similar, around 5,500 herds. This is because the 5-km vaccination strategy is more effective than 2-km ring vaccination; even though 5-km vaccination involves more vaccinated herds that need to be tested; it affects a smaller area, resulting in a number of tested herds similar to 2-km vaccination. The screening strategies testing less vaccinated pigs (EU- and EU+-) do not affect the number of herds to be tested, only the number of animals per farm. The screening strategies testing more unvaccinated cattle and pigs however (EU+ and EU+-), largely increase the number of herds to be tested. The increase is largest for the culling strategy (more than double), as the screening areas contain only unvaccinated farms. The increase is smallest for the 5-km vaccination strategy, because of the smaller proportion of unvaccinated farms in the tested farms. Finally, around half of all the tested farms, must be retested, fairly independent of control or end-screening strategy.

In the number of animals to be tested the differences between the control and end-screening strategies are larger, compared to the number of tested herds. Comparing the culling and vaccination strategies for the EU-screening strategy, the number of tested animals is six to twenty times higher for the vaccination strategies. The largest part of these animals is vaccinated pigs: when pig farms are excluded from vaccination, the number of tested animals is halved (compare *vac2p* to *vac2* and *vac5p* to *vac5*). A similar effect is brought about by the EU- strategy: by testing only a 5/95 sample on vaccinated pig farms, the number of tested animals is halved as well. When more unvaccinated cattle and pig farms are sampled (EU+ strategy), the number of tested animals obviously increases. Again, this increase is largest for the control strategy with the most unvaccinated farms, i.e. *min* and *cul1*, and the smallest for the control strategy with the most vaccinated farms, i.e. the 5-km vaccination strategy *vac5*. When both alternative screening strategies are combined, the effect of sampling less vaccinated pigs and more unvaccinated cattle and pigs counteract. This is only beneficial for the *vac2* and *vac5* strategies (i.e. the only strategies in which pig farms are vaccinated), where the number of tested animals in the EU+- strategy is less than in the EU strategy.

From this we conclude that from a practical point of view it should be avoided to test all animals on pig farms. This can be achieved either by taking a 5/95 sample on vaccinated pig farms, or by not vaccinating pig farms at all. Whether this increases the risk of not detecting seropositive animals will be studied in the next two sections.

3.4.2 Results for number of (un)detected farms

The end screening is aimed at detecting the infected herds that were not detected during the epidemic (see table 2.5). But, because only samples are tested and serological tests are not perfect, some of the infected herds will be declared (falsely) negative and some non-infected herds will be declared (falsely) positive. Table 3.4 shows the results of the end screening in terms of number of farms for the different control and end-screening strategies.

The largest part of the infected farms that were not detected during the epidemic are detected by the end screening. The minimal strategy yielded the largest number of not detected herds during the epidemic, so it shows the largest number of detected herds during the end screening (around 105 farms tested truly positive). More interesting are the numbers of infected herds that are also missed by the end screening. For the minimal strategy 25 (15-36) farms are tested falsely negative, for 1-km culling 0.5 (0.0-2.4) farms are tested falsely negative, and for 2-km and 5-km vaccination 2.1 (0.3-6.3) and 1.5 (0.1-4.5) farms are tested falsely negative. The (seropositive) animals that remain on these farms constitute the final risk after the country has been declared free of infection (see next section). When alternative end-screening strategies are applied, the number of true positive and false negative farms hardly shifts. This will be examined in more detail in the next section.

The number of falsely positive tested herds is directly related to the number of farms to be tested. The higher this number, the more false positive herds can be expected. Because of the high herd specificity of 99.99% the number of false positive herds per epidemic is limited (at a cost of a high retesting rate). For instance, when 5463 (2,122-10,420) herds are tested (2-km vaccination strategy with EU end-screening strategy, see table 3.3), 2.0 (0.7-3.8) farms are tested falsely positive.

3.4.3 Results for seropositive animals remaining after the end screening

With or without vaccination, a considerable number of the infected farms are not detected during the epidemic (see table 2.6). On such farms undetected animals remain that are assumed to have seroconverted, and that should be detected during the end screening. In the model, carrier animals (about half of the seropositive cattle) were not explicitly modelled, as they do not play a significant role in the within- and between-herd transmission, but they are included in the group of seropositive animals. The total number of seropositive animals per epidemic differs largely for the different control strategies (see table 3.5(a)).

The minimal strategy *(min)* yields the highest number of undetected animals per epidemic (around 767) and the culling strategy *(cul1)* the lowest (around 8). Ring vaccination in 2km *(vac2)* produces more undetected animals (average of 50) than 5-km vaccination *(vac5, average of 35)*, because of the higher effectiveness and thus smaller epidemics of the latter strategy.

The end screening drastically reduces the number of undetected seropositive animals for all control strategies. These seropositive animals remain on farms that are falsely declared negative (see table 3.4), and as such these numbers are a measure of the risk posed by seropositive animals after the end screening. The average number of undetected animals after the basic EU end-screening strategy is still very high (average of 62) for the minimal strategy, because of the high outbreak sizes. This number is the smallest for the culling strategy (average of 1.0), but the numbers for the vaccination strategies are only slightly higher (average of 3.5 for 2-km vaccination and 2.1 for 5-km vaccination). The most important effect of the end screening however, is that for all strategies expect the minimal all 95% percentiles of the number of undetected animals are reduced to reasonably small absolute values (9.2 undetected animals in the country for the culling strategy and at most 20.3 for the vaccination strategies). The differences between the four vaccination strategies are again due to the different effectiveness of the control strategies. The larger an epidemic has been, the more farm outbreaks will have escaped clinical detection during the epidemic and the more undetected animals will remain after the end screening.

The number of seropositive animals remaining after the end screening slightly increases when less samples are taken on vaccinated pig farms (EU- strategy) and slightly decreases when more samples are taken on unvaccinated cattle and pig farms (EU+ strategy), but overall the alternative end-screening strategies have little effect. This can be explained by considering the number of seropositive animals per (undetected) farm for the different species and vaccination status (see table 3.5(b)). Most undetected animals remain on unvaccinated sheep farms and on vaccinated cattle and sheep farms. The basic EU strategy already targets these three groups (sampling all vaccinated farms and a large part of the unvaccinated sheep farms), that leaves little room for decreasing the risks even further. As a consequence, sampling less animals on vaccinated pig farms (EU strategy) increases only the 95% percentile of the number of undetected animals, but does not alter the overall risk markedly (see table 3.5(a)). Conversely, sampling more animals on unvaccinated cattle and pig farms (EU+ strategy), will only decrease the 95% percentile of the number of undetected animals for cattle farms, but the overall risk is again unaffected (see table 3.5(a)).

From these calculations we conclude that when pig farms are vaccinated, it is safe to test only a 5/95 sample instead of all animals on these farms, and that testing more unvaccinated cattle and pig farms will not reduce the risk of seropositive animals after the end screening.

Table 3.3 Number of farms and animals to be (re)tested for different control and end-screening strategies: median values (90% interval)

Control strategy	End-screening strategies: EU		EU-		EU+		EU+-	
	number of farms to be tested							
min	19,880	(16,101-22,759)	19,880	(16,101-22,759)	44,434	(36,322-50,543)	44,434	(36,322-50,543)
cul1	2,479	(1,028-4,916)	2,479	(1,028-4,916)	6,012	(2,931-11,408)	6,012	(2,931-11,408)
vac2	5,463	(2,122-10,420)	5,463	(2,122-10,420)	8,858	(3,973-17,348)	8,858	(3,973-17,348)
vac2p	5,520	(1,940-12,300)	5,520	(1,940-12,300)	10,129	(4,008-22,274)	10,129	(4,008-22,274)
vac5	5,973	(2,994-10,967)	5,973	(2,994-10,967)	7,565	(3,899-14,003)	7,565	(3,899-14,003)
vac5p	5,403	(2,478-11,669)	5,403	(2,478-11,669)	7,874	(3,872-16,704)	7,874	(3,872-1,6704)
	number of animals to be tested (x 1,000)							
min	379	(302-441)	379	(302-441)	1,641	(1,324-1,887)	1,641	(1,324-1,887)
cul1	45	(19-92)	45	(19-92)	217	(111-411)	217	(111-411)
vac2	669	(20-1,196)	311	(104-530)	828	(318-1,535)	475	(211-877)
vac2p	295	(93-565)	295	(93-565)	529	(209-1,105)	529	(209-1,105)
vac5	974	(488-1,799)	432	(222-723)	1,053	(550-1,956)	509	(276-874)
vac5p	381	(185-712)	381	(185-712)	521	(270-1,013)	521	(270-1,013)
	number of farms to be retested							
min	7,869	(6,316-9,085)	7,869	(6,316-9,085)	24,882	(20,189-28,438)	24,882	(20,189-28,438)
cul1	948	(392-1,930)	948	(392-1,930)	3,358	(1,713-6,343)	3,358	(1,713-6,343)
vac2	2,691	(1,027-5,062)	2,583	(992-4,876)	5,011	(2,300-9,755)	4,902	(2,267-9,561)
vac2p	2,411	(813-5,365)	2,411	(813-5,365)	5,609	(2,287-1,2275)	5,609	(2,287-12,275)
vac5	3,246	(1,625-5,744)	3,081	(1,568-5,500)	4,351	(2,313-7,840)	4,184	(2,214-7,592)
vac5p	2,513	(1,165-5,310)	2,513	(1,165-5,310)	4,302	(2,183-9,198)	4,302	(2,183-9,198)

Table 3.4 **Number of farms that are tested positive (truly and falsely) and number of farms tested falsely negative for different control and end-screening strategies: median values (90% interval)**

Control strategy	End-screening strategies							
	EU		EU-		EU+		EU+-	
	number of farms tested truly positive							
min	104.9	(63.9-143.7)	104.9	(63.9-143.7)	114.2	(72.2-157.5)	114.2	(72.2-157.5)
cul1	1.1	(0.0-4.6)	1.1	(0.0-4.6)	1.5	(0.0-5.1)	1.5	(0.0-5.1)
vac2	13.6	(1.7-39.3)	13.5	(1.7-38.6)	13.7	(1.7-39.8)	13.6	(1.7-38.7)
vac2p	15.6	(1.7-46.7)	15.6	(1.7-46.7)	15.8	(1.9-46.9)	15.8	(1.9-46.9)
vac5	9.8	(2.0-28.7)	9.8	(2.0-28.4)	9.8	(2.0-28.7)	9.8	(2.0-28.4)
vac5p	10.6	(1.9-31.5)	10.6	(1.9-31.5)	10.6	(1.9-31.5)	10.6	(1.9-31.5)
	number of farms tested falsely negative							
min	25.3	(15.4-36.3)	25.3	(15.4-36.3)	15.5	(9.0-21.8)	15.5	(9.0-21.8)
cul1	0.5	(0.0-2.4)	0.5	(0.0-2.4)	0.5	(0.0-1.6)	0.5	(0.0-1.6)
vac2	2.1	(0.3-6.3)	2.2	(0.3-7.1)	2.0	(0.2-6.1)	2.2	(0.2-7.0)
vac2p	2.6	(0.3-8.1)	2.6	(0.3-8.1)	2.4	(0.3-7.6)	2.4	(0.3-7.6)
vac5	1.5	(0.1-4.5)	1.6	(0.2-5.0)	1.4	(0.1-4.4)	1.5	(0.2-5.0)
vac5p	1.6	(0.2-4.8)	1.6	(0.2-4.8)	1.6	(0.2-4.7)	1.6	(0.2-4.7)
	number of farms tested falsely positive							
min	5.0	(4.0-5.7)	5.0	(4.0-5.7)	13.6	(11.1-15.5)	13.6	(11.1-15.5)
cul1	0.6	(0.3-1.2)	0.6	(0.3-1.2)	1.9	(0.9-3.5)	1.9	(0.9-3.5)
vac2	2.0	(0.7-3.8)	2.1	(0.8-3.9)	3.2	(1.4-6.3)	3.3	(1.4-6.3)
vac2p	2.2	(0.7-4.8)	2.2	(0.7-4.8)	3.7	(1.4-8.1)	3.7	(1.4-8.1)
vac5	2.7	(1.3-5.0)	2.7	(1.3-5.1)	3.2	(1.7-6.1)	3.3	(1.7-6.2)
vac5p	2.7	(1.2-5.7)	2.7	(1.2-5.7)	3.5	(1.7-7.4)	3.5	(1.7-7.4)

