Comparing the epidemiological and economic effects of control strategies against classical swine fever in Denmark

A. Boklund a,*, N. Toft b, L. Alban c, Å. Uttenthal d

a Department of Diagnostics and Research, National Veterinary Institute, Technical University of Denmark, Bülowsvej 27, DK-1790 Copenhagen, Denmark
b Department of Large Animal Sciences, Faculty of Life Sciences, University of Copenhagen, Grønnegaardvej 8, DK-1870 Frederiksberg C, Denmark
c Danish Meat Association, Axelborg, Axeltorv 3, DK-1609 Copenhagen V, Denmark
d Department of Virology, National Veterinary Institute, Technical University of Denmark, Lindholm, DK-4771 Kalvehave, Denmark

ARTICLE INFO

Article history:
Received 20 May 2008
Received in revised form 14 April 2009
Accepted 15 April 2009

Keywords:
Classical swine fever
CSFV
Control strategy
Biosecurity
Pig density
InterSpread
Simulation
Economics
Denmark

ABSTRACT

In 2006, total Danish pork exports were valued at €3.8 billion, corresponding to approximately 5% of the total Danish exports, and an outbreak of a notifiable disease would have dramatic consequences for the agricultural sector in Denmark. Several outbreaks of classical swine fever (CSF) have occurred in Europe within the last decade, and different control strategies have been suggested. The objective of this study was to simulate the epidemiological and economic consequences of such control strategies in a CSF epidemic under Danish conditions with respect to herd demographics and geography and to investigate the effect of extra biosecurity measures on farms. We used InterSpread Plus to model the effect of nine different control strategies: the minimum measures required by the EU plus depopulation of contact herds (EUplus), extra depopulation of neighbouring herds, extra surveillance within the protection and surveillance zones, extra biosecurity in SPF herds—or in all herds, vaccination of all pigs in the 1 or 2 km zones using live vaccine as a protective measure (vaccination-to-kill), vaccination of all weaners and finishers in the 1 or 2 km zones using an E2 marker vaccine as a suppressive measure (vaccination-to-live). Each epidemic was simulated to start in four different index herds: production herds located in low, medium and high pig density areas, respectively; and a nucleus herd in an area of high pig density. For each control strategy and index case, we calculated the size and duration of the epidemic, the number of depopulated and/or vaccinated herds and animals, the control costs borne by the public and the pig industry, respectively, as well as the loss of exports associated with the epidemic.

The simulations showed that the EUplus strategy is the most effective of the evaluated strategies with respect to limiting the size, duration and cost of the epidemic, regardless of the index case. However, regarding the number of slaughtered animals, the vaccination-to-live strategies appeared to be more effective.

Epidemics become larger and last longer if the index case is a nucleus herd. This implies that biosecurity in nucleus herds is extremely important to avoid transmission of CSF to these herds.

Simulations showed that a Danish CSF epidemic will be moderate in most cases and will include fewer than 10 cases and last less than 2 weeks on average. However, for some iterations, long-lasting and large epidemics were observed. Irrespective of the size and duration, an epidemic is expected to be very costly due to the export losses.

© 2009 Elsevier B.V. All rights reserved.
1. Introduction

Outbreaks of notifiable diseases regularly occur in Europe, some with dramatic consequences for the agricultural sector. In 1997/1998, an epidemic of CSF in the Netherlands resulted in 429 infected herds. The epidemic, which lasted for more than a year, led to the slaughter of 1715 herds (yielding a total of 1.8 million pigs) (Elbers et al., 1999) and cost US$ 2.3 billion (Meuwissen et al., 1997). Furthermore, more than 7 million pigs were slaughtered for animal welfare reasons (Elbers et al., 1999). In the autumn of 2000, a smaller CSF epidemic occurred in England including 16 infected herds over a period of 4.5 months (Sharpe et al., 2001). In early 2001, the UK also suffered from an epidemic of foot and mouth disease (FMD), which affected pigs, cattle and sheep. The 2001 UK FMD epidemic included more than 2000 infected herds and lasted for 7 months with total costs amounting to more than £8 billion (Anderson, 2002).

Even a temporary ban on exports due to a CSF epidemic would be devastating for the Danish pig industry. In 2006, the Danish pork export was valued at €3.8 billion, corresponding to approximately 5% of the total Danish export. Danish export of pig products amounts to 85% of the pork produced and goes to more than 130 countries. Of the exported pork, 70% was exported to other EU member states, in particular Germany, the UK, France, and Italy, while 30% was exported to non-EU countries like Japan, Russia and the US. Moreover, 4.9 million pigs were exported in 2007. The main part of these consisted of piglets.

An outbreak of CSF will put an immediate stop to all Danish exports for the first 2–3 days. Thereafter, exports to the EU markets will continue from areas outside the identified zones, while the entire export to non-EU markets will be disrupted for a longer period. Therefore, the duration of an epidemic will be extremely important. However, ethical aspects will also contribute to the discussion and decisions on which control strategy to choose. From the large epidemics in Europe seen in the last decade, it has become clear that mass culling of animals has become less ethically and economical acceptable (Scudamore and Harris, 2002; Pluimers et al., 2002).

In case of an outbreak of CSF, the minimum control strategy defined by the European Commission (EC) is (1) depopulation of infected herds; (2) movement restrictions and (3) surveillance within the 3 km protection zone and the 10 km surveillance zone; and (4) surveillance of herds that could have been infected through contacts with other infected herds (Anonymous, 2001). Additional control measures include depopulation within a certain distance from infected herds or, possibly, depopulation of high-risk herds and vaccination. Vaccination with marker vaccines might be recommended in areas with high pig densities to avoid mass slaughter of animals (Anonymous, 2001). However, the use of vaccination with a marker vaccine has yet to be tried in an outbreak situation.

Different control strategies against CSF have already been evaluated by use of simulation models. Nielen et al. (1999) showed that using pre-emptive slaughter to control an epidemic was efficient, and that this strategy led to smaller size of the epidemic combined with less welfare slaughter, which resulted in fewer costs of the epidemic. Mangen et al. (2002) showed that the optimal strategy depended on the pig density in the affected area. In densely populated areas (DPLAs1), they found that each of three alternative strategies were more effective than the basic EU strategy: (1) depopulation of herds within a radius of 750–1000 m of infected herds; (2) vaccination with slaughter and subsequent rendering when capacity was available; and (3) vaccination with subsequent storage of pig meat that would later be sold on the EU market. In their simulations, the expected size of the epidemic was reduced from 170 infected herds to 29–39 infected herds, and the expected duration from 373 days to 96–139 days. In sparsely populated areas (SPLAs), they found that all four strategies were equally efficient, leading to an epidemic with five infected herds and duration of 64–100 days. As long as the epidemic stayed in SPLAs the spread of the infection was strongly linked to movement contacts alone.

