Control of Highly Pathogenic Avian Influenza

Epidemiological and economic aspects

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Contents

Preface

Outbreaks of contagious animal disease have detrimental effects on the Dutch livestock sector as well as on Dutch society as a whole. Control strategies differ in their epidemiological effects and have different economic consequences. For the Dutch Ministry of Economy, Agriculture and Innovation (EL&I) this was reason to ask Wageningen UR to investigate the consequences of control strategies for epidemic contagious diseases. In 2007 the results were reported for Classical Swine Fever, followed in 2009 by Foot-and-Mouth Disease. This report shows the result of the research on high pathogenic Avian Influenza (HPAI), and is the last of the triptych of the study on epidemiological and economic consequences of alternative strategies to control the major epizootic livestock diseases in the Netherlands.

This report is the result of a close cooperation between three institutes of Wageningen UR: CVI, the department of Business Economics 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 HPAI.

The authors would like to thank Natasha Longworth (BEC, Wageningen UR) for providing the poultry farm database and the simulations of the high risk period, Armin Elbers for providing the within-flock mortality data observed during the Dutch H7N7 epidemic of 2003 and Guus Koch (CVI), Stephanie Wiessenhaan (EL&I), Huibert Maurice (EL&I) and Susanne Waelen (EL&I) for discussing the model assumptions and results. The financial support of the Dutch Ministry of EL&I enabled this research and is highly appreciated.

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Managing Director LEI	Director CVI

Summary

Epidemics of highly pathogenic Avian Influenza (HPAI) can have a large impact on animal welfare and the poultry industry, and - due to the zoonotic character - also on public health. Because of multiple possible introduction routes, reservoirs and mutations in low pathogenic AI (LPAI), poultry flocks in the Netherlands are at a continuous risk of being infected by HPAI. In case of an outbreak the infected farms need to be depopulated, transport regulated, protection and surveillance zones set up and dangerous contacts traced, all according to the requirements of the EU. Additionally, control measures can be taken to reduce the susceptible farm density in the affected area by pre-emptive culling or vaccination.

A new epidemic of HPAI in the Netherlands can have an equally large impact as the previous one in 2003. Controlling epidemics of notifiable diseases, in this case AI, by massive killing of mostly uninfected animals is criticised more and more, mainly on ethical grounds, and there is an increasing need for improvement of the current control measures. This research supports the decision-making process.

S.1 Epidemiological aspects

The effectiveness of several control strategies is evaluated using an epidemiological model that describes virus transmission within a flock and between flocks. Model parameters are estimated from transmission experiments, mortality data of infected flocks and outbreak data of the Dutch HPAI epidemic in 2003. This model is applied to the Dutch poultry farm data of 2008, involving 2834 commercial poultry farms with in total 109m birds. These farms are not evenly distributed over the country, but we distinguish between sparsely, medium and densely populated poultry areas (denoted by SPPA, MPPA and DPPA). In each of these regions high-risk periods from introduction to first detection were used from previous simulations by N. Longsworth, department of Business Economics (BEC) of Wageningen UR, as initialisation of our simulations. At the time of first detection 2 (1-6) farms were infected in the SPPA, 7 (1-22) in the MPPA and 27 (4-70) in the DPPA. Using these starting points five basic control strategies were evaluated: the EU strategy, pre-emptive culling in 1-, 3- and 10-km rings around detected farms and emergency vaccination in a 3-km radius. Fur-

thermore the effect of culling and vaccination capacity, premature slaughter on broiler farms, combination strategies and vaccination coverages was assessed. Finally, the effect on the 110,000 hobby flocks in the Netherlands was studied by considering them as 'dead-end hosts': able to be infected, but unable to infect others. With a relative susceptibility of 0.014 compared to commercial poultry farms (Bavinck et al., 2009), the expected number of infected hobby flocks is calculated, as well as the number of culled and vaccinated hobby flocks. The results for the basic control strategies in the DPPA are shown in Table S.1.

Table S.1 **Simulation results for basic control strategies in a densely populated poultry area (DPPA) in the Netherlands a)**

Strategy	Duration (days)		# Detected farms		# Pre-emptively culled farms		# Total culled farms		# Vaccinated farms	
EU	88	(46-203)	278	(80-491)	0	(0-0)	278	(80-491)	0	(0-0)
cul1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
cul3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
cul10	26	(0-48)	40	(1-225)	630	(11-1,350)	681	(12-1,541)	0	(0-0)
vac3	67	(0-113)	140	(1-331)	23	(11-54)	163	(12-374)	397	(0-678)

a) Median values and 5%-95% interval of epidemic duration and number of detected, pre-emptively culled, culled and vaccinated farms, for the EU strategy (EU), for respectively 1-, 3- and 10-km pre-emptive ring culling (cul1/cul3/cul10) and for 3-km emergency vaccination (vac3).