Table 3.5 **Number of undetected seropositive animals per epidemic (a) for different control strategies and different end-screening strategies and (b) for different control strategies and different species and vaccination status (only before end screening): median values (90% interval)**

(a) number of seropositive animals per epidemic for different end-screening strategies

	before end screening		after end screening							
			EU		EU-		EU+		EU+-	
min	767	(466-1090)	62	(33-94)	62	(33-94)	43	(20-73)	43	(20-73)
cul1	8	(0-42)	1.0	(0.0-9.2)	1.0	(0.0-9.2)	0.5	(0.0-8.3)	0.5	(0.0-8.3)
vac2	50	(7-148)	3.5	(0.3-14.8)	4.2	(0.3-17.0)	3.3	(0.3-14.4)	4.0	(0.3-16.4)
vac2p	58	(6-180)	4.7	(0.3-20.3)	4.7	(0.3-20.3)	4.5	(0.3-19.9)	4.5	(0.3-19.9)
vac5	35	(6-99)	2.1	(0.3-9.4)	2.4	(0.3-11.1)	2.0	(0.3-9.1)	2.3	(0.3-10.9)
vac5p	36	(5-109)	2.3	(0.3-11.0)	2.3	(0.3-11.0)	2.3	(0.3-11.0)	2.3	(0.3-11.0)

(b) number of seropositive animals per epidemic for different species and vaccination status (before end screening)

	non-vacc. total		non-vacc. cattle		non-vacc. sheep		non-vacc. pigs		non-vacc. hobby	
min	767	(466-1,090)	21	(8-36)	738	(439-1,048)	0	(0-2)	9	(0-29)
cul1	8	(0-42)	0	(0-3)	7	(0-40)	0	(0-0)	0	(0-0)
vac2	4	(0-35)	0	(0-3)	3	(0-34)	0	(0-0)	0	(0-0)
vac2p	8	(0-44)	0	(0-3)	7	(0-43)	0	(0-0)	0	(0-0)
vac5	0	(0-13)	0	(0-2)	0	(0-13)	0	(0-0)	0	(0-0)
vac5p	0	(0-17)	0	(0-2)	0	(0-17)	0	(0-0)	0	(0-0)
	vacc. total		vacc. cattle		vacc. sheep		vacc. pigs		vacc. hobby	
min	-	(–)	-	(–)	-	(–)	-	(–)	-	(–)
cul1	-	(–)	-	(–)	-	(–)	-	(–)	-	(–)
vac2	42	(4-125)	26	(0-84)	12	(0-43)	0	(0-9)	0	(0-9)
vac2p	49	(4-151)	30	(1-96)	15	(0-55)	-	(–)	0	(0-10)
vac5	32	(5-94)	20	(3-66)	8	(0-31)	0	(0-8)	0	(0-8)
vac5p	34	(5-101)	23	(1-71)	10	(0-34)	-	(–)	0	(0-8)

4 Economic consequences of different control strategies against FMD

Authors: R. Bergevoet, C. van Wagenberg and N. Bondt

4.1 Introduction

The last outbreak of FMD on 26 farms in 2001 not only confronted the livestock sector with serious consequences and restrictions but it also had a large impact on society as a whole. This event did cost the Dutch society an amount of €900m. or 0.3% of its annual Gross National Product. The total costs for farmers were estimated at €320m. For the other parts of the livestock chain the costs were estimated at €215m. and the cost for the tourism and recreation sector were estimated at €275m. (CPB 2001 cited by Huirne et al., 2002). A new epidemic of FMD in the Netherlands can have an equally large impact. Therefore it is worthwhile to investigate strategies that can limit the economic impact of new epidemics.

When evaluating the costs of an epidemic different components can be distinguished:

- *Direct costs related to the control of the epidemic*
  These include the costs for the infrastructure for the control of the epidemic, the cost associated with culling and destroying of infected and contact animals, the costs associated with destruction of feed and milk on detected farms, and the compensation and vaccination costs.
- *Cost related to trade restrictions*
  Due to an epidemic the national and international market access for animals of susceptible species and their products is restricted. An epidemic of FMD will result in trade restrictions that are related to the epidemic per se and do not depend on the specific characteristics of the control strategy chosen. After the last outbreak it takes time until all the restrictions in trade are lifted and the situation from before the epidemic is restored.
- *Ripple effects*
  The effects from outbreaks of FMD that are felt upstream and downstream along the livestock value chain-breeding, feed production, input supply, slaughter, processing, final sale and consumption.

Spill-over effects

The effects from outbreaks of FMD on tourism and other services. Since other than typical agricultural production is becoming more important for the rural economy these spill-over effect are likely to become a large part of the total epidemic costs.

In the previous chapters different control strategies were evaluated from an epidemiological perspective. The aim of this chapter is to evaluate, compare and rank the different simulated strategies to control and eradicate FMD from an economic perspective. The following questions will be addressed:

1. What is the optimal strategy from an economic perspective: culling within 1km zones, or vaccination 2 or 5 km around detected farms?
2. What are the consequences of alternative strategies?
   a. excluding pigs from vaccination;
   b. excluding animals on hobby farms from preventive culling.
3. What is the distribution of costs between animal species and cost types?
4. What is the value loss of products of vaccinated animals?

For the calculations in this chapter we focus on the costs that differ between the strategies. We calculate the costs for the period from onset of the epidemic until the moment the Netherlands is officially declared FMD free, according to OIE standards1. Costs originating after this period are not calculated.

The remaining part of the chapter is structured as follows: paragraph 4.2 describes the material and methods. Paragraph 4.3 gives the most important results, which will be discussed in paragraph 4.4. Paragraph 4.5 gives the conclusions and recommendations of the economic analysis.

4.2 Material and methods

Areas considered

Research has shown that the epidemiology of an epidemic depends on the chosen control strategy and on the animal density in the area in which outbreaks occurs. Therefore sparsely populated livestock areas (SPLA) and densely populated livestock areas (DPLA) are distinguished.

[1] OiE Terrestrial Animal Health Code, Article 8.5.1; appendix 4 gives the text.

For the SPLA, the province of Friesland was chosen. In this area the minimal EU scenario, 1-km culling around each detected farm and 2-km and 5-km vaccination around each infected farm were compared.

For the DPLA, the 3 regions of Gelderse Vallei (area in the province of Gelderland), Oost-Nederland (Eastern part of the Netherlands) and the province of Noord-Brabant, were chosen. The minimal EU strategy was left out of the analyses, because this strategy resulted in an endemic situation. In addition to the 1-km culling around each detected farm and vaccination in 2km and 5km around each detected farm, the alternative strategies that exclude hobby farms from preemptive culling, or pig farms from vaccination, were considered.

Material

The epidemiological data as presented in chapter 3 were used as input for the economic calculations. To calculate the economic effects the following epidemiological epidemic characteristics were used:

- the number of farms that were infected, culled, and/or vaccinated, in a transport prohibition area;
- the farm type (cattle, pig, sheep, hobby);
- the compartments with infected farms;
- the duration of the epidemic.

The epidemiological data contained information on the farm type and the number of animals. However within a species no distinction was made between the different animal categories. For example, the number of affected cattle were given but not whether these were dairy cows, veal calves or beef cattle. Therefore, for the different regions also the number of animals and farm types were collected from CBS/LEI (Landbouwtelling). Based on these data 'hybrid' cattle farms and 'hybrid' pig farms were constructed. A hybrid farm contained the average distribution of different animal types typical for the region in which the farm was situated. A hybrid cattle farm consisted of dairy cows, young stock, veal calves and other cattle. A hybrid pig farm consisted of sows with piglets and fattening pigs. Input data for the economic evaluation were collected from available literature, consultation of experts and data sets (appendix 2 gives the details and the origin of the data).

Method

Different strategies (see paragraph 2.5) were evaluated from an economic perspective. To evaluate the economic consequences of the different control and eradication strategies a Partial Budget model was developed (Dijkhuizen en

Morris, 1997). In a Partial Budget model only the costs and benefits that differ between the evaluated alternatives are included. Therefore, the types of costs that do not or only differ marginally between strategies and therefore do not alter the order of the strategies, were excluded from the calculations. These include the costs that were related to the epidemic of FMD per se and did not depend on the control strategies, such as costs of non-FMD sensitive branches as horses, poultry and arable land and the costs of non-agricultural industry as tourism. The following costs were included in the calculations:

- *Operational costs*
  These are costs related to the costs of crisis centres, tracking and tracing, clinical examination and clinical inspection and the costs of police involvement in the enforcement of movement restrictions were estimated. Based on the total cost of the 2001 epidemic in the Netherlands (Huirne et al., 2001), it was estimated that the fixed operational costs were €43m. and that the variable operational costs were €3m. per week.
- *Costs related to culled animals and destructed feed and milk*
  The costs of culled animals is the number of culled animals times the value of each animal. The costs of destructed feed and milk are the number of culled animal's times the average value per animal of the stock of feed and milk on the farm.
- *Costs of culling and disinfection culled farms*
  The labour costs of culling of animals and disinfection of farms.
- *Costs of empty housing in culled farms*
  The costs of empty housing between moment of culling and moment of repopulation after the epidemic and a 30-day period after last detection.
- *Costs of repopulation culled farms*
  The culled farms incurred costs after repopulation because of suboptimal utilisation of their capacity.
- *Costs of vaccinating*
  The labour costs of vaccination of animals and the vaccine costs.
- *Value loss of vaccinated animals*
  The value loss of vaccinated animals is the number of vaccinated animals times the average value loss of each animal if sold on the Dutch market. The estimates for the value loss of products from vaccinated pigs were based on Hoste (2006). For veal calves they were based on De Rond (2008). Vaccinated hobby animals were not slaughtered and incurred no value loss.

- *Value loss of milk from vaccinated animals and costs for logistic processes of milk from vaccinated animals*
  During the epidemic and the 30-day period after last detection milk from vaccinated dairy cows is treated similar to non-vaccinated animals. The milk from vaccinated animals after this period has to be logistically processed for a period of 12 months and corresponding costs were calculated. It is assumed that the most likely outlet for milk from vaccinated dairy cows will be cheese that will be sold within the EU. From 1,000 kg of raw milk can be produced: cheese (110 kg) and side products like whey powder (60.3 kg), butter (9 kg) and buttermilk powder (1 kg). Because it is assumed that the infrastructure to process relatively small amounts of side products does not exist, there will be value loss for these side products. This value loss is estimated by the dairy industry (NZO personal communication 2008) at €0.0825 per litre of raw milk. In addition, the costs related to the logistic processes to collect and separately process the milk from vaccinated animals are estimated at €0.015 per litre of raw milk.
- *Costs of logistic processing of vaccinated animals*
  During the epidemic and the 30-day period after last detection vaccinated veal calves, pigs and sheep are processed similarly to non-vaccinated animals. Vaccinated animals that are still alive after this period, have to be logistically slaughtered and corresponding costs were calculated. Vaccinated hobby animals were not slaughtered and incurred no additional costs.
- *Costs of transportation prohibition of non-infected farms*
  The costs of non-infected farms in a area with a transport prohibition for a 6-week period because of missed returns were calculated.
- *Costs of empty houses and repopulation of non-infected farms in infected compartments*
  We assumed that veal calves could not be imported in infected compartments resulting in empty housing. Other animal types were sufficiently available in the Netherlands and in the area with movement restrictions to prevent empty housing. Veal calves that were slaughtered during the epidemic and the 30-day period after last detection, could not be replaced and the corresponding empty-housing and repopulation costs were calculated.