In a study that included vaccination as an additional control option, Bergevoet et al. (2007) simulated that the cost-effective strategy depended on the number of herds infected prior to the first detection of an infected herd—the so-called high-risk period (HRP). If only two to five herds were infected during the HRP, approximately €2.5 million could be saved on average or approximately €8 million in extreme situations. However, if 11–20 herds were infected during the HRP, approximately €18 million could be saved on average or approximately €50 million in extreme situations.

Given that the optimal strategies vary and that there appears to be interaction between demographics, infrastructure, herd characteristics and the predicted size and duration of an epidemic, we find it important to study the spread and control of CSF for Denmark specifically. The farm densities and the contacts between herds differ between countries, making it difficult to extrapolate the results directly from other countries. In Denmark, the farm densities vary from 50 to 1380 pigs per km$^2$, and moreover, the contact structure varies between herd types. Nucleus herds produce and sell breeding stock to a large number of production herds, which implies that nucleus herds could have a large impact on disease spread. The potentially larger impact on disease spread has already been recognized for endemic production diseases and extra biosecurity measures are required for nucleus herds.

Hence, the question remains: is there a unique, optimal control strategy for a Danish CSF epidemic, or is the optimal choice of control strategy dependent on the demographics and herd structure in the area in which the index case is located?

The objective of this study was to explore the epidemiological and economic consequences of different control strategies against CSF under typical Danish conditions with respect to herd demographics and geography. Another objective was to investigate the effect of extra biosecurity measures on farms.

---

1 DPLA (SPLA) is defined as > 300 (≤ 300) pigs per km$^2$ at a regional level (Mangen et al., 2002).
2. Materials and methods

2.1. The simulation model

We used the software program InterSpread Plus version 1.047.20 to model the spread of CSF Virus (CSFV) in the Danish population of domestic pigs. InterSpread Plus (Sanson, 1993; Stern, 2003) is a stochastic disease-event model that models epidemics using Monte Carlo simulation.

In InterSpread Plus, the stochastic and spatial simulation of the spread and control of CSF starts with an initialisation phase, in which farm-specific data (geographic location, numbers of animals and farm type) and infected herds (index cases) are loaded into the model. Thereafter, the stochastic spread mechanisms act spatially by use of geographic location of farms. In InterSpread Plus, the farm is considered the epidemiological unit, and spread of CSF within farms is not simulated. Control strategies consist of different combinations of the following four control measures: depopulation, movement restrictions, surveillance and vaccination. The total number of parameters varies between strategies from 500 to 600, distributed across 40–50 sections.

2.2. Parameterization of the initialisation phase of Interspread

2.2.1. Demographics of Danish pig herds

The Danish Central Husbandry Register (CHR) contains data on the geographical locations of farms, the number of animals on the farm and whether the herd has an SPF health status or not. In the simulations, we used the following data from the CHR: a unique identification number, geographical x and y coordinates and the number of sows and finishers on the farm. Furthermore, farms were either described as specific pathogen free (SPF) herds or conventional herds and as one of the following categories: nucleus herd, production herd, boar station, weaner production or quarantine herd. Finally, we classified each farm according to the proportion of finishers to sows.

In July 2006, a total of 12,275 herds were registered in the CHR. Herds with sows had between 1 and 2628 sows, with a median of 167 sows. Herds with finishers had between 1 and 13,000 finishers, with a median of 500 finishers. Of the 12,275 herds, 3590 were classified as SPF herds, 264 were classified as nucleus herds, and 19 were classified as boar stations. Herds with >200 sows and <1000 finishers or herds with 100–200 sows and <500 finishers were classified as commercial herds selling weaners (2230 herds). Moreover, 9680 herds were classified as finisher herds or farrow-to-finisher herds, and 364 herds were classified as small herds.

2.2.2. The four index cases

We simulated four index cases for the epidemic: a nucleus herd in Southern Jutland, a sow herd on Zealand, a sow herd in Northern Jutland and a sow herd in Southern Jutland. These three areas in Denmark had different farm densities: Zealand had the lowest farm density (273 pigs/km²), Northern Jutland had a medium farm density

Table 1

<table>
<thead>
<tr>
<th>Herd type</th>
<th>Location</th>
<th>Herd status</th>
<th>Number of sows</th>
<th>Number of finishers</th>
<th>Number of average monthly movements of</th>
<th>Pig density in district (pigs/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleus herd</td>
<td>Southern Jutland</td>
<td>SPF</td>
<td>260</td>
<td>0</td>
<td>2.6 3.6 0</td>
<td>1,175</td>
</tr>
<tr>
<td>Sow herd</td>
<td>Zealand</td>
<td>SPF</td>
<td>210</td>
<td>100</td>
<td>0.17 3 2.5</td>
<td>273</td>
</tr>
<tr>
<td>Sow herd</td>
<td>Northern Jutland</td>
<td>SPF</td>
<td>230</td>
<td>700</td>
<td>0.08 2.9 5.7</td>
<td>882</td>
</tr>
<tr>
<td>Sow herd</td>
<td>Southern Jutland</td>
<td>SPF</td>
<td>310</td>
<td>1,630</td>
<td>0 3.6 4.5</td>
<td>1,341</td>
</tr>
</tbody>
</table>

a Herd status could be either SPF or conventional.

Fig. 1. Map showing swine densities in Denmark (July 2006). Circles indicates the three areas of different swine densities where index herd in simulation of hypothetical spreading of classical swine fever are located.
established cell lines (Uttenthal et al., 2003) and a TaqMan case consisted of a virus isolation in both primary and days was 47 and within a range of between 19 and 83 days probabilities were modified until the median number of l

individual farm lambda (number of movements, and this figure was used as the 1-year period were recalculated into an average daily r

tributions to illustrate (1) that different herd types move from markets were described by separate Poisson dis-

describing person contacts, and local spread within a range of 2 km. The five movement types describing movements of sows, weaners and finishers as well as movements to and from markets were described by separate Poisson dis-

2.3. Parameters describing InterSpread Plus spread mechanisms

Based on experimental studies, we simulated herds as being infectious from 5 to 10 days after infection. This was in accordance with other simulation studies (Jalvingh et al., 1999; Mangen et al., 2002).