Based on 1,000 model simulations per control strategy, it is concluded that:

- the EU strategy is not sufficient to halt an epidemic in a DPPA or MPPA;
- pre-emptive culling effectively reduces the epidemic duration, at the expense of a higher epidemic impact (i.e. more culled farms);
- emergency vaccination is not as effective in shortening the epidemic, but the epidemic impact is kept at a minimum;
- the EU strategy suffices in an SPPA;
- the small chance that an epidemic jumps from an SPPA to a denser area is not influenced by the control strategy;
- the culling capacity of 20 farms per day is sufficient to cull infected farms within one day after detection in all control strategies;
- expanding the pre-emptive culling radius from 3km to 10km is ineffective due to the limited culling capacity;
- premature slaughter on broiler farms has little effect because the number of broiler farms in the DPPA is relatively small and because it has the lowest culling priority;

- combining pre-emptive culling in an inner radius with vaccination in an outer radius has no added value compared to culling-only strategies;
- with realistic vaccination coverages of 50% and 80% of the birds on a farm, most to all within-flock outbreaks are detected, yielding a negligible number of undetected infected animals; and
- a considerable number of 50-150 hobby flocks (out of 110,000) are expected to be infected despite a reduced susceptibility compared to commercial farms.

S.2 Economic analysis

The following research questions were addressed:

- What is the optimal strategy to control and eradicate AI from an economic perspective?
- What is the distribution of costs between cost types*?*
- What is the effect of reduced prices of products in the movement restriction zone on the total costs of the epidemics?
- What is the effect of specific modifications of strategies?
    a. excluding hobby farms from preventive culling;
    b. premature slaughter of broilers in the movement restriction zone to lower the poultry density in an area;
    c. unlimited culling and vaccination capacity.

To evaluate the economic consequences of the different control and eradication strategies a model was developed. Included in the economic analysis are:

- compensation for depopulated poultry;
- depopulation (taxation, culling, transport & destruction, cleansing & disinfection);
- tracing;
- screening;
- vaccination;
- additional surveillance in the vaccination zone when the vaccination zone is larger than the BT zone;
- monitoring of vaccination efficacy (sampling and testing);
- compensation for welfare slaughter of reared pullets.

Only those costs and benefits that were expected to differ substantially between the evaluated alternatives were included. Therefore, excluded from the calculations were:

- costs that do not or only marginally differ between strategies and therefore do not alter the order of the strategies;
- costs that were related to the epidemic of AI per se and do not depend on the control strategies applied, such as trade distortions costs;
- costs that can occur during an epidemic of AI in non-AI sensitive branches and the costs of non-agricultural industry such as tourism.

S.3 Most important economical findings

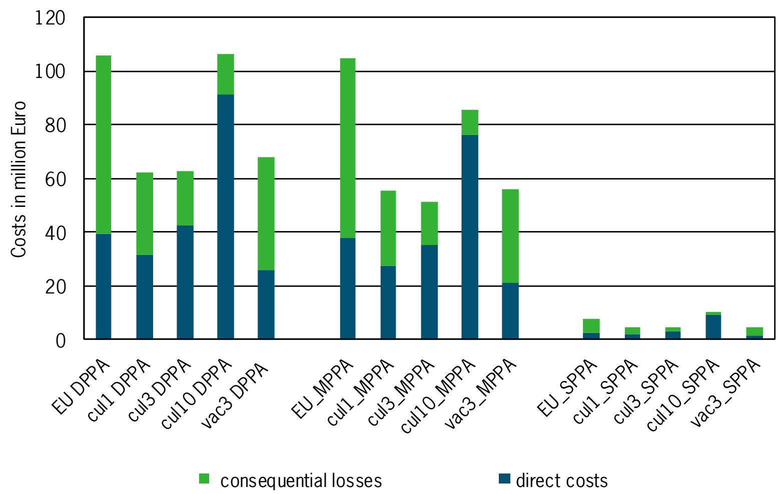
From an economic perspective, culling around infected farms in a radius of 1 or 3km (cul1, cul3) is the optimal strategy to control and eradicate AI. Of the other evaluated alternatives vaccination of layer farms in a 3-km radius (vac3) also yields substantially lower costs than the EU minimum scenario (EU) or culling in a radius of 10km (cul10), although it results in a substantially larger and longer epidemic (Figure S.1).