- *Export market losses*
  The costs of animals and products that because of an epidemic could not be exported to the normal markets, were calculated. During the epidemic and the 30-day period after last detection this concerned the EU and third countries markets for live animals, meat and meat products from all the Netherlands and for milk and milk products from infected compartments. After this period, this concerned the third countries market for live animals, meat, meat products, milk and milk products from infected compartments for another 60 days without vaccination and for another 150 days with vaccination (according to OiE standards[1]).

4.3 Results

In this section the following results of the calculations are presented:
- the 50% percentile value (50% of the results have a value that is lower than or equal to the presented value);
- the 5% percentile and the 95% percentile (5% of the results have a value that is lower/higher than the presented value).

The 50% percentile can be considered an average[2] outcome, whereas the 5% percentile can be considered an optimistic and the 95% percentile a pessimistic outcome. The results are presented as the difference in costs of a strategy compared to a baseline strategy and per area and infection source.

SPLA areas
The cost of an epidemic in Friesland that starts in a cattle farm, as an example of an epidemic in an SPLA area, are presented in table 4.1. Table 4.1 compares the costs of the 1-km culling strategies (cul1) and 2-km (vac2) and 5-km (vac5) vaccination around each detected farm with the costs of the minimal EU strategy (EU). The minimal EU strategy has a lower number of farms culled and lower costs compared to 1-km culling or the two vaccination strategies. However, the differences in total costs in the different strategies are small for all percentiles.

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[1] OiE Terrestrial Animal Health Code, Article 8.5.1; appendix 4 gives the text.
[2] In the strict definition the 50% percentile is the median and not the average. Only when the distribution of the results is normal the median and average are equal.

Table 4.1	**Different strategies compared to the minimal EU strategy with an epidemic that starts in Friesland**								
	Number of culled farms a)			**Last week of detection**			**Total cost in million €**		
	percentile			**percentile**			**percentile**		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
EU	7	2	46	3	1	12	58	48	102
Difference with baseline scenario EU									
cul1	49	0	249	0	0	-4	3	0	7
vac2	23	0	71	0	0	-4	3	0	6
vac5	23	0	67	0	0	-6	7	0	19
a) Includes hobby farms.									

DPLA areas

Table 4.2 compares the costs of 2-km of 5-km vaccination around a detected farm to the costs of culling all susceptible farm animals in 1km around a detected farm for the simulated epidemics in 4 DPLAs. Because application of the minimal EU strategy in DPLAs resulted in an endemic situation, no results are presented for this strategy.

Culling strategies

Table 4.2 shows that the total costs of the culling strategy vary between the regions and between the 5%, 50% and 95% percentile. For example, in *Gelderse Vallei start in cattle farm*, the costs in the 5% percentile are €94m. and in the 95% percentile €615m.

The costs in *Oost-Nederland start in cattle farm* are always lower than the costs in the other DPLAs, whereas the *Gelderse Vallei* always has the highest costs. The reason for this is the high number of farms and animals in the Gelderse Vallei.

Table 4.2	Different strategies compared to 1-km culling around a detected farm								
	Number of culled farms a)			Last week of detection			Total cost in million €		
	percentile			percentile			percentile		
	50%	5%	95%	50%	5%	95%	50%	5%	95%
Gelderse Vallei start in cattle farm									
cul1	971	206	3217	9	4	15	236	94	615
Difference with baseline scenario cul1									
vac2	-711	-136	-2510	1	1	2	-8	5	-89
vac5	-741	-138	-2646	-3	0	-4	-8	12	-111
Oost-Nederland start in cattle farm									
cul1	393	84	1595	6	3	13	110	67	327
Difference with baseline scenario cul1									
vac2	-257	-48	-1126	1	0	3	9	-4	-12
vac5	-261	-48	-1188	0	0	-3	37	3	28
Gelderse Vallei start in pig farm									
cul1	1656	495	3980	9	5	15	334	140	728
Difference with baseline scenario cul1									
vac2	-1150	-325	-2871	1	1	1	-31	1	-130
vac5	-1192	-332	-3010	-2	-1	-4	-9	14	-75
Noord-Brabant start in pig farm									
cul1	579	166	2030	7	4	14	185	98	483
Difference with baseline scenario cul1									
vac2	-399	-105	-1531	0	0	2	-17	-4	-31
vac5	-405	-106	-1615	-1	-1	-4	37	10	22
a) Includes hobby farms.									

Vaccination strategies

The vaccination strategies in which all for FMD susceptible animals in a circle of 2km *(vac2)* or 5km (*vac5)* around each detected farm are vaccinated were compared with the strategy that involved 1-km culling around each detected farm (cul1). Table 4.2 indicates that vac5 is the preferred strategy in the average and pessimistic outcome in *Gelderse Vallei start in cattle farm*. In *Oost-Nederland* and in *Noord-Brabant* vac5 is more expensive that culling. Vac2 has the lowest costs in *Noord-Brabant* in all outcomes and in the average and pessimistic outcome in *Gelderse Vallei start in pig farm*.

4.3.1 Alternative strategies: excluding pigs from vaccination

As Bergevoet et al. (2007) have shown, vaccinating pigs in case of an epidemic of FMD or CSF has serious consequences for the pig industry and involves high costs. When evaluating the economic consequences of including or excluding pigs from vaccination in the control of FMD, a 'during the epidemic' phase and an 'after the epidemic' phase can be distinguished.

During the epidemic phase there is no difference between the possible destinations of vaccinated and non-vaccinated fattening pigs in infected areas. The meat from animals in areas with movement restriction can only be consumed at the domestic Dutch market and piglets from breeding farms (vaccinated and non-vaccinated) can only be placed within the area with movement restrictions. During the epidemic phase export of animals and meat from animals is banned. When an area is confronted with an outbreak, according to the contingency plan, pig farmers have to be able to keep animals on their farm for a period of at least 6 weeks. This is to prevent the spread of the infection by movement of potentially infected animals. However, after this period serious welfare problems can occur on pig farms. Therefore, possibilities for the movement of animals to a slaughterhouse (for fattening farms) or the movement of piglets to fattening farms (for breeding farms) are included in the contingency plans. However, fattening farms are less likely to accept vaccinated piglets on their farms, because of the high costs of logistic slaughtering and canalisation of the meat from vaccinated animals after the end of the epidemic (Bergevoet et al., 2007).

After the epidemic phase, when the Netherlands is officially declared free (30 days after last detection), export of animals and meat within the EU is possible. However, products of vaccinated pigs have to be processed separately (logistic slaughtering) from the products of non-vaccinated animals, because these have reduced market access (especially for countries outside the EU). Logistic slaughtering and reduced market access of products of vaccinated animals confronts the industry with substantial costs. Hoste et al. (2007) calculated a loss of €0.40 per kilogram of meat from vaccinated animals.

Vaccinated piglets and piglets born from vaccinated sows present an additional challenge for the pig industry. The Netherlands exports large numbers of live piglets to neighbouring countries. If pigs are included in a vaccination strategy, after an epidemic usually live vaccinated pigs remain and new piglets are born from vaccinated sows. Vaccinated piglets have to be slaughtered logistically and the revenues of the products of these animals will be lower. The market acceptance of vaccinated piglets, both in the domestic as well as in the export market, is expected to be limited. This can result in serious economic consequences for the vaccinated sow farms.

Excluding pigs from vaccination might limit the consequences of an epidemic of FMD for the pig industry. Therefore, the situation in which pigs were excluded from vaccination is considered. As the results presented in chapter 2 indicate, the epidemiological impact is limited. The number of outbreaks nor the duration of the total epidemic differ substantially from the outcomes in which vaccination of pigs is included. In this section the economic consequences are evaluated. Table 4.3, figure 4.1a and figure 4.1b show the results.

Table 4.3 shows that in almost all regions and independent of the size of the vaccination area, the total costs of an epidemic are lower when pigs are excluded from vaccination compared to when pigs are vaccinated. Only in *Gelderse Vallei* in the pessimistic outcomes with vaccinating in a 2-km area the costs when including pigs from vaccination (vac2) are lower than when excluding pigs from vaccination (vac2p). This is caused by the additional duration of the epidemic by 3 weeks in the pessimistic outcome and the large proportion of veal calves in *Gelderse Vallei*. For almost all regions and sizes of the vaccination area, costs of an epidemic are lower when pigs are excluded from vaccination compared to culling in 1km, except for the 5% and 50% percentile with vac5p in *Oost-Nederland start in cattle farm* and the 5% percentile with vac5P in *Gelderse Vallei start in cattle farm*. The reason for these lower costs is that no additional measures have to be taken by the pig industry to separate products of vaccinated and non-vaccinated pigs after the epidemic. Also no value loss occurs due to the presence of vaccinated pigs.

Figures 4.1a and 4.1b indicate that when pigs are excluded from vaccination the distribution of the costs changes. The share of the dairy industry in the costs not only increases relatively to the other animal species but also increases in absolute terms in the average outcome. In *Gelderse Vallei* in the pessimistic outcome of vac2 the costs for the dairy sector increase more that that the cost for the pig sector decrease.

Table 4.3	**Difference in costs between strategies where pigs are included or excluded from the vaccination strategy (compared to the culling strategy)**								
	Number of culled farms a)			**Last week of detection**			**Total cost in million €**		
	percentile			**percentile**			**percentile**		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
Gelderse Vallei start in cattle farm									
vac2	-711	-136	-2,510	1	1	2	-8	5	-89
vac2p	-703	-135	-2,426	2	1	5	-16	0	-44
vac5	-741	-138	-2,646	-3	0	-4	-8	12	-111
vac5p	-737	-138	-2,619	-2	0	-2	-39	3	-148
Oost-Nederland start in cattle farm									
vac2	-257	-48	-1,126	1	0	3	9	-4	-12
vac2p	-257	-48	-1,122	1	0	3	-4	-7	-88
vac5	-261	-48	-1,188	0	0	-3	37	3	28
vac5p	-262	-47	-1,189	-1	0	-3	19	2	-56
Gelderse Vallei start in pig farm									
vac2	-1150	-325	-2,871	1	1	1	-31	1	-130
vac2p	-1140	-325	-2,805	2	1	4	-47	-8	-113
vac5	-1192	-332	-3,010	-2	-1	-4	-9	14	-75
vac5p	-1189	-332	-2,982	-2	0	-2	-57	-2	-141
Noord-Brabant start in pig farm									
vac2	-399	-105	-1,531	0	0	2	-17	-4	-31
vac2p	-398	-105	-1,492	0	0	4	-35	-9	-44
vac5	-405	-106	-1,615	-1	-1	-4	37	10	22
vac5p	-406	-105	-1,606	-1	0	-2	-14	-1	-88

a) Includes hobby farms.