The spread of CSF virus was simulated by five contact types describing animal movements, two contact types describing person contacts, and local spread within a range of 2 km.

The five movement types describing movements of sows, weaners and finishers as well as movements to and from markets were described by separate Poisson distributions to illustrate (1) that different herd types move different animal types; and (2) that the distance animals are moved varies with the type of animals moved.

Movements taking place between July 2005 and June 2006 were extracted from the official Danish movement database. For each farm, observed movements during this 1-year period were recalculated into an average daily number of movements, and this figure was used as the individual farm lambda (λ) in a Poisson distribution in the model. Average movements were calculated for sows and weaners and for movements to and from markets. Based on the same movement data, we restricted which herd types could deliver pigs to each other. For example, nucleus herds could only receive pigs from other nucleus herds, SPF herds could not receive pigs from conventional herds, and weaners could only be moved from herds with sows, etc. A more detailed description of the simulated movements is available in Boklund (2008), Appendix E.

Of the 12,275 herds registered, only 3016 had recorded that animals were moved to other herds between July 2005 and June 2006. In the same period, 10,404 herds moved animals to the abattoir. Among farms that moved animals to other herds, the number of movements varied from once a year to every second day (weaners) or twice a day (sows).

Based on a simulation of the epidemic in the Netherlands in 1997 (Mangen et al., 2002), we simulated the probability of transmission of CSFV via animal movements (high-risk contacts) as 0.277.

The two types of person contact had different risks of virus transmission. People who visited a farm and did not go on to another farm were modelled as low risk persons, and people who visited a farm and went to another farm afterwards or who came from another farm were modelled as medium risk persons (e.g. professional contacts such as the veterinarian). We modelled these two contact types as Poisson distributions, where lambda was the median number of contacts calculated from a study from 1999 to 2000 in which the biosecurity of 226 Danish pig herds was investigated (unpublished results).

Based on simulations from the Netherlands (Mangen et al., 2002), the CSF virus was modelled to spread within 2 km of the infected herd as a so-called local spread. Local spread could be a consequence of limited airborne spread or mechanical spread of CSF virus by birds, mice, etc. (Dewulf et al., 2001; Weesendorp et al., 2008). Within a radius of 500 m, the probability of spread for each day was set to 0.0122, from 500 m to 1 km it was 0.004, and up to 2 km it was 0.00003.

2.4. The control strategies

The control strategies consisted of different combinations of the following four control measures: surveillance, movement restrictions, depopulation and/or vaccination. These four measures could be applied for different time periods in different zones and in different combinations. In this study, a total of nine different control strategies were simulated.

2.4.1. The EUplus strategy

This control strategy consisted of the minimum control measures that EU countries are obliged to implement in case of a CSF outbreak: depopulation of infected herds, surveillance and movement restriction in the 3 and 10 km zones and surveillance in herds that have been in contact with infected herds (Anonymous, 2001). Furthermore, depopulation of contact herds and neighbouring herds was included. These measures are not compulsory.

CSF-infected herds were assumed to be depopulated 1 day after detection. Neighbouring herds within 500 m and herds that had received animals from an infected herd were simulated to be depopulated 2 days after detection of the infected herd. Herds in contact with an infected herd (person contact or vehicles) were simulated to be surveyed.

For a period of 3 days after detection of the first infected herd, 98% of all national movements of pigs were
restricted. The remaining 2% were assumed to consist of illegal movements or exceptional movements approved by the authorities.

Movement restrictions were modelled for 37 days in the 3-km protection zone. This period was based on the council directive (Anonymous, 2001), which stipulates a movement restriction period of 30 days from the end of the cleaning and disinfection of an infected herd. The extra 7 days would include time to kill the animals on the infected farm and clean and disinfect. If several herds were detected within the same area, a herd would stay in the protection zone until 37 days after the last detection date. All herds in the protection zone were assumed to be surveyed within the first week after the zone was established, with a 50% probability of detection if clinical signs were present (Engel et al., 2005). Before the restrictions in the protection zone were lifted, clinical and laboratory examinations would be carried out in all herds with a 95% probability of CSF detection in infected farms.

In the 10-km surveillance zone, the movement restrictions were simulated as a period of 28 days, which were assumed to be 7 days in which to kill the animals, clean and disinfect, followed by a 21-day waiting period in compliance with the directive (Anonymous, 2001). In this area, 50% of the herds were assumed to be clinically examined within the first 21 days after establishment of the zone. Before lifting the zone, 50% of the herds would be subjected to clinical and laboratory examination, with a 95% probability of detection.

As a simulation of the basic surveillance maintained by farmers, veterinarians and consultants, 80% of all herds would be surveyed on a daily basis, with detection probability ranging from 0.1 on day 8 after the first clinical signs appeared to 0.95 on day 29 after the first clinical signs appeared.

The remaining eight control strategies were modelled in the same way as the EUplus control strategy but with different additions or modifications. Further details of the model inputs and assumptions are available in Boklund (2008), Appendix E.

2.4.2. The extra surveillance strategy

In addition to the EUplus strategy, an extra clinical examination was performed in herds within the protection zone, and an early clinical examination of all herds within the surveillance zone as well as blood tests of all herds in the surveillance zone were performed.

2.4.3. The extra biosecurity strategies

Based on the knowledge of a higher level of biosecurity in SPF herds (Boklund et al., 2003; Boklund et al., 2004), the percentage of herds under basic surveillance was raised from 80% to 90% of the SPF herds. Moreover, to illustrate the use of quarantine, use of defined loading areas and changing rooms in these herds, the risks related to visitor, the purchase of sows and the transport of finishers were reduced by 25%. In another strategy, the same changes were made for all farms to illustrate the potential gain if all herds maintained the same high level of biosecurity.

2.4.4. The depopulation strategy

Instead of depopulating all herds within 500 m of an infected herd, all herds within 1 km of an infected herd were depopulated.