S.4 Other economic findings

- In SPPA: no considerable differences between strategies from an economic point of view.
- The distribution of costs varies between the chosen strategies. Consequential losses are lowest when more animals are pre-emptively culled.
- In particular, the lower egg price in the movement restriction zone has a large impact on the total costs of the epidemic.
- Premature slaughter of broilers in the movement restriction zone to lower the poultry density in that area has only minor effects on the total costs of the epidemic and increases the direct costs. However, farmers are economically better off when the young broilers are killed even if no compensation is paid for the animals.
- Excluding hobby flocks from pre-emptive culling is assumed not to affect the course of the epidemic in commercial livestock; however, adequate precautions (such as preventive vaccination of the hobby flocks) have to be taken to prevent infection of their owners.

- An extended capacity for culling or vaccination has substantial positive effects on the course, duration and costs of the epidemic.

Figure S.1	Direct costs and consequential losses of different control strategies (mean values)



DPPA = densely populated poultry area, MPPA = medium populated poultry area, SPPA = sparsely populated poultry area, EU = EU minimum strategy (culling infected farms + surveillance and movement restriction zone), cul1 = EU +culling poultry farms in a 1-km radius, cul3 = EU + culling in a 3-km radius, cul10 = EU + culling in a 10-km radius, vac3 = EU + vaccination in a 3-km radius

Samenvatting

Epidemieën van hoog pathogene aviaire influenza (HPAI) kunnen een grote invloed hebben op het dierenwelzijn, de pluimveesector en, vanwege de zoönotische aard, ook op de volksgezondheid. Vanwege de vele mogelijke insleeproutes, reservoirs en mutaties in laag pathogene AI (LPAI) loopt het pluimvee in Nederland voortdurend het gevaar te worden besmet met HPAI. In geval van een uitbraak moeten de besmette boerderijen worden geruimd, moet het transport worden gereguleerd, moeten er beschermings- en toezichtsgebieden worden opgezet en moeten gevaarlijke contacten worden opgespoord, dit alles volgens de vereisten van de EU. Er kunnen ook bestrijdingsmaatregelen worden genomen om de blootgestelde bedrijfsdichtheid in het getroffen gebied te verkleinen door preventief ruimen of vaccineren.

Net zoals in 2003, kan een nieuwe HPAI epidemie grote gevolgen hebben voor de pluimveesector. Het bestrijden van aangifteplichtige ziektes zoals AI door grootschalig preventief ruimen, wordt maatschappelijk steeds minder geaccepteerd, en de roep om alternatieve bestrijdingsmaatregelen zoals vaccinatie wordt steeds luider. Dit onderzoek ondersteunt het besluitvormingsproces.

S.1 Epidemiologische aspecten

De effectiviteit van verschillende bestrijdingsstrategieën wordt geëvalueerd met behulp van een epidemiologisch model dat de virusoverdracht binnen en tussen koppels beschrijft. Modelparameters worden geschat uit transmissie-experimenten, sterftegegevens van besmette koppels en gegevens over de uitbraak van de Nederlandse HPAI-epidemie in 2003. Dit model wordt toegepast op de gegevens over Nederlandse pluimveehouderij uit 2008 met 2.834 commerciële pluimveebedrijven en in totaal 109 mln. vogels. Deze bedrijven zijn niet gelijkmatig verdeeld over het land, maar we maken een onderscheid tussen dun, matig dicht en dichtbevolkte pluimveegebieden (aangegeven met SPPA (sparsely populated poultry area), MPPA (medium populated poultry area) en DPPA (densely populated poultry area)). In elk van deze regio's werden hoog-risico periodes - van introductie tot eerste opsporing - gebruikt uit eerdere simulaties door N. Longsworth, afdeling Business Economics (BEC) van Wageningen UR, ter initialisatie van onze simulaties. Hieronder worden de gemiddelde resultaten kort gepresenteerd. Het 95% betrouwbaarheidsinterval staat tussen haakjes. Bij de eerste detectie waren er 2 (1-6) boerderijen besmet in het SPPA, 7 (1-22) in het MPPA en 27 (4-70) in het DPPA. Vanuit deze beginpunten werden vijf basis bestrijdingsstrategieën geëvalueerd: de EU-strategie, preventief ruimen in een straal van 1, 3 en 10 km rondom de gedetecteerde boerderijen en noodvaccinatie in een straal van 3 km. Ook werd het effect van het ruimen, de vaccinatiecapaciteit, het voortijdig slachten bij vleeskuikenbedrijven, combinatiestrategieën en de vaccinatiedekking beoordeeld. En tot slot werd de invloed op de 110.000 hobbypluimveekoppels in Nederland onderzocht door deze te beschouwen als 'dead-end hosts' (kunnen wel worden besmet, maar zijn niet in staat om het virus te verspreiden naar anderen). Door middel van de relatieve vatbaarheid van 0,014 in vergelijking met commerciële pluimveebedrijven (Bavinck et al., 2009) wordt het verwachte aantal besmette hobbypluimveekoppels evenals het aantal geruimde en gevaccineerde hobbypluimveekoppels berekend. De resultaten voor de basis bestrijdingsstrategieën in de DPPA zijn weergegeven in tabel S.1.