Figure 4.1a **Comparing including or excluding pigs from vaccination in 2km: distribution of cost amongst the different livestock sectors (50% percentile)**

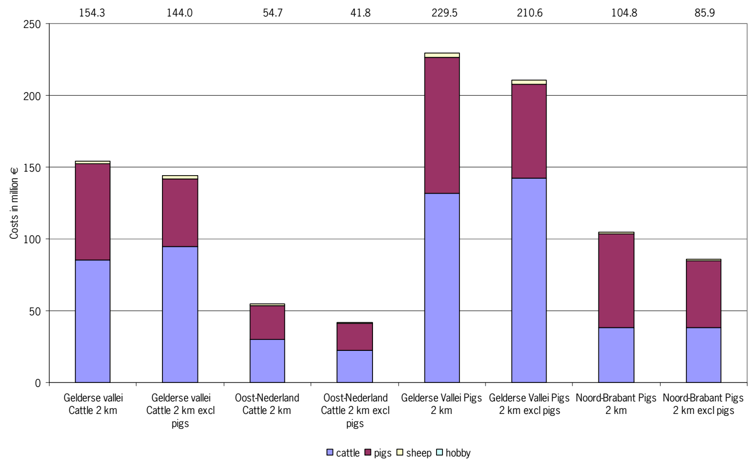
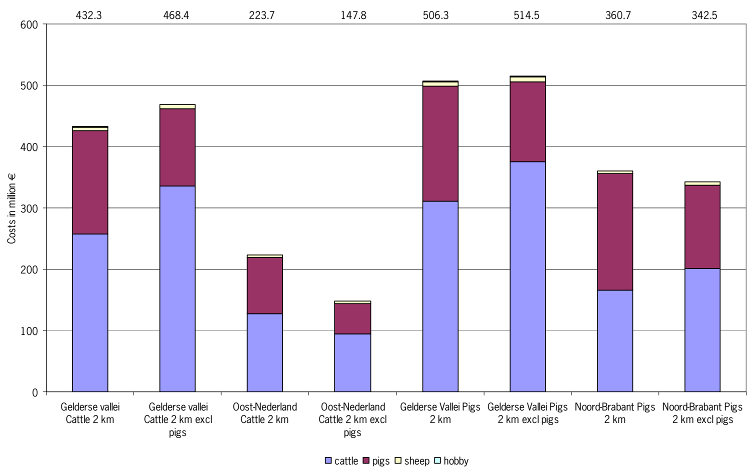


Figure 4.1b **Comparing including or excluding pigs from vaccination in 2km: distribution of cost amongst the different livestock sectors (95% percentile)**



Which of the 2-km and 5-km vaccination strategies has the lowest costs excluding pigs from vaccination depends on the specific DPLA. For *Gelderse Vallei start in cattle farm* the cost related to 5-km vaccination are lower than those related to 2-km vaccination for the average outcome (-€39m. with 5km versus -€16m. with 2km compared to culling in 1km) and the pessimistic outcome (-€148m. with 5km versus -€44m. with 2km compared to culling in 1km). For *Oost-Nederland start in cattle farm* the vaccination in 5km has higher costs than vaccination in 2km in all outcomes. For *Gelderse Vallei start in pig farm* the vaccination in 5km has lower costs than vaccination in 2km in the average outcome (-€57m. with 5km versus -€47m. with 2km compared to culling in 1km) and the pessimistic outcome (-€141m. with 5km versus -€113m. with 2km compared to culling in 1km).

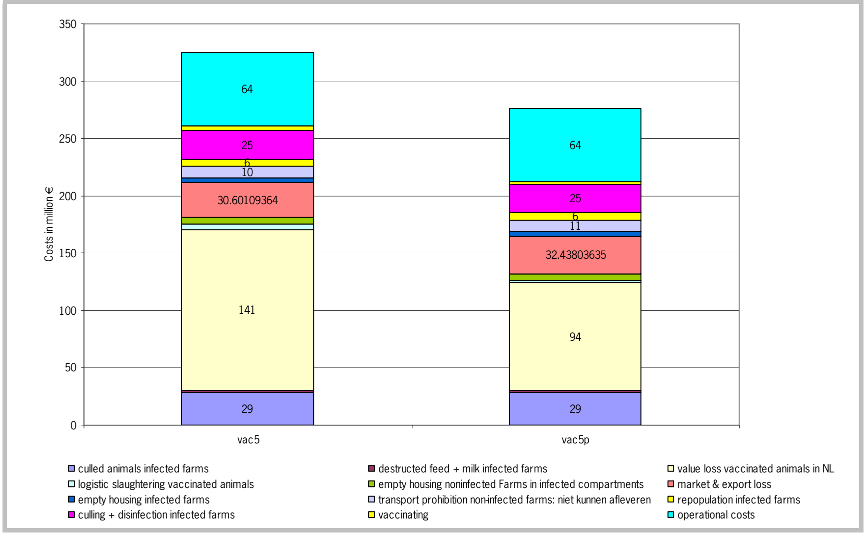
For *Noord-Brabant start in Pig farm* the vaccination in 5km has higher costs than vaccination in 2km in the average outcome (-€14m. with 5km versus -€35m. with 2km compared to culling in 1km). But for the pessimistic outcome the 5km has lower cost (-€88m. with 5km versus -€44m. with 2km compared to culling in 1km).

Figure 4.2 compares the total cost and its components of the vaccination strategie in a 5-km area in *Gelderse Vallei start pig farm* that include and exclude pigs from vaccination.

As can be seen from figure 4.2 the value loss of products of vaccinated animals is the most important part of the total costs. The 2nd largest costs are the operational costs to fight the epidemic. The difference between including and excluding pigs is mainly caused by the value loss of products of vaccinated animals. The value loss of products of vaccinated animals is discussed in detail in paragraph 4.3.3.

As can be seen from figure 4.2 the value loss of products of vaccinated animals is the most important part of the total costs. The 2nd largest costs are the operational costs to fight the epidemic. The difference between including and excluding pigs is mainly caused by the value loss of products of vaccinated animals. The value loss of products of vaccinated animals is discussed in detail in paragraph 4.3.3.

Figure 4.2 **Cost components of vaccination in 5km in *Gelderse Vallei start pig farm* for vac5 (including pigs in vaccination) or vac5p (excluding pigs from vaccination)**



4.3.2 Alternative strategies: excluding animals on hobby farms from preventive culling

As previous epidemics of contagious diseases have shown, culling animals on hobby farms (here small sheep flocks of 10 animals were assumed) lead to a lot of protest and resistance from the general public. As described in chapter 2, the epidemiological consequences of excluding hobby animals from culling are limited. The number of hobby farms that have to be preventively culled is substantial in the scenarios that only involve culling. The number of hobby farms that have to be culled in scenarios that involve vaccination is limited, because from the moment vaccination is started preventive culling is stopped. In these cases only in the beginning of the epidemic preventive culling is used to limit the spread of the epidemic.

Table 4.4 shows the costs for culling strategies including and excluding hobby farms. The costs of strategies in which hobby farms are not preventively culled are in most scenarios lower because the cost for culling hobby farms can be avoided. Because of the small number of animals per farm the time taken to preventively cull the animals and the related costs per animal are relatively high.

Table 4.4	Difference in costs comparing culling on hobby farms (cul1) and non-culling on hobby farms (cul1h)								
	Number of culled farms percentile			Last week of detection percentile			Total cost in million € percentile		
	50%	5%	95%	50%	5%	95%	50%	5%	95%
Gelderse Vallei start in cattle farm									
cul1	*971*	206	3217	*9*	4	15	*236*	94	615
cul1h	*-150*	-37	-555	*0*	0	0	*-7*	-1	-15
Oost-Nederland start in cattle farm									
cul1	*393*	84	1595	*6*	3	13	*110*	67	327
cul1h	*-74*	-16	-314	*0*	0	0	*1*	0	-17
Gelderse Vallei start in pig farm									
cul1	*1656*	495	3980	*9*	5	15	*334*	140	728
cul1h	*-273*	-76	-700	*0*	0	0	*-2*	-2	-15
Noord-Brabant start in Pig farm									
cul1	*579*	166	2030	*7*	4	14	*185*	98	483
cul1h	*-117*	-34	-326	*0*	0	1	*1*	-2	14

4.3.3 More insight into the value loss of products of vaccinated cattle

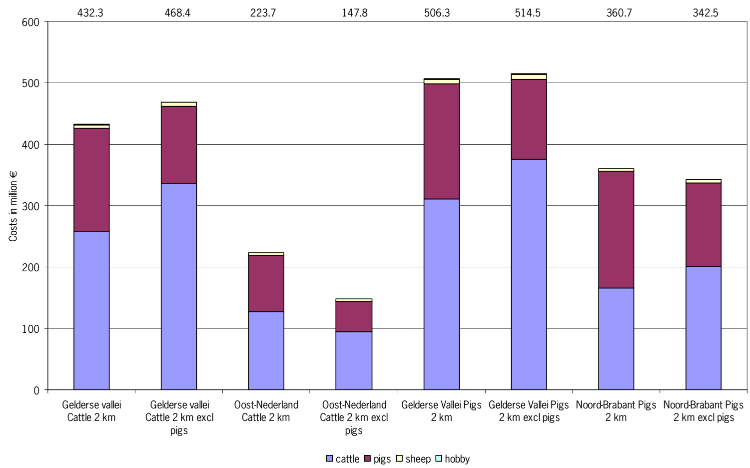
In figure 4.3 the value loss for products of the different animal species are given. The operational cost are excluded, because these cannot be specifically allocated to different species. The results are presented for *Noord-Brabant start in pig farm* with a 2-km and 5-km vaccination strategy in which pigs are excluded from vaccination. The value loss of products of vaccinated animals is almost equally distributed between dairy cows and veal calves.

Milk of vaccinated cows

A situation, in which vaccination is included in a strategy to control an epidemic of FMD, is new for the Dutch dairy industry. In the last FMD epidemic vaccination was also implemented, but then the vaccinated animals were culled after the epidemic. Now the vaccinated animals stay alive.

It is uncertain for the dairy sector what the reaction of the market is when confronted with products from vaccinated animals. The amount of milk that has to be reallocated because of market restrictions depends not only on the number of dairy cows that were vaccinated but also on how the market will treat the milk of non-vaccinated farms in infected compartments.

Figure 4.3 **Value loss of products vaccinated cattle per animal type (Noord-Brabant start in pig farm, 2-km and 5-km vaccination, excluding pigs from vaccination, 50% percentile)**



The dairy industry indicates that the milk of the vaccinated animals will probably be used for cheese production. It is expected that the amount of cheese produced from milk of vaccinate cows is such, that all of it can be sold within the EU. So, if the retail in the EU accepts this cheese, there will not be any value loss for cheese. However, the main value loss occurs because the side products of cheese production as whey, butter and buttermilk powder cannot be processed in the normal production routine. In the situation without an outbreak these side products from different production plants are collected and processed in one plant. Due to the increase in scale of the dairy processing industry, it is not possible to separate and process these products to create normal added value during an epidemic with vaccination as a control strategy. In case of vaccination, the dairy industry expects that these products have to be considered as waste products with very little value.

Efforts aiming to reduce the costs related to the processing of the milk of vaccinated cows into cheese should focus on creating added value of the side products of the cheese production. For example using these products at factories that produce only for the domestic market or finding alternative use for these products such as pig nutrition. Logistic cooperation between dairy companies during an epidemic might reduce the logistic costs and also limit the number of locations where the milk from vaccinated animals has to be processed, thereby further reducing the value loss of milk from vaccinated dairy cows.

In case the market will not accept dairy products from regions in which animals are vaccinated, a much larger volume of milk has to be processed separately. In appendix 3 an indication of the number of infected compartments, the number of dairy cows in these compartments, and the amount of milk produced daily by cows in these compartments is given. These data suggest that in this case the amount of milk produced exceeds the volume that can be processed as cheese and other products have to be produced from milk from vaccinated dairy cows, like consumption milk and milk powder. This could increase the costs substantially.

Veal calves

On average, there were 615,000 white veal and 230,000 rose veal calves held over the years 2005-2006 in the Netherlands. The annual production is 210,000 tons of veal meat. Of the total Dutch veal production 95% is being exported to about 60 countries of which France, Italy and Germany are the most important. The veal supply chain is dominated by several large integrated veal production companies: VanDrie Group, Alpuro Group, Denkavit and the Pali Group. These companies enter into integration contracts with calf farmers, have their own factories for calf milk replacement and/or slaughter the calves in their own slaughter houses (De Rond, 2008).