2.4.5. The vaccination-to-kill strategies

Rather than depopulating herds within 500 m, herds within a range of 1 km or 2 km of an infected herd were vaccinated once with a live Chinese strain vaccine (C-strain). Vaccination would start 7 days after the first herd was detected to illustrate that time would be needed to decide on a vaccination strategy, get the permission from the EU Commission and to buy the vaccines. Immunity was assumed to start 2 days after vaccination and to be complete 7 days after vaccination (Dewulf et al., 2004; Dewulf et al., 2005). The herd was the unit of interest, and, as some herds were expected to be infected before vaccination, the time to complete immunity was extended by 2 days compared with Dewulf et al. (2004), who showed immunity on day 0 after vaccination. The available resources were assumed to include 50 vaccination teams, who could each vaccinate approximately 600 sows and 3000 finishers a day, resulting in vaccination of 150,000 finishers and 30,000 sows per day (Anders Hoigaard, Danish Food and Veterinary Administration, personal communication). Vaccination would start at the edge of the zone and continue towards the centre. When the epidemic ended, all vaccinated animals were assumed to be slaughtered and destroyed.

2.4.6. The vaccination-to-live strategies

Instead of depopulating herds within 500 m, all finishers in herds within a range of 1 km or 2 km of an infected herd were vaccinated twice within 3 weeks with an E2 subunit vaccine (marker vaccine). Immunity was simulated to start 8 days after and to be moderate 10 days after the first vaccination (van Oirschot, 2003). However, full immunity was not simulated until 14 days after the first vaccination, and a booster vaccination was needed to activate the secondary immune response. The available resources were assumed to be equal to those of the vaccination-to-kill strategies. However, the risk of running short of people was higher, because all herds had to be vaccinated twice. Therefore, the number of animals vaccinated per day was reduced by 50%. Vaccination would start at the edge of the zone and continue towards the centre.

When the epidemic ended, all vaccinated animals were kept within the vaccination zones until they were eventually slaughtered. Only finishers were assumed to be vaccinated when this strategy was chosen so that CSF-free status could be regained within a relatively short time span.

2.5. The cost of a CSF epidemic

The costs of CSF epidemics controlled by different strategies were calculated on the basis of the output from InterSpread Plus. Essentially, we followed the approach taken in Boklund et al. (2008), and therefore costs were divided into three major components:
(1) **Public costs:** the control costs covered by the national budget during the epidemic or as compensation to the farmers. The elements of these costs were:
   a. the lost value of depopulated pigs
   b. the costs of culling, rendering and cleaning
   c. 20% of the costs related to production losses (partial compensation for empty housing units)
   d. the costs of establishing and controlling surveillance and protection zones
   e. the costs of blood tests
   f. the costs of vaccination

(2) **Industry costs:** the control costs and other costs directly associated with the epidemic. Specifically, these costs included:
   a. 80% of the production losses due to empty housing units
   b. welfare slaughter
   c. losses from the initial 3-day national standstill

(3) **Export losses:** An outbreak of CSF can be expected to be followed by a ban on the export of live pigs and pig products either for parts of the country or the whole country (Anonymous, 2001; Anonymous, 2007). The duration of this ban would depend on the control strategy applied and would differ between EU countries and non-EU countries. The duration of the export bans are subject to a substantial amount of uncertainty, especially if vaccination is used, because experience of reactions to vaccinated pork is lacking. Many factors will influence the duration of the export ban, such as: confidence in the Danish veterinary authorities in the exporting country, the way in which the epidemic is handled by the authorities, the size and duration of the epidemic till the point of negotiation, the estimated length of the HRP, etc. These considerations were included in the following assumptions on market reactions. EU markets were assumed to react in the same way for all strategies. We assumed that EU markets would accept zoning and that they would fully reopen 40 days after the last infected herd was depopulated. Furthermore, we assumed that in the event of a CSF outbreak, the EU would accept zoning around infected herds and that pork produced outside these zones could be exported to EU markets. The reactions from non-EU markets were assumed to differ depending on the type of control used.
   a. Non-vaccination strategies: we assumed that non-EU countries would remain closed for 100 days. This was based on expert opinion and on the experiences from the FMD epidemic in the UK (Thompson et al., 2002).
   b. Vaccination-to-kill: we assumed that non-EU markets would reopen 180 days after the last vaccinated pigs were slaughtered and rendered. The longer time to reopening reflects the fact that, for each non-EU country, risk analysis and bilateral negotiations would probably have to be conducted, including inspections by veterinary authorities of the non-EU country, before exports could be resumed. Not all non-EU markets are expected to demand these extra measures prior to reopening; however, we assumed that they would, both for simplicity and due to lack of confidence in reliable estimates of the proportion of such markets.
   c. Vaccine-to-live: we assumed that non-EU markets would not reopen until 100 days after the last vaccinated pigs were slaughtered, i.e. up to 283 days\(^2\) would pass after the last confirmed outbreak.

It was assumed that, while non-EU markets remained closed, the pork products would be sold on the EU market at a reduced price, approximately 20% below the price obtained on the closed markets. This reflects the fact that the closure of non-EU markets would lead to an oversupply of pork and that the prices of some cuts are higher for non-EU markets. It was expected that the EU would compensate 50% of the losses in the restricted zones, and these compensations were subtracted in the cost calculations. We assumed that, when the markets reopened, the export would be fully restored to the level prior to the outbreak.

Parameters for the economic calculations were primarily based on the opinions of experts from Danish Meat Association, Danish Pig Production, the National Veterinary Institute and the Danish Food and Veterinary Administration.

### 2.6. Output analyses

For each combination of index case and control strategy, the model was run for 500 iterations, and the output regarding the detected, depopulated, traced and vaccinated herds, as well as information about protection and surveillance zones and the transmission history, were stored in text files.

Based on the outputs, the distributions of the size and duration of the epidemic, as well as the number of depopulated and vaccinated herds/animals, were summarized using minimum, maximum, quartiles and median values. Duration was calculated as the number of days from first detection of an infected herd till detection of the last infected herd. The outputs from the individual iterations were used to calculate the values needed to estimate the distribution of the epidemic in each iteration, summarized by the minimum, maximum, quartiles and median costs for the public, industry and export components, respectively.

### 3. Results and discussion of the results

#### 3.1. Predicted sizes and durations of an epidemic

The simulations predict minimal differences in the size and duration of CSF epidemics when the index case is a production herd situated on Zealand, or in Northern or Southern Jutland (Data not shown). However, if an epidemic starts in a nucleus herd, the size and duration will almost double, compared with an epidemic starting in a production herd (Tables 2 and 3).

\(^2\) We assumed that weaners and finishers were vaccinated, which implies that the period from vaccination till the last animal is slaughtered will be half a year.
Table 2
Predicted number of CSF-infected herds and duration of epidemics in Denmark. Different control strategies are compared when the index case was a production herd located in Southern Jutland, 2006.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name of control strategy</th>
<th>Description of control strategy</th>
<th>Surveillance</th>
<th>Depopulationa</th>
<th>Vaccination</th>
<th>Number of herds infected per epidemic (quartiles of iterations)</th>
<th>Number of days in each epidemicb (quartiles of iterations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min. 25 50 75 Max.</td>
<td>Min. 25 50 75 Max.</td>
</tr>
<tr>
<td>1</td>
<td>EUplus</td>
<td>The minimum strategy demanded by the EU plus a few extra measures</td>
<td>Normal</td>
<td>500 m</td>
<td>–</td>
<td>1 1 4 9 29</td>
<td>1 6 6 9 230</td>
</tr>
<tr>
<td>2</td>
<td>Extra surveillance</td>
<td>+ Extra surveillance in the zones</td>
<td>Extra</td>
<td>500 m</td>
<td>–</td>
<td>1 1 4 9 33</td>
<td>1 6 6 9 229</td>
</tr>
<tr>
<td>3</td>
<td>SPF biosecurity</td>
<td>Reduced risk of transmission to SPF herds and extra surveillance within SPF herds</td>
<td>Extra in SPF</td>
<td>500 m</td>
<td>–</td>
<td>1 1 3 8 28</td>
<td>1 5 6 8 165</td>
</tr>
<tr>
<td>4</td>
<td>Extra biosecurity, all</td>
<td>Reduced risk of transmission to all herds and extra surveillance within all herds</td>
<td>Extra in all herds</td>
<td>500 m</td>
<td>–</td>
<td>1 1 3 7 29</td>
<td>1 5 6 8 86</td>
</tr>
<tr>
<td>5</td>
<td>Depopulation</td>
<td>+ Depopulation within a range of 1 km from infected herds</td>
<td>Normal</td>
<td>1 km</td>
<td>–</td>
<td>1 1 3 8 32</td>
<td>1 5.8 6 9 232</td>
</tr>
<tr>
<td>6</td>
<td>Vaccination-to-kill, 1 km</td>
<td>+ Vaccination within 1 km – depopulation of vaccinated herds when resources are available</td>
<td>Normal</td>
<td>1 km</td>
<td>–</td>
<td>1 2 5 10 41</td>
<td>1 7 8 11 235</td>
</tr>
<tr>
<td>7</td>
<td>Vaccination-to-kill, 2 km</td>
<td>+ Vaccination within 2 km – depopulation of vaccinated herds when resources are available</td>
<td>Normal</td>
<td>2 km</td>
<td>–</td>
<td>1 2 5 10 41</td>
<td>1 6 8 11 235</td>
</tr>
<tr>
<td>8</td>
<td>Vaccination-to-live, 1 km</td>
<td>+ Vaccination within 1 km – without depopulation</td>
<td>Normal</td>
<td>1 km</td>
<td>–</td>
<td>1 2 5 10 41</td>
<td>1 6 8 11 235</td>
</tr>
<tr>
<td>9</td>
<td>Vaccination-to-live, 2 km</td>
<td>+ Vaccination within 2 km from infected herd – without depopulation</td>
<td>Normal</td>
<td>2 km</td>
<td>–</td>
<td>1 2 5 10 42</td>
<td>1 6 8 11 233</td>
</tr>
</tbody>
</table>

a Depopulation of neighbouring herds within a radius of 500 or 1000 meters.
b The period from the first to the last herd is detected.
Table 3
Predicted number of CSF-infected herds and duration of epidemics in Denmark. Different control strategies are compared when the index case was a nucleus herd located in Southern Jutland, 2006.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name of control strategy</th>
<th>Description</th>
<th>Surveillance</th>
<th>Depopulation</th>
<th>Vaccination</th>
<th>Number of herds infected per epidemic (quartiles of iterations)</th>
<th>Number of days in each epidemic (quartiles of iterations)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min. 25 50 75 Max.</td>
<td>Min. 25 50 75 Max.</td>
</tr>
<tr>
<td>1</td>
<td>EUplus</td>
<td>The minimum strategy demanded by the EU plus a few extra measures</td>
<td>Normal</td>
<td>500 m</td>
<td>–</td>
<td>1 4 8 15 248</td>
<td>1 4 8 15 248</td>
</tr>
<tr>
<td>2</td>
<td>Extra surveillance</td>
<td>+ Extra surveillance in the zones</td>
<td>Extra</td>
<td>500 m</td>
<td>–</td>
<td>1 4 8 15 164</td>
<td>1 11 13 17 254</td>
</tr>
<tr>
<td>3</td>
<td>SPF biosecurity</td>
<td>Reduced risk of transmission to SPF herds and extra surveillance within SPF herds</td>
<td>Extra in SPF</td>
<td>500 m</td>
<td>–</td>
<td>1 3 7 13 131</td>
<td>1 11 12 17 241</td>
</tr>
<tr>
<td>4</td>
<td>Extra biosecurity, all</td>
<td>Reduced risk of transmission to all herds and extra surveillance within all herds</td>
<td>Extra in all herds</td>
<td>500 m</td>
<td>–</td>
<td>1 3 6 11 183</td>
<td>1 9 11 14 249</td>
</tr>
<tr>
<td>5</td>
<td>Depopulation</td>
<td>+ Depopulation within a range of 1 km from infected herds</td>
<td>Normal</td>
<td>1 km</td>
<td>–</td>
<td>1 3 8 14 143</td>
<td>1 10 12 17 283</td>
</tr>
<tr>
<td>6</td>
<td>Vaccination-to-kill, 1 km</td>
<td>+ Vaccination within 1 km – depopulation of vaccinated herds when resources are available</td>
<td>Normal</td>
<td>–</td>
<td>1 km</td>
<td>1 5 9 16 452</td>
<td>1 12 15 22 280</td>
</tr>
<tr>
<td>7</td>
<td>Vaccination-to-kill, 2 km</td>
<td>+ vaccination within 2 km – depopulation of vaccinated herds when resources are available</td>
<td>Normal</td>
<td>–</td>
<td>2 km</td>
<td>1 5 10 16 232</td>
<td>1 12 15 24 284</td>
</tr>
<tr>
<td>8</td>
<td>Vaccination-to-live, 1 km</td>
<td>+ vaccination within 1 km – without depopulation</td>
<td>Normal</td>
<td>–</td>
<td>1 km</td>
<td>1 5 10 16 231</td>
<td>1 12 15 23 284</td>
</tr>
<tr>
<td>9</td>
<td>Vaccination-to-live, 2 km</td>
<td>+ vaccination within 2 km from infected herd – without depopulation</td>
<td>Normal</td>
<td>–</td>
<td>2 km</td>
<td>1 5 10 16 262</td>
<td>1 12 15 24 284</td>
</tr>
</tbody>
</table>

* Depopulation of neighbouring herds within a radius of 500 or 1000 m.

b The period from the first to the last herd is detected.
There is limited difference between the control strategies regardless of the point of origin. Thus, the existing control strategy (EUplus strategy) is predicted to be effective in case of an outbreak of CSFV.