In a study on the financial damage for veal calve chains De Rond (2008) concludes that revenue losses of the vaccinated veal calves are substantial. A large part of the damage is related to the fact that many white veal calves will be older than 8 months at slaughter at the end of the epidemic. These white calves then have to be sold as rose calves against a substantially lower price. Also, the carcasses of the vaccinated animals have to be maturated and deboned separately, incurring additional costs.

Efforts that aim to reduce the costs related to veal calves should focus on shortening the duration of the epidemic. This limits the number of calves older than 8 months. Slaughtering of calves during the epidemic, which are likely to become older than 8 months before the end of the epidemic, freezing or storing their meat to put on specific/domestic markets after the epidemic, can also decrease these costs. However, the capacity of these markets to absorb large quantities of veal is limited. Furthermore, it is unclear whether the calves slaughtered during the epidemic can be sold within the EU after the epidemic.

4.3.4 Summary of the results

In the previous paragraphs the different relevant themes were discussed in details. In table 4.5 summarises the costs for each strategy. Whereas in the previous paragraphs the costs of the alternatives were compared with a base-line strategy in table 4.5 the total calculated costs are given. This enables evaluation of the strategies on there own merits. As previously, for all strategies a large difference in costs between the optimistic, average and pessimistic results can be observed.

Table 4.5	Summary table with the total costs of the different strategies discussed in the previous paragraphs								
	Number of culled farms			**Last week of detection**			**Total cost in million €**		
	percentile			**percentile**			**percentile**		
	50%	**5%**	**95%**	**50%**	**5%**	**95%**	**50%**	**5%**	**95%**
Friesland start in cattle farm									
cul1	*56*	2	295	*3*	1	8	*61*	48	109
vac2	*30*	2	117	*3*	1	8	*61*	48	108
vac5	*30*	2	113	*3*	1	6	*65*	48	121
Gelderse Vallei start in cattle farm									
cul1	*971*	206	3,217	*9*	4	15	*236*	94	615
cul1h	*821*	169	2,662	*9*	4	15	*229*	93	600
vac2	*260*	70	707	*10*	5	17	*227*	99	526
vac2p	*268*	71	791	*11*	5	20	*220*	95	571
vac2h	*236*	63	643	*10*	5	17	*230*	98	525
vac5	*230*	68	571	*6*	4	11	*228*	106	504
vac5p	*234*	68	598	*7*	4	13	*197*	98	467
vac5h	*206*	61	509	*6*	4	11	*230*	109	502
Oost-Nederland start in cattle farm									
cul1	*393*	84	1,595	*6*	3	13	*110*	67	327
cul1h	*319*	68	1,281	*6*	3	13	*110*	67	309
vac2	*136*	36	469	*7*	3	16	*119*	62	315
vac2p	*136*	36	473	*7*	3	16	*106*	60	239
vac2h	*116*	31	424	*7*	3	16	*119*	62	319
vac5	*132*	36	407	*6*	3	10	*146*	69	355
vac5p	*131*	37	406	*5*	3	10	*128*	68	271
vac5h	*112*	31	360	*6*	3	11	*146*	69	361

Table 4.5	Summary table with the total costs of the different strategies discussed in the previous paragraphs (continued)								
	Number of culled farms			Last week of detection			Total cost in million €		
	percentile			percentile			percentile		
	50%	5%	95%	50%	5%	95%	50%	5%	95%
Gelderse Vallei start in pig farm									
cul1	*1656*	495	3980	*9*	5	15	*334*	140	728
cul1h	*1383*	419	3280	*9*	5	15	*331*	138	712
vac2	*506*	170	1109	*10*	6	16	*302*	141	597
vac2p	*516*	170	1175	*11*	6	19	*287*	132	615
vac2h	*455*	148	997	*10*	6	16	*305*	140	603
vac5	*464*	163	970	*7*	4	11	*325*	154	653
vac5p	*467*	163	998	*7*	5	13	*276*	138	586
vac5h	*409*	143	861	*7*	5	11	*323*	160	647
Noord-Brabant start in Pig farm									
cul1	*579*	166	2030	*7*	4	14	*185*	98	483
cul1h	*462*	132	1704	*7*	4	15	*187*	97	497
vac2	*180*	61	499	*7*	4	16	*169*	95	452
vac2p	*181*	61	538	*7*	4	18	*150*	89	439
vac2h	*153*	53	450	*8*	4	16	*177*	94	462
vac5	*174*	60	415	*6*	3	10	*222*	108	505
vac5p	*173*	61	424	*6*	4	12	*171*	98	395
vac5h	*144*	52	355	*6*	3	11	*222*	109	514

4.4 Discussion

Model study

The results presented here are derived with the help of models. Models are frequently used to calculate the consequences of different control strategy scenarios. These models contain the most recent scientific insights into the spread of the disease and the effects of control strategies. However, some input data for the current situation in the Netherlands were not available, because the Netherlands only suffered incidental epidemics of FMD. These input data were based on reasoned assumptions. Furthermore, some input data (like the between-herd transmission) were only available for virus strain O/NET/2001. The results should thus be seen as an arbitrary but reasonable estimate of the effects of control strategies, given these limiting conditions. The results provide an estimate of the differences between the scenarios. The resulting insight provide a basis for the discussion about the optimal control strategy for FMD in the Netherlands.

Estimated costs of all the evaluated strategies in this study were lower than the total reported costs of the last epidemic in the Netherlands, which only involved 26 detected farms. This is because in the Partial Budget method used in this study only the costs that differ between the control strategies were included and not the total costs. For example, costs related to tourism and those that depend on an epidemic per se, irrespective of the control strategy, were not included in the costs calculated in this study.[1]

It is difficult to predict the effect of a specific FMD introduction in the Netherlands. Events with a random character play an important role at the start and during an epidemic. In the epidemiological model probability is used to model this. Due to chance there is a wide variety of possible outcomes. Using multiple model runs provides insight into this variation. It is assumed that an actual epidemic will behave like one of the simulated epidemics.

Interpretation of the economic results depends on the risk attitude of the decision maker. A risk-neutral decision maker is assumed to choose a strategy that on average has the lowest costs. A risk-averse decision maker is assumed to base the decision on the minimising the chance on unpleasant outcomes (Hardaker et al., 1997). To support the risk neutral decision maker we presented the 50% percentile of the costs. This means that 50% of the simulated epidemics have calculated costs that are less or equal than the presented number. To support the risk-averse decision maker we presented the 95% percentile of the costs. This means that 95% of the simulated epidemics have calculated costs that are less or equal than the presented number. Only in 5% of the simulated outcomes the costs are higher.

A specific feature of the used simulation method is that at the start of the epidemic a decision on how to fight the epidemic is taken, and the decision maker sticks to this decision during the epidemic. This often is not what actual happens during an epidemic. In reality, it is a process of monitoring and adapting the control strategy based on a series of decisions rather than on one decision. Or, as Ge (2008) puts it: 'The epidemic can only be understood backwards, but it must be controlled forward.'

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[1] The costs for tourism are difficult to predict since they depend on (a) the location of the outbreak (the tourist industry at the Veluwe in the Gelderse Vallei is more important than in the Peel in Eastern Brabant) and (b) the viewpoint of the analyst (for example are only the effects for the local industry considered or the effects for the Dutch tourist sector as a whole. Part of the tourists might spend their holidays later or elsewhere in the Netherlands which shows effects locally but not nationally).

The economic results suggest that several control measures themselves incur high costs. For example vaccinating in a circle of 5km around a detected farm results in high numbers of vaccinated animals and large amounts of products of vaccinated animals that have to be processed. A decision maker can decide on control strategy with measures with relatively low costs at the start of an epidemic, while he/she can take additional costly measures during the epidemic in case it is about to explode. This might result in a more economically efficient control than an instant massive response at the start of an epidemic. This means that measures which have an irreversible effect and a large impact, e.g. culling or vaccinating a large number of animals, should be taken cautiously but timely. To be able to take such a dynamic decision, decision makers have to predefine what kind of information they need at what moment in the decision process, so that efforts can be made to collect this information at the right moments during the epidemic. Furthermore, control measures should be implemented in a 'smart' way. For example, when it is decided to vaccinate one could start with a circle of 2km and if needed expand this circle to 5km instead of starting at the border of the 5km zone and than working to the centre.

In addition to the direct costs of the epidemic for the primary producers ripple effects and spill over effects can be observed during an epidemic. Ripple effects are the effects of an epidemic of FMD that are felt upstream and downstream along the livestock value chain-breeding, feed production, input supply, slaughter, processing, final sale and consumption. For example, the stand-still measures in infected compartments prevent the slaughter of animals for a period of at least six weeks. Especially when multiple compartments are affected, this can seriously affect the supply of slaughterhouses. In previous epidemics of FMD in the Netherlands this caused a temporarily stop in the production of slaughterhouses. This problem is especially prevalent for slaughterhouses for veal calves. For the pig industry it might be a somewhat different picture, because currently a large amount of slaughter pigs are exported to be slaughtered outside the country. In case of an epidemic live export of slaughter animals will not be possible. The additional supply of pigs that now have to be slaughtered within the Netherlands might compensate the stagnating supply from the infected compartments.

Due to an epidemic the market access for products of susceptible species is seriously restricted. An epidemic of FMD will result in trade restrictions that are related to the epidemic per se and do not depend on the specific characteristics of the control strategy chosen. After the last outbreak it takes time until all the restrictions in trade are removed and the situation regarding export of animals and products is back tot the situation before the initial outbreak. Especially for the Dutch pig sector, an epidemic of FMD can have high consequences, because of the export of large numbers of live pigs. These pigs must then be sold in the Netherlands. It can therefore be expected that prices in the areas affected by restrictions will fall.

Spill-over effects are the effects of an epidemic of FMD on non-agricultural sectors as tourism and other services. Because non-agricultural production is increasingly important for the rural economy, these spill-over effect are likely to become a an increasingly important part of the total epidemic costs.

5 Discussion and conclusions

In this research the epidemiological and economic consequences of different control strategies evaluated. Therefore the following research questions are addressed:

1. What is the optimal control strategy in case of an outbreak of FMD from an epidemiological and economic perspective? Evaluated are the control strategy as required by the EU, culling within a 1-km ring, and vaccination within 2-km or 5-km rings around detected farms.
2. What are the consequences of alternative strategies?
   a. excluding pigs from vaccination;
   b. excluding animals on hobby farms from preemptive culling.
3. What are the consequences for screening and declaring freedom of infection when different control strategies that include vaccination are applied?
4. What is the distribution of costs between animal species and cost types?
5. What is the lost value of products of vaccinated animals?

In this chapter the research results will be discussed and conclusions will be drawn.

5.1 The epidemiology of FMD

Method

To study the effect of differentiated strategies to control Foot-and-Mouth Disease (FMD) epidemics, we developed a model that describes the transmission of FMD between animals and between farms. The model parameters are based on data from transmission experiments and from the 2001 FMD epidemic in the Netherlands (with virus strain O/NET/2001), or assumptions were made when insufficient information was available (such as interspecies transmission). The most important assumptions are about the relative susceptibility and infectivity of cattle-, sheep-, pig- and hobby farms, in this study estimated for the virus strain O/Net/2001. Extrapolation of the results to different virus strains (like pig strains if they exist) should be done with caution. With this model large numbers of hypothetical epidemics were simulated, starting in different areas in the Netherlands, either on a cattle or a pig farm.