The simulations show a small effect of extra biosecurity in SPF herds and a larger effect if extra biosecurity is maintained in all herds. Despite of the positive effect of biosecurity, it will be difficult to obtain a high level of biosecurity in all Danish pig herds if the argument is protection against CSF, since the threat of CSF to some farmers appear small. However, herds can often benefit from a high level of biosecurity because of the protection against other pathogens. In that case, the effect on a CSF epidemic would be a positive side effect.

In most cases (75%), the simulations suggest that vaccination of Danish pig herds will not reduce the number of detected herds, and, in some cases, it will even prolong the epidemic slightly. The model was set up to vaccinate from the outer edge of the vaccination zone and towards the centre. The time to protection from vaccination was longer than when herds were depopulated, thus causing a slightly longer time to protection.

### 3.2. Depopulation

Only a small variation in the number of depopulated herds was observed, depending on the location of the index herd. The median number of depopulated herds on Zealand and in Northern and Southern Jutland was 8, 10 and 12, respectively (data not shown). However, if the epidemic starts in a nucleus herd, the numbers of depopulated and vaccinated herds will double compared with if the epidemic starts in a production herd in the same area (Fig. 2). In extreme cases, up to 500 herds are predicted to be depopulated during a CSF epidemic if the epidemic starts in a nucleus herd, compared with fewer than 100 herds if the epidemic starts in a nucleus herd.

The number of depopulated and/or vaccinated herds and animals in the different control strategies show the same tendencies as the sizes and durations. The median number of depopulated animals decreases from 19,000 to 14,000 if a vaccination-to-live strategy is used instead of the EUplus strategy when the epidemic starts in a nucleus herd (Fig. 3). However, if a vaccination-to-kill strategy is used in the 2-km zone, the number of depopulated animals will increase to almost 25,000. This is a result of the fact that, in this strategy, vaccinated animals must be slaughtered and rendered at the end of the epidemic. If the epidemic starts in a production herd, the figures are smaller; however, the conclusions are the same (Fig. 3). If vaccination of herds with no subsequent slaughter of vaccinated pigs was simulated, the number of slaughtered animals decreased.

### 3.3. Economic results

The total costs of the simulated CSF epidemics vary between the four index cases. However, within each index case, the median industry and public costs do not differ between the control strategies when the uncertainty of the assumptions is taken into consideration. There is an indication that strategies involving extra biosecurity will be the least costly. However, the cost of maintaining this extra biosecurity is not included in the analysis, because this cost will have exists at all times and not only during the epidemic.

![Fig. 2. Box plot of the number of depopulated and vaccinated (Vac) herds in simulated CSF epidemics starting in a production herd (dark boxes) or a nucleus herd (white boxes) in Southern Jutland, Denmark, 2006. Please, see Table 2 for an explanation of the control strategies.](image-url)
The costs of the epidemic increased by almost €100 or €200 million when vaccination-to-kill or vaccination-to-live strategies, respectively, were implemented (Table 4). The extra costs were caused by the prolonged period in which exports to non-EU countries were banned. The lost exports cover approximately 75% of the total costs for the non-vaccination strategies, 84% of the total costs for the vaccination-to-kill strategies, and 89% of the costs in the vaccination-to-live strategies.

While the differences in the total costs between the three areas were relatively small (€8–12 million), the total costs increased by €30 million when the epidemic started in a nucleus herd compared with a production herd. This is both due to the extra costs of depopulation caused by the larger size of the epidemic and the additional loss of exports due to a longer duration of the epidemic.

4. General discussion

4.1. Size and duration of the epidemic

The results underline the importance of biosecurity, especially in nucleus herds. Owners of nucleus herds are already aware of their obligations; if a new pathogen is introduced to a nucleus herd: (1) the economic effect of the disease is much larger than in a production herd due to the loss of trading partners, breeding value, etc.; and (2) the disease spreads more efficiently from nucleus herds because of the large number of purchasers of sows and boars. Because of the high level of biosecurity in nucleus herds, the probability of an epidemic starting in a nucleus herd is small. However, we predict that an epidemic starting in a nucleus herd will be larger, last longer and have larger economic consequences.

The number of culled animals is important from an ethical point of view. Most pigs are produced to be slaughtered at some point. Public opinion regarding the slaughter of animals that are not included in the food chain will depend on the ethical view of the individual. Different ethical views have been described (Sandoe et al., 2008). However, especially in countries where mass slaughter of animals has recently been seen, the public had difficulty in accepting strategies that result in the culling of large numbers of animals (Pluimers et al., 2002). Compared with the number of animals slaughtered in the simulated epidemics, the number of animals slaughtered in the Dutch epidemic in 1997/1998 was much higher (1.8 millions, of which 1.1 million were slaughtered for animal welfare reasons) (Elbers et al., 1999). In contrast to the ethical point of view, the economic results showed that, even though vaccination gave the lowest numbers of slaughtered animals, it resulted in the highest costs of the epidemic, due to the increased export losses. There were no discernible differences in direct costs to the public and industry between vaccination and non-vaccination strategies. Thus, vaccination might be more beneficial for non-exporting countries than for exporting countries like Denmark.