Results for high farm density

In general, the larger an epidemic can become, the larger the effect of control is and the larger the differences between control strategies are. Potentially large epidemics occur for instance in areas with a high farm density. For this reason we will focus on the results of the simulated epidemics in the highest density area, the Gelderse Vallei (with about 4 commercial farms per km^2), where the epidemic starts in a cattle farm. When 1-km ring culling is applied, the median number (and 5%-95% percentiles) of detected farms is 45 (17-97), over a period of 67 (30-124) days. In this scenario the number of culled farms is 974 (342-1870), which compares to a total number of farms in the Gelderse Vallei of around 4000. Vaccination is less effective in the beginning of an epidemic than culling, as vaccinated animals are not instantaneously protected. In order to try and achieve the same effect as a given ring culling strategy, vaccination may be applied in larger rings. A 2-km vaccination strategy (with 72 (23-162) detected farms, lasting 76 (41-133) days) does not measure up to 1-km culling, but the epidemic impact (detected and preemptively culled farms) is much smaller. The 5-km vaccination strategy yields the smallest epidemic size (43 (19-89) detected farms) and duration (52 (34-91) days). It should be kept in mind though that the vaccination capacity needed in the 5-km vaccination strategy will most probably become limiting in more than halve of the epidemics (with 149 (0-800) farms to be vaccinated per day in the first week of the vaccination campaign).

Results for low farm density

In areas with a lower farm density, epidemics are predicted to be much smaller. In the lowest density area, Friesland (with about 2 commercial farms per km^2), control measures of preemptively culling or vaccinating farms in the neighbourhood are even unnecessary. Instead, the minimal control strategy as required by the EU suffices.

Affected farms

In all cattle dense areas about 80-90% of the infected farms are cattle farms. Even in a pig dense area as Noord-Brabant (de Peel), when the virus is introduced on a pig farm, approximately 75% of the infected farms are cattle farms and only 10% are pig farms. This is caused by the much higher number of cattle farms in the country (36,000) compared to pig farms (9,000), even in Noord-Brabant. Furthermore, these results are caused by the relative susceptibility and infectivity of cattle-, sheep-, pig- and hobby farms estimated in this study for the virus strain O/Net/2001. Extrapolation of the results to different virus strains (like pig strains if they exist) should be done with caution.

In most areas commercial sheep farms (18000) comprise around 10% of the detected farms while the share of hobby farms (20000 in this study) never exceeds 4%.

Undetected farms
The number of infected farms that is not clinically detected during the epidemic (before the end screening) differs greatly between strategies: for the minimal strategy around 9% of the infected farms is not detected, while this percentage is 4%-7% for 1-km culling, 11%-18% for 2-km vaccination and 12%-20% for 5-km vaccination. For the non-vaccination strategies these undetected farms are mostly sheep farms, but for the vaccination strategies they are mostly vaccinated cattle farms.

Excluding hobby farms from preemptive culling
Under our model assumptions, excluding hobby farms (here small sheep flocks of 10 animals) from preemptive culling has a negligible effect on epidemic control. When hobby farms are excluded from preemptive culling, the number of farms to be culled in the 1-km culling strategy reduces with 20%, but the number of animals to be culled is only 3% smaller.

Excluding pig farms from vaccination
Not vaccinating pig farms in the 2 or 5-km vaccination zones, has a limited but significant effect on epidemic size and duration (for the virus strain O/Net/2001 under study). The median values are hardly affected, but the 95% percentiles are considerably larger, indicating an increased risk of large epidemics. Whether these differences are sufficiently small for the benefits of excluding pig farms from vaccination to compensate for the increased risk, is evaluated in the economical analysis.

5.2 Freedom of infection

EU end-screening strategy
According to the EU legislation all animals on all vaccinated farms must be serologically tested after the epidemic. Of the unvaccinated farms in the protection zone (3km), all sheep farms have to be visited, and a 5/95 sample of animals must be taken. Of the unvaccinated farms in the surveillance zone (3-10km), a 2/95 sample of sheep farms must be tested, and of each visited farm a sample of 5/95 animals must be taken.

The end screening as required by the EU results in 16,000-23,000 farms (5%-95% percentiles) to be tested when the minimal strategy is applied, 1,000-5,000 farms when 1-km culling is applied and 2,000-11,000 farms when 2-km or 5-km vaccination is applied. About half of these farms must be retested to exclude or confirm infection.

Number of seropositive animals before end screening
Before the end screening, a number of seropositive animals are still present on infected herds that were not detected during the epidemic (seropositive for non structural FMD proteins, as detected by an NS Elisa). The minimal strategy yields 767 (466-1090) seropositive animals per epidemic, ring culling in 1-km yields 8 (0-42) seropositive animals per epidemic, while 2-km ring vaccination results in 50 (7-148) seropositive animals and 5-km ring vaccination in 35 (6-99) seropositive animals per epidemic. The 2-km ring vaccination strategy yields more seropositive animals than 5-km ring vaccination, because it is a less effective strategy, leading to larger and longer epidemics.

Risk of seropositive animals after end screening
Even with the most stringent end-screening strategy, the serological tests are never 100% sensitive and thus there is always a (small) chance that seropositive animals are missed during the end screening. When these seropositive animals are exported after the country has been declared free of infection, and detected by an importing country, they pose a serious threat to the export position of the Netherlands. Another threat is, of course, the risk of new outbreaks, if they still carry virus, after the end-screening according to the EU legislation, 1.0 (0.0-9.2) seropositive animals remain using the 1-km culling strategy, 3.5 (0.3-14.8) using the 2-km vaccination strategy and 2.1 (0.3-9.4) using the 5-km vaccination strategy. Although the median values differ, the ranges are comparable. When these numbers of seropositive animals are considered to represent an acceptable risk, emergency vaccination would be a safe alternative to preemptive culling.

Alternative screening strategies
The seropositive animals present before end screening are mainly vaccinated cattle, vaccinated sheep and non-vaccinated sheep (and not pigs or unvaccinated cattle). As these groups of animals are already targeted in the EU-screening strategy, there is little potential for increasing the detection rate by using more stringent screening strategy. When, as an alternative to the EU legislation, unvaccinated cattle and pigs are tested, the results of the end screening

are not affected. So, this increased sampling effort on unvaccinated cattle and pig farms does not decrease the risk of seropositive animals. Another alternative is to take a 5/95 sample of vaccinated pigs (instead of testing all). According to the model results, this halves the total number of animals to be tested, but the end-screening results hardly change. So, this reduced sampling effort on vaccinated pig farms does not increase the risk of seropositive animals.

5.3 Economic consequences

What is the optimal strategy: culling, 2-km or 5-km vaccination?

- Culling strategy is the economically preferred strategy in SPLAs.
- Vaccination is the economically preferred strategy in DPLAs.
- In DPLAs with very high densities of livestock vaccination in 5km around detected farms results in the lowest costs whereas in other DPLAs vaccination in 2km around detected farms results in the lowest costs.

Alternative strategies: excluding pigs from vaccination and excluding animals on hobby farms from preventive culling

When vaccination is chosen as strategy in DPLA regions, excluding pigs from vaccination should be seriously considered since there is a relevant reduction in costs. This result is caused by the relative susceptibility and infectivity of cattle-, sheep-, pig- and hobby farms estimated in this study for the virus strain O/Net/2001. Extrapolation of the results to different virus strains (like pig strains if they exist) should be done with caution.

Abolishing preventive culling of animals on hobby farms (here small sheep flocks of 10 animals) should seriously be considered. Preventive culling of animals on hobby farms does not attribute much to a faster elimination of the epidemic but contributes a lot to the negative perception of the public towards the needed interventions. Excluding animals on hobby farms from preventive culling does not substantially affect the costs of an epidemic but it improves the societal acceptance of the eradication strategies.

Distribution of costs

The dairy industry, veal calve industry and the pig industry all suffer a lot from an epidemic of FMD. Although vaccination can limit the costs of an epidemic it also introduces the potential problem of reduced market access for products of vaccinated animals.

For the dairy industry a large part of the costs originate from the inability to create value from side products of the processing of milk of vaccinated cows. For the veal calve industry the highest costs originate from animals getting older than eight months at slaughter during an epidemic, so that their meat cannot be sold as white veal.

For the pig industry the highest costs originate from the reduced market acceptance of animals and their products from infected compartments by (international) trade partners.

Value loss due to vaccination

Market acceptance by the trade partners of products originating from vaccinated animals might cushion the economic effects of an epidemic. An integrated effort of the government and the livestock industry to limit the consequences of an epidemic of FMD to inform the trade partners about the Dutch approach to fight the disease is needed.

A coordinated action between the relevant stakeholders during an epidemic can reduce the value loss of milk from vaccinated dairy cows. Logistic cooperation between dairy companies can reduce the logistic costs and limit the number of locations where the milk from vaccinated animals has to be processed. Initiate consultations with the trade partners on the market acceptance of products from vaccinated animals.

Insight into ways to reduce the value loss of products of vaccinated animals with a focus on cattle (dairy products and veal calves) is needed to decrease the potential costs of a vaccination strategy to eradicate a FMD epidemic.

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Appendix 1

Results of within-herd model

To illustrate the effects of the within-herd model, outbreaks are simulated at different infection-vaccination intervals for three model farms that consist of 100 cattle, 100 sheep and 1,000 pigs. In the final simulations, real farm data (i.e. actual farm location and number of animals) will be used. For each animal type (cattle, sheep/goats, pigs) and each infection-vaccination interval 10,000 simulations are run. The results are shown in figures A.1 and A.2 and discussed below.

Fraction of outbreaks detected

First it is examined how many of the 10,000 simulated outbreaks are detected as a function of the vaccination time. When an outbreak is not detected, this is either because the first animal to be infected is already protected by the vaccine or because the outbreak is so small that the number of clinical cases stays below the detection limit.

For cattle the fraction of detected outbreaks decreases rapidly when the herd is infected between 1 and 8 days after vaccination (see figure A1.1). The fraction of detected outbreaks for pigs shows the same trend, but it is shifted to later infection times, because the vaccine takes more time to build immunity. So, cattle and pig farms need to be vaccinated well in advance of infection for the vaccine to have an effect. For sheep and goats on the other hand, the model predicts that the vaccine has an effect even when the herd is vaccinated after it has already been infected. This is because the vaccine works reasonably fast, while the infection progresses relatively slowly (compared to cattle and pigs), giving the sheep more time to develop immunity.

Even for unvaccinated farms (at an infection-vaccination interval -21 days, or, equivalently, infection takes place 21 days before vaccination) not all outbreaks are detected. For cattle and pigs this only happens when the first infected animal has such a short infectious period that it does not manage to transmit the virus; this occurs in less than 1% of the outbreaks. For sheep it is also possible that the infection spreads gradually over the herd and eventually dies out without ever reaching the detection limit of 6 clinical cases, because of the low reproduction number, the high detection limit and the high percentage of subclinical infections. Such an undetected outbreak can have affected a considerable fraction of the total herd. In our model farm of 100 sheep 14% of the outbreaks are not detected; for the real sheep farm data (largely consisting of small farms) however, this percentage can be as high as 72%, according to the model.

Clinical detection time

Suspicion arises when the detection limit of clinical cases is reached; detection follows the day after. Unvaccinated infected cattle farms are detected 9.0 (7.1-11.4) days after infection, sheep and goats farms after 23 (15.6-31.5) days and pig farms after 8.1 (6.7-9.9) days (see most negative infection-vaccination intervals in figure A1.1). For vaccinated farms the clinical detection time for cattle and pigs is a bit longer than for unvaccinated farms, suggesting that if the first infected animal manages to infect others, it takes more time to reach the clinical detection limit. For vaccinated sheep and goats farms we observe an opposite effect: the detection time of vaccinated sheep farms is shorter than for unvaccinated farms. Due to the different infection dynamics, only fast propagating infections in sheep farms manage to reach the detection limit.

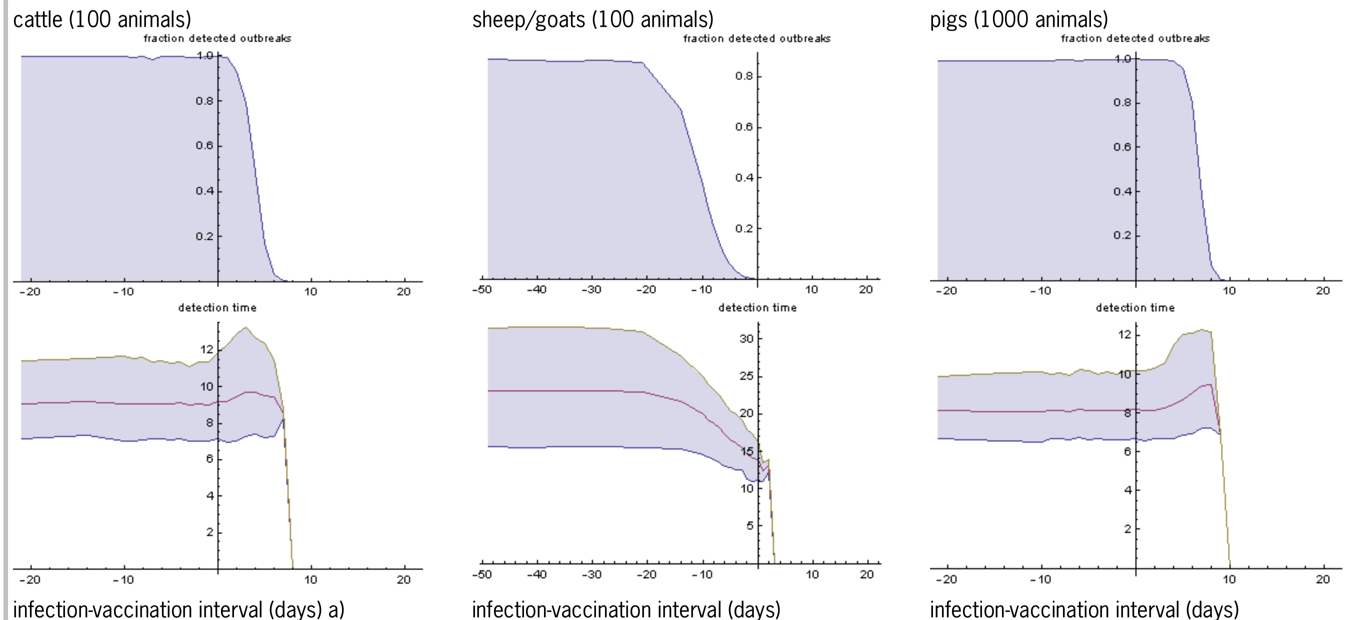
Number of affected animals at time of clinical detection

The number of affected animals at the time of clinical detection comprises all animals that have contributed to the total infection pressure (meaning all I and R animals). For unvaccinated farms the number of affected animals at the time of clinical detection is 20 (9-36) for cattle, 26 (13-43) for sheep/goats and 100 (55-157) for pigs (see most negative infection-vaccination intervals in figure A.2). Around 10%-30% of the farm animals are affected at the time of clinical detection. For vaccinated farms the number of affected animals is much lower.

Number of affected animals at the end of an undetected outbreak

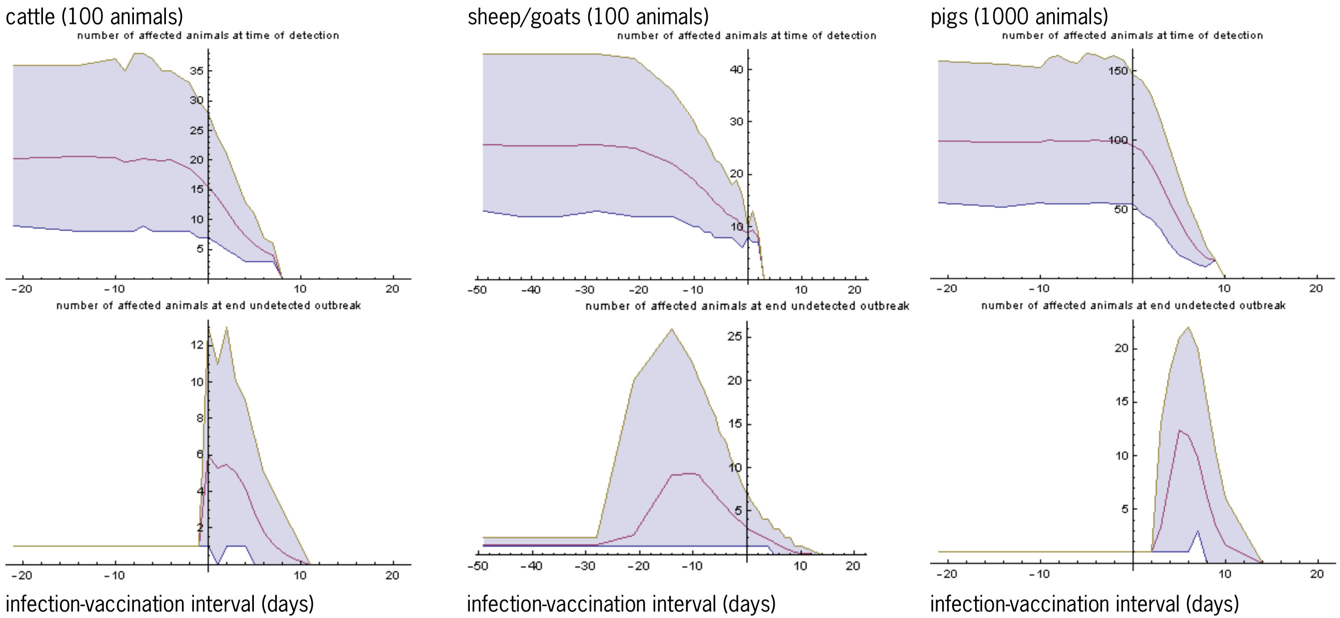
The outbreaks that are not detected affect a small number of animals. Figure A1.2 shows that the number to be expected will be reasonably small for cattle, but could be considerable for sheep/goats and pigs. Although these undetected outbreaks will play a smaller role in the between-herd transmission, most of them need to be detected during the end screening.

Figure A1.1 **Results FMD within-herd model: fraction of detected outbreaks (above) and detection time of farm in days (below) as a function of infection time (time of vaccination at t=0); mean (red line) and 95% interval (shaded area)**



a) The infection-vaccination interval is defined as the time of infection minus the time of vaccination, i.e. a positive interval means the herd is vaccinated before it is infected, and a negative interval means the herd is vaccinated after it is infected.

Figure A1.2 **Results FMD within-herd model: number of affected animals at time of detection (above) and at the end of an undetected outbreak (below) as a function of infection time (time of vaccination at t=0); mean (red line) and 95% interval (shaded area)**



a) The infection-vaccination interval is defined as the time of infection minus the time of vaccination, i.e. a positive interval means the herd is vaccinated before it is infected, and a negative interval means the herd is vaccinated after it is infected.

Appendix 2

Data and assumptions used for the economic evaluation

Distribution between animal types
source: CBS Statline; year: 2005

cattle	dairy cows	37.7%
	young stock	29.4%
	veal calves	21.8%
	other cattle	11.0%
pigs	sows (including piglets)	8.4%
	fattening pigs	48.7%
sheep	ewe (including lambs)	100.0%
hobby	ewe (including lambs)	100.0%

This figure is the national average. In the different strategies the specific regional distribution is used.

Value of culled animals and destructed feed and milk
source: price: valuetables d.d. May 2008
source: feed: Meuwissen, 2004 (pg 13, table 8)

		price	feed
cattle	dairy cows	€759/animal	€44.00/animal
(of which milk: 1,5 day x 23 kg melk per cow per day x 31 cents per kg milk = € 10,70 per cow)			
	young stock	€577/animal	€- /animal
	veal calves	€411/animal	€26.00/animal
	other cattle	€759/animal	€33.30/animal

(dairy: excluding destructed milk)

sheep	ewe (including lambs)	€73/animal	€1.60/animal
pigs	sows (including piglets)	€522/animal	€33.00/animal
	fattening pigs	€77/animal	€3.70/animal
hobby, sheep	ewe (including lambs)	€73/animal	€1.60/animal

<u>Value loss of vaccinated animals (sold in the Netherlands)</u>

cattle	dairy cows	€410/vaccinated animal

explanation:
production of milk per cow per year (*source: LEI*): 7,940 kg, which equals 21.8 kg per cow per day
<u>value loss</u> of milk of vaccinated cows: 180 days x 21.8 kg milk per cow per day x value loss of €82.50 euro per 1,000 kg milk = €323 per dairy cow
<u>plus</u> logistic processing and separate transport of milk of vaccinated cows: 180 days x 21.8 kg milk per cow per day x costs of separate transport of milk €15.50 euro per 1,000 kg milk = €61 per dairy cow
<u>plus</u> 28% replacement per year (KWIN pg 161) x 180 days x €525 revenues per cow for slaughtering (KWIN 2007/2008, pg 162) x value loss (estimation) 35% = €26 per dairy cow

young stock	€5/vaccinated animal

explanation:
6% of young stock sold per year (KWIN, pg 161; concerning young stock 1-2 year) x 0.5 year x €500 (KWIN pg 162; concerning young stock 2 year, O3-quality) x value loss (estimation) 35% = € 5.25 per young stock

veal calves	€450/vaccinated animal

explanation:
142 slaughter weight per calf (KWIN, pg 220; concerning white veal calves) x €4.60 per kg x 74% value loss (De Rond, 2008; pg 30, table 17) = €483.37 per veal calf

190 kg slaughter weight per calf (KWIN, pg 221; concerning rosé veal calves) x €2.79 per kg x 55% value loss (De Rond, 2008; pg 30 table 17) = €291.55 per veal calf
With 558,000 white veal calves and 118,000 rosé veal calves in 2006 (Bont et al., 2007, LEI report 6.07.16) the average value loss per veal calf is: <u>€ 449.89</u>.

other cattle €26/vaccinated animal

Assumption same value loss as slaughtered dairy cows: <u>€ 25.73</u> per animal

sheep ewe (including lambs) €34/vaccinated animal

explanation:
revenues of Flevolanders per ewe per year = € 193,41 (KWIN, pg 238). This is for half a year: € 96,71. Estimated value loss 35%: <u>€ 33.85</u> per ewe (including lambs).

pigs sows (including piglets) €262/vaccinated animal

explanation:
value loss of sows = 37% replacement per year x 0.5 year x € 152 per sow x estimated 35% lower revenues: € 9.84 per sow
<u>plus</u> value loss of piglets = 5.6 piglets present per sow present x € 45 value loss per piglet (LEI-report 5.07.06, pg 134/135) = € 252 per sow.
Total value loss: <u>€ 261.81</u> per sow.

fattening pigs €40/vaccinated animal

explanation:
revenues per slaughtered pig = € 113.80 (KWIN, pg 287) x estimated 35% lower revenues = <u>€ 39.83</u> per fattening pig.

hobby, sheep ewe (including lambs) €<u>0</u>/vaccinated animal

Costs of logistic slaughtering of vaccinated animals (after 30 days after last detection)
source: Meuwissen, 2004

cattle	veal calves	€14/vaccinated animal
growth period	veal calves	190 days
pigs	fattening pigs	€9/vaccinated animal
growth period	fattening pigs	120 days
sheep	sheep	€4/vaccinated animal
growth period	sheep	365 days

Costs of empty houses of non-infected farms in infected compartments

growth period	veal calves	190

Market and export losses

costs of storage: €154 per tonne per 6 months (Bergevoet et al., Oct. 2007; pg 123)
this means: costs of storage €/kg/day 0.000843836 (= 154/1000/ 182.5 days)

Fase:

1) during epidemic (1st detection to last detection + 30 days);
2) after epidemic (last detection + 30 days to FMD-free declaration):
    - without vaccination and living duration 60 days (excl. 30 days after last detection);
    - vaccination and living duration 150 days (excluding 30 days after last detection).