In simulations of the CSF epidemic in the Netherlands in 1997–1998, Mangen et al. (2001) found a positive effect of the use of vaccinations. However, their simulations were started from a situation in which 37 herds were already infected when the first infected herd was detected. Another simulation study by the same author showed...
Table 4
Predicted costs of CSF epidemics among Danish pig herds comparing different control strategies when the index herd is a production or nucleus herd in Southern Jutland, 2006.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name of control strategy</th>
<th>Description of control strategy</th>
<th>Southern Jutland – production herd</th>
<th>Southern Jutland – nucleus herd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>25</td>
</tr>
<tr>
<td>1</td>
<td>EIplus</td>
<td>The minimum strategy demanded by the EU plus a few extra measures</td>
<td>Industry 16.4 16.5 18.1 22.1 25.6</td>
<td>13.6 21.8 31.0 35.6 43.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.6 2.7 3.5 4.7</td>
<td>0.5 3.3 5.2 6.1 7.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 106.3 108.3 112.3 116.3 117.4</td>
<td>105.9 114.6 120.2 130.9 128.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 123.5 126.4 133.1 141.9 147.7</td>
<td>120.0 139.8 156.4 172.6 180.1</td>
</tr>
<tr>
<td>2</td>
<td>Extra surveillance</td>
<td>+ Extra surveillance in the zones</td>
<td>Industry 16.4 16.5 18.2 22.0 25.6</td>
<td>13.6 22.2 31.6 35.4 42.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 1 1.9 3.1 3.9 5.1</td>
<td>0.7 3.7 5.9 6.8 8.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 106.3 108.3 112.7 115.9 117.2</td>
<td>107.0 114.6 119.4 129.0 127.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 123.7 126.7 133.9 141.8 147.9</td>
<td>121.3 140.5 156.7 171.2 178.1</td>
</tr>
<tr>
<td>3</td>
<td>SPF biosecurity</td>
<td>Reduced risk of transmission to SPF herds and extra surveillance within SPF herds</td>
<td>Industry 16.4 16.5 18.1 21.9 25.2</td>
<td>13.6 21.3 30.0 34.0 42.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.6 2.6 3.3 4.4</td>
<td>0.5 3.1 4.9 5.7 7.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 106.3 108.3 112.4 115.3 117.4</td>
<td>105.9 114.0 119.3 128.8 128.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 123.5 126.4 133.1 140.5 147.0</td>
<td>120.0 138.4 156.4 172.6 177.4</td>
</tr>
<tr>
<td>4</td>
<td>Extra Biosecurity, all</td>
<td>Reduced risk of transmission to all herds and extra surveillance within all herds</td>
<td>Industry 16.4 16.5 18.2 21.7 24.8</td>
<td>13.6 20.0 27.1 31.8 36.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.6 2.6 3.1 4.2</td>
<td>0.5 2.9 4.6 5.3 6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 106.3 108.3 112.2 114.1 116.8</td>
<td>105.9 112.6 117.5 122.2 123.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 123.5 126.3 132.7 138.9 145.8</td>
<td>120.0 135.5 149.2 159.3 166.8</td>
</tr>
<tr>
<td>5</td>
<td>Depopulation</td>
<td>+ Depopulation within a range of 1 km from infected herds</td>
<td>Industry 16.4 16.5 18.1 22.1 25.3</td>
<td>13.7 22.1 30.9 35.5 44.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.7 3.2 4.1 5.8</td>
<td>1.6 4.8 7.1 8.9 9.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 106.3 108.3 111.8 115.4 116.3</td>
<td>105.9 114.1 119.4 129.8 127.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 123.5 126.4 133.1 141.6 147.4</td>
<td>121.2 141.0 157.4 173.3 181.3</td>
</tr>
<tr>
<td>6</td>
<td>Vaccination-to-kill, 1 km</td>
<td>+ Vaccination within 1 km – depopulation of vaccinated herds when resources are available</td>
<td>Industry 16.4 17.4 22.9 25.0 29.5</td>
<td>13.6 25.4 35.1 39.2 45.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.2 2.3 3.0 4.3</td>
<td>0.4 2.9 4.5 5.7 6.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 190.5 194.6 197.7 203.0 207.2</td>
<td>189.6 200.3 205.1 217.9 218.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 207.2 213.1 222.9 231.0 236.8</td>
<td>203.6 228.3 244.8 262.7 270.8</td>
</tr>
<tr>
<td>7</td>
<td>Vaccination-to-kill, 2 km</td>
<td>+ Vaccination within 2 km – depopulation of vaccinated herds when resources are available</td>
<td>Industry 16.4 17.4 22.9 25.1 29.4</td>
<td>13.6 25.4 35.4 39.4 48.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.3 2.7 3.8 5.4</td>
<td>0.4 3.5 6.7 7.4 9.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 190.5 194.6 197.6 203.5 207.2</td>
<td>189.6 199.9 205.5 221.2 222.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 207.2 213.2 223.2 232.3 237.9</td>
<td>203.6 228.8 246.9 268.0 280.2</td>
</tr>
<tr>
<td>8</td>
<td>Vaccination-to-live, 1 km</td>
<td>+ Vaccination within 1 km – without depopulation</td>
<td>Industry 16.4 17.4 23.0 25.1 29.4</td>
<td>13.6 25.4 35.4 39.4 48.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.2 2.3 3.0 4.2</td>
<td>0.4 2.8 4.5 5.2 6.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 297.8 302.4 305.4 311.3 310.9</td>
<td>297.4 307.7 313.2 329.6 330.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 315.0 320.9 330.6 339.3 344.4</td>
<td>311.4 335.9 353.1 374.2 385.2</td>
</tr>
<tr>
<td>9</td>
<td>Vaccination-to-live, 2 km</td>
<td>+ Vaccination within 2 km from infected herd – without depopulation</td>
<td>Industry 16.4 17.4 23.0 25.1 29.4</td>
<td>13.6 25.5 35.4 39.5 48.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public 0.8 1.2 2.3 3.0 4.3</td>
<td>0.4 2.9 4.5 5.3 6.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Export 297.8 302.4 305.4 311.3 310.9</td>
<td>297.4 307.7 313.2 329.2 332.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total 315.0 321.0 330.7 339.6 344.6</td>
<td>311.4 336.1 353.2 374.0 387.6</td>
</tr>
</tbody>
</table>
that preventive slaughter or vaccination was effective in reducing the size and duration of epidemics in densely populated livestock areas (DPLAs) but not in sparsely populated areas (SPLAs) (Mangen, 2002). Mangen (2002) defined a DPLA as an area with >300 pigs per km² at the regional level. According to this definition, half of the counties in Denmark are DPLAs, and both Northern and Southern Jutland are defined as DPLAs. However, Mangen (2002) also predicted that 99 herds out of 113 were infected via local spread. Although the same parameters were used for local spread in our simulations, our predicted epidemics spread mostly via movements (data not shown). When the number of infected herds increased, the ratio between the number of herds infected via local and movement spread did not change. Therefore, the differences described here could be an indication of a difference in the herd densities, contact structure and trade patterns between the two countries (Boklund, 2008). The study by Mangen et al. (2001) predicted that the economic costs of an CSF epidemic would be approximately €500 million. The difference between their results and ours could be due to the fact that they simulated larger epidemics.