Products:

- live animals;
- meat and meat products;
- milk and milk products.

Variants:

- no export (all exports in storage);
- exports possible to EU-memberstates (only storage of exports to third countries);
- exports possible to EU- + third countries (no storage needed).

<u>Number of animals</u>
(source: Land- en Tuinbouwcijfers; 2006)

Dairy cows	1,420,000
Young stock	1,314,000
Veal calves	844,000
Other cattle	168,000
Sheep (ewe)	648,000
Pigs (sows)	946,000
Fatteners	5,476,000

<u>Live animals</u>

Export losses due to export limitations are mainly concerning piglets.

Exports in 2006: 4,915,481 pigs.[1] *Source: ZMP Vieh und Fleisch 2007* (pg 147).

Number of fattening pigs in the Netherlands is 5.476.000. *Source: Land- en Tuinbouwcijfers, LEI/CBS, 2006*.

This means: export of 0.90 live animals per fattening pig per year, which equals 0.0025 live animals per fattening pig per day. Assumed these are all piglets with a value of €45 per piglet and a reduction of value of an estimated 75%.

Assumptions export loss of piglets:

>> exports: 0.0025 animals per fattening pig per day;
>> no exports: 0.0025 animals per fattening pig per day x €45 x 75%;
>> exports possible within EU: no export losses.

[1] Exports of live pigs in the report of Hoogendam (2008; titled 'Long distance transport of pigs, bovines and poultry in Europe'): 8.068.792 pigs, of which to Germany (DE): 5.590.085, to Italy (IT): 548.384, to Belgium (BE): 703.011, to Spain (ES): 1.227.312

NOTE: For the other animal categories the export problems of live animals are limited and therefore not included in the calculations.

Sheep

Exports: 329,627 animals; 12,314 tonnes product weight in 2006 (total), of which 479 tonnes (= 4%) to third countries. *Source: ZMP Vieh und Fleisch, 2007*.

Assumptions for sheep:

>> exports: 19 kg per ewe per year that is 0.052 kg per ewe per day;

>> no exports: 0.052 kg per day x costs of storage per kg;

>> exports possible within EU: 0.052 kg per day x 4% (perc. non-EU) x costs of storage per kg.

Pigs

Exports: 921,750 tonnes product weight in 2006 (total), of which 172,908 tonnes (= 19%) to third countries. *Source: ZMP Vieh und Fleisch 2007*.

Assumptions for pigs:

>> exports: 168 kg per fattening pig per year that is 0,46 kg per fattening pig per day;

>> no exports: 0.46 kg per pig per day x costs of storage per kg;

>> export EU: 0.46 kg per pig per day x 19% (perc. non-EU) x costs of storage per kg;

Export losses for sows are assumed to be negligible.

Veal calves

Exports: 188,000 tonnes of veal, of which 29,000 tonnes (= 15%) to 'others' (assumed: 'non-EU'). *Source: report E.H.M. de Rond, 2008*.

Assumptions for veal calves:

>> exports: 222 kg per veal calf per year that is 0,61 kg per veal calf per day;

>> no exports: 0,61 kg per calf per day x costs of storage per kg;

>> exports possible within EU: 0,61 kg per calf per day x 15% (perc. non-EU) x costs of storage per kg.

Other cattle

Exports: 394,887 tonnes -/- 188,000 tonnes of veal = 206,887 tonnes in total, of which estimated 15% to third countries (assumed to be equal to veal calves; this would mean 31,033 tonnes to third countries). *Source: ZMP Vieh und Fleisch 2007.*

Assumptions other cattle:

>> exports: 1,231 kg per other cattle per year that is 3,37 kg per other cattle per day;

>> no exports: 3.37 kg per animal per day x costs of storage per kg;

>> exports possible within EU: 3.37 kg per animal per day x 15% (estimated perc. non-EU) x costs of storage per kg.

Indirect costs farmer

1) Costs of empty housing at infected farms

number of weeks standstill after last detection: 4.285714286 weeks (=30 days)

gross margin (saldo, *source: KWIN Veehouderij 2007/2008*):

cattle	dairy cows	€5.27/day	*(€1,925 per cow per year; KWIN pg 187)*
	young stock	€-/day (included in gross margin of dairy cows)	
	veal calves	€0.13day	

(558 x gross margin white veal calves + 118 x gross margin rosé veal calves)/ 676; KWIN, pg 220 and pg 221: €47 per calf place per year; that is €0.13 per calf per day)

other cattle €0.07/day

(143 x €6 per suckling cow per year; KWIN, pg 228; 214 x €41 per beef cattle per year; KWIN, pg 210; that is €0.074 per other cattle per day)

sheep	ewe (including lambs)	€0.26/day
pigs	sows (including piglets)	€0.96/day
	fattening pigs	€0.18/day

2) Costs of transportation prohibition non-infected farms: not being able to deliver animals during 6 weeks. *Source: Huirne et al., 2002; pg 152, table 4.8.*

animal	type	
cattle	dairy cows	€5.46/animal (= 0.13 per cow per day x 42 days)
	young stock	€-/animal (included in costs dairy cows)
	veal calves	€10.08/animal (= 0.24 per calf per day x 42 days)
	other cattle	€-/animal
sheep	ewe (including lambs)	€1.68/animal
pigs	sows (including piglets)	€17.64/animal
	fattening pigs	€2.10/animal
hobby farm	ewe (including lambs)	€-/animal

3) Costs of repopulation of infected farms

Assumption for repopulation of cattle farms: gross margin per animal per day during half of the production period; dairy and sows: assumption gross margin per animal per day during 3 months.

animal	type	
cattle	dairy cows	€480/animal (91 days x €5.27/day)
	young stock	€- /animal
	veal calves	€13/animal (1/2 x 200 days x €0.13/day)
	other cattle	€7/animal (1/2 x 200 days x €0.07/day)
sheep	ewe (including lambs)	€26/animal
pigs	sows (including piglets)	€87/animal (91 days x €0.96/day)
	fattening pigs	€11/animal (1/2 x 120 days x €0.18/day)
hobby farm	ewe (including lambs)	€0/animal

Control system costs

1) costs of culling + desinfection (*source: Huirne et al., Nov. 2002; pg 152, table 4.8*)

animal	type	
cattle	dairy cows	€1.000/animal

(= including young stock, see Huirne et al; Meuwissen, 2004 however calculates with € 1.000 per piece of young stock)

	young stock	€0/animal
	veal calves	€150/animal
	other cattle	€1,000/animal
sheep	ewe (including lambs)	€100/animal
pigs	sows (including piglets)	€400/animal
	fattening pigs	€150/animal

2) costs of vaccinating (*source: Meuwissen, 2004; pg 13, table 8*)

animal	type	
cattle	dairy cows	€8,80/animal
	young stock	€8,80/animal
	veal calves	€2,60/animal
	other cattle	€8,80/animal
sheep	ewe (including lambs)	€2,60/animal
pigs	sows (including piglets)	€7,20/animal
	fattening pigs	€1,80/animal

Operational costs of disease control

Huirne et al. (Nov. 2002) states that the outbreak of FMD in 2001 costed the Dutch government approximately €142m., the joint agribusiness (animal health fund, DGF) also €142m. and the EU €90m. Total: €374m. These are the total costs of the FMD-outbreak including compensation and buying up.

Assumption is that 23% of the total costs concern direct costs of control and enforcement, according to the report of the Dutch Ministry of Agriculture, Nature and Food Quality (report 'MKZ 2001 Eindverantwoording', appendix 2; Jan. 2003). This means that these direct costs amount to €86m.

Next assumption is that approximately half of these direct costs will be fixed costs, that means the part that is not depending on the length of the outbreak, and half of the costs will be variable costs. Based on this assumption a fixed sum of €43m. has been calculated plus a sum of €3m. per week. The duration of the outbreak in 2001 was 14 weeks.

Direct costs of control and enforcement, derived from the ANFQ-report (2003):

- realisation costs of sampling at suspected farms: 13.6 (mln NLG);
- destruction including transport: 23.7;
- realisation costs of screening: 11.2;
- material costs (if not mentioned before): 34.3;
- costs of RVV: 18.1;
- costs of hired workers (if not mentioned before): approximately 15.0 (of a total of 52.8);
- realisation costs of LASER (if not mentioned before): 11.8;
- costs LNV (if not mentioned before): 12.2;

Total: 139.9 mln NLG (of a total of 609.6 mln; that is 23%).

Appendix 3

Table A3.1		Number of cattle and daily milk production in the infected compartments								
Province	**Start in**	**# Infected compartments**			**Total # cows in inf. comp. (* 1,000)**			**Milk production per day (in M kg)**		
		percentile			**percentile**			**percentile**		
		5%	**50%**	**95%**	**5%**	**50%**	**95%**	**5%**	**50%**	**95%**
vaccination in 2km										
Gelderland	cattle	3	7	12	168	386	651	3.5	8.1	13.7
Overijssel	cattle	2	5	9	242	508	895	5.1	10.7	18.8
Gelderland	pigs	5	9	13	273	501	734	5.7	10.5	15.4
Noord-Brabant	pigs	3	6	11	166	399	779	3.5	8.4	16.4
vaccination in 5km										
Gelderland	cattle	2	5	10	140	305	546	2.9	6.4	11.5
Overijssel	cattle	2	4	8	210	457	780	4.4	9.6	16.4
Gelderland	pigs	4	8	12	233	440	676	4.9	9.2	14.2
Noord-Brabant	pigs	3	6	10	166	370	674	3.5	7.8	14.2

Appendix 4

From the OiE Terrestrial Animal Health Code (www.oie.int)

Article 8.5.8.

Recovery of free status

1. When an FMD *outbreak* or FMDV *infection* occurs in an FMD free country or zone where vaccination is not practised, one of the following waiting periods is required to regain the status of FMD free country or zone where vaccination is not practised:
   a. 3 months after the last *case* where a *stamping-out policy* and serological *surveillance* are applied in accordance with Articles 8.5.40. to 8.5.46.; or
   b. 3 months after the *slaughter* of all vaccinated animals where a *stamping-out policy*, emergency vaccination and serological *surveillance* are applied in accordance with Articles 8.5.40. to 8.5.46.; or
   c. 6 months after the last *case* or the last vaccination (according to the event that occurs the latest), where a *stamping-out policy*, emergency vaccination not followed by the slaughtering of all vaccinated animals, and serological *surveillance* are applied in accordance with Articles 8.5.40. to 8.5.46., provided that a serological survey based on the detection of antibodies to non-structural proteins of FMDV demonstrates the absence of *infection* in the remaining vaccinated population.

Where a *stamping-out policy* is not practised, the above waiting periods do not apply, and Article 8.5.2. or 8.5.4. applies.

2. When an FMD *outbreak* or FMDV *infection* occurs in an FMD free country or zone where vaccination is practised, one of the following waiting periods is required to regain the status of FMD free country or zone where vaccination is practised:
   a. 6 months after the last *case* where a *stamping-out policy*, emergency vaccination and serological *surveillance* in accordance with Articles 8.5.40. to 8.5.46. are applied, provided that the serological *surveillance*

based on the detection of antibodies to non-structural proteins of FMDV demonstrates the absence of virus circulation; or

b. 18 months after the last *case* where a *stamping-out policy* is not applied, but emergency vaccination and serological *surveillance* in accordance with Articles 8.5.40. to 8.5.46. are applied, provided that the serological *surveillance* based on the detection of antibodies to non-structural proteins of FMDV demonstrates the absence of virus circulation.

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