In Finland, simulation studies have predicted that in most cases only few herds will be infected in an epidemic and that the largest epidemics will include fewer than 13 herds (2008). However, the pig density in Finland is very low. Of 458 municipalities, only 4 have >100 pigs per km². Niemi et al. (2008) predicted that the economic costs of a Finnish CSF epidemic could be below €33 million. However, even though their predictions of the number of infected herds were in accordance with ours, we predict larger economic costs based on the large amount of exports from Denmark.

From previous CSF epidemics, we have seen that sometimes many herds are involved in large epidemics such as the epidemic in the Netherlands in 1997–1998. However, most of the epidemics that have occurred in Western Europe over the last 20 years have been restricted to include a smaller number of infected herds, as was the case in Germany in the 1990s (Fritzemeier et al., 2000) and in England in 2000 (Mackinnon, 2001). This is in keeping with the results of our simulation study, in which most often (75%) few infected herds are predicted, while only in the extreme situations, epidemics are predicted to include hundreds of infected herds and to last almost 1 year. In Germany, infection was often introduced through direct or indirect contact to wild boar (Fritzemeier et al., 2000). However, in Denmark wild boar is not present. Furthermore, simulations have shown that the presence of wild boar will increase the probability of infection but not the size and duration of the epidemic (Boklund et al., 2008).

Vaccination was simulated within 1 or 2 km’s distance to infected herds. The 2-km vaccination zone would most probably be used, if vaccination were to start today (personal communication Sten Mortensen, Danish Veterinary and Food Administration). It is therefore remarkable that we do not see difference between the to vaccination zones except from the difference in number of vaccinated animals. However, it would be interesting to conduct further simulations assuming use of vaccination on extreme epidemics only, to get a more detailed knowledge of the differences between the vaccination strategies.

In this study, the sensitivity of clinical examinations and laboratory tests was included in the probability of detecting surveyed herds. However, the specificity of clinical examinations and laboratory tests was assumed to be 100%. In reality, a small number of false positive reactions must be expected. This means that the observed number of detected herds and the duration of the epidemic would be slightly larger than the results of the simulations.

The most influential parameters in the simulation model were the risks related to different movement types, the length of the HRP and the percentage of herds under basic surveillance by the farmer and veterinarian (Boklund, 2008). Thus, this once again illustrates that efforts should be made to optimize the surveillance in herds and to maintain awareness of clinical signs that could resemble those of CSF, since early detection of the first infected herd is crucial with respect to minimizing the size and duration of the epidemic.

The resources for depopulation and vaccination of herds did not influence the results of the simulations. However, we did not simulate other resources, such as resources for surveillance, rendering, etc. These resources could limit the possibility of handling the epidemic in situations with large outbreaks. On the other hand, it would be possible to import extra staff from neighbouring countries, which is what happened in the UK in 2001.

In the simulations presented here, geographical x and y coordinates for all Danish pig herds were used. It has been stated that the use of polygons would be better (Taylor, 2003). However, within the Danish pig population only few herds are kept out doors. Therefore, we must assume that the effect of not using polygons is limited. However, the coordinates for Danish farms are normally for the main building of the farm, which implies that the housing systems for the pigs could be located at some distance from the coordinates. This implies that the local spread could be slightly biased.

Movements of animals were described as Poisson distributions. One of the assumptions in the Poisson distribution is independence between events. However, this assumption is violated, as movements are not independent. Often after a movement has occurred, there will be a reduced probability of a movement the day after, and then the probability will increase until a certain point. However, because the lambda in the Poisson was calculated as the average number of movements over a period of 1 year for animal movements, for each single herd, we still feel that the movements of animals were best described by individual Poisson distributions for each herd.

4.2. Economic consequences and underlying assumptions

The economic consequences of a Danish CSF epidemic are largely governed by the loss in exports, which accounts for more than three-quarters of the total costs of the investigated control strategies. Unfortunately, the loss in exports is also associated with more uncertainty than the other components. Market reactions are very difficult to predict when an epidemic of a notifiable disease occurs.
The reactions will be influenced by the knowledge of disease status in Europe, and the time until exports can be resumed will depend on the duration of the epidemic, the length of the HRP, the capability of documenting freedom from CSF, confidence in the veterinary authorities in the exporting country, etc. Furthermore, more practical experience with marker vaccines is needed. It is uncertain how pork and pork products from animals vaccinated with a marker vaccine can be traded; practical experience is lacking. Based on the legislation (Anonymous, 2001), pork and pork products from animals vaccinated with a marker vaccine might be exported on certain conditions without processing or marking and treating the meat, but special acceptance from the other EU countries will be needed. Therefore, this subject will have to be discussed by the standing veterinary committee when a country applies for acceptance of vaccination with a marker vaccine.

In the calculations, it was assumed that all markets were regained as soon as they reopened. However, it is probably likely that Danish export markets will be taken over by other exporting countries, and regaining those markets could take some time. Therefore, the predicted losses are probably underestimated. The UK regained FMD-free status in January 2002 after the last case of FMD in September 2001. However, the best guess of Thompson et al. (2002) was that trade was fully resumed in October 2002 (optimistic guess) or in the autumn of 2003 (pessimistic guess). Furthermore, market reactions will probably depend on the size and duration of the epidemic. For a large, widespread and long-lasting epidemic, reactions from export markets might be more cautious than for a small, contained and short outbreak. This reflects the fact that even more time might be needed to document freedom from disease and to conduct the necessary risk analysis to ascertain export markets prior to reopening.

5. Conclusion

Based on this simulation study, we conclude that the strategy consisting of the minimum control measures required by the EU plus depopulation of contact herds is the most effective among the evaluated strategies with respect to limiting the size, duration and cost of the epidemic. However, regarding the number of culled animals, the vaccination-to-live strategies appear to be more effective.

Epidemics become larger and last longer if the index case is a nucleus herd. This implies that biosecurity in nucleus herds is extremely important to avoid transmission of CSF to these herds.

Simulations showed that the size and duration of a Danish CSF epidemic will be more moderate in most cases. However, for some iterations, long-lasting and large epidemics were observed. Irrespective of the size and duration, an epidemic is expected to be very costly due to export losses.

Acknowledgements

Thanks to Anne-Mette Olsen, Finn Udesen, Karsten Flemin, Poul Tolstrup Christensen and Sten Mortensen for discussions and input to the model, and to Mark Stevenson, Nicolas Moles-Benfell and Masood Maumoon for their help with technical problems and definitions on Inter-Spread Plus.

Appendix A. Supplementary data


References