Tabel S.1 **Simulatieresultaten voor basis controlestrategieën in een dicht bevolkt pluimveegebied (DPPA) in Nederland a)**

Strategie	Duur (dagen)		# Gedetecteerde bedrijven		# Preventief geruimde bedrijven		# Totaal geruimde bedrijven		# Gevaccineerde bedrijven	
EU	88	(46-203)	278	(80-491)	0	(0-0)	278	(80-491)	0	(0-0)
Ger1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
Ger3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
Ger10	26	(0-48)	40	(1-225)	630	(11-1,350)	681	(12-1,541)	0	(0-0)
Vac3	67	(0-113)	140	(1-331)	23	(11-54)	163	(12-374)	397	(0-678)

a) Mediaanwaarden en 5%-95% interval van duur epidemie en aantal gedetecteerde, preventief geruimde, geruimde en gevaccineerde bedrijven, voor de EU-strategie (EU), voor het ruimen in een straal van 1, 3 en 10 km (ger1/ger3/ger10) en voor 3 km noodvaccinatie (vac3).

Gebaseerd op 1.000 modelsimulaties per bestrijdingsstrategie is geconcludeerd dat:

- de EU-strategie niet toereikend is om een epidemie te bedwingen in een DPPA of MPPA;
- preventief ruimen de duur van de epidemie effectiefverkort, maar met een groter aantal geruimde bedrijven tot gevolg. ;
- noodvaccinatie niet zo effectief is voor het verkorten van de epidemie, maar dat de grootte van de epidemie tot een minimum wordt beperkt;
- de EU-strategie voldoende is voor een SPPA;

- de geringe kans dat een epidemie zich van een SPPA naar een dichter bevolkt gebied uitbreidt niet wordt beïnvloed door de bestrijdingsstrategie.
- de ruimingscapaciteit van 20 bedrijven per dag in alle bestrijdingsstrategieën voldoende is om de besmette bedrijven te ruimen binnen een dag na detectie.
- het uitbreiden van de straal voor preventief ruimen van 3 ot 10 km niet effectief is vanwege de beperkte ruimingscapaciteit.
- het voortijdig slachten bij vleeskuikenbedrijven weinig effect heeft omdat het aantal vleeskuikenbedrijven in het DPPA relatief klein is en omdat dit de laagste ruimingsprioriteit heeft.
- het combineren van preventief ruimen met vaccineren geen toegevoegde waarde heeft in vergelijking met de strategieën voor alleen ruimen.
- met realistische vaccinatiedekkingen van 50% en 80% van de vogels op een bedrijf de meeste tot bijna alle uitbraken binnen de koppels worden gedetecteerd, wat een verwaarloosbaar aantal niet gedetecteerde besmette dieren oplevert en
- dat van een aanzienlijke hoeveelheid hobbypluimveekoppels van 50-150 (van de 110.000) wordt verwacht dat ze besmet worden ondanks een verminderde vatbaarheid in vergelijking met commerciële boerderijen.

S.2 Economische analyse

De volgende onderzoeksvragen zijn behandeld:
- Wat is, vanuit economisch perspectief, de optimale strategie om AI te bestrijden en uit te roeien?
- Wat is de verdeling van de kosten tussen de kostensoorten?
- Wat is het effect van verlaagde productprijzen in de gebieden met vervoersbeperkingen op de totale kosten van de epidemie?
- Wat is het effect van specifieke aanpassingen aan de strategieën? Zoals:
  a. hobbybedrijven uitsluiten van preventief ruimen;
  b. voortijdig slachten van vleeskuikens in de gebieden met vervoersbeperkingen om in een gebied de dichtheid van het pluimvee te verlagen;
  c. ongelimiteerde capaciteit om dieren snel te kunnen ruimen ruimen en een ongelimiteerde vaccinatiecapaciteit.

Er is een model ontwikkeld om de economische gevolgen van de verschillende bestrijdings- en uitroeiingstrategieën te evalueren. De volgende zaken zijn opgenomen in de economische analyse:

- compensatie voor geruimd pluimvee;
- ruiming (taxatie, ruiming, transport & vernietiging, schoonmaak & desinfectie);
- tracering;
- onderzoek;
- vaccinatie;
- extra toezicht in het vaccinatiegebied wanneer het vaccinatiegebied groter is dan het bt-gebied;
- monitoring van effectiviteit van vaccinatie (monstername en testen);
- compensatie voor welzijnsslacht voor fokhennen.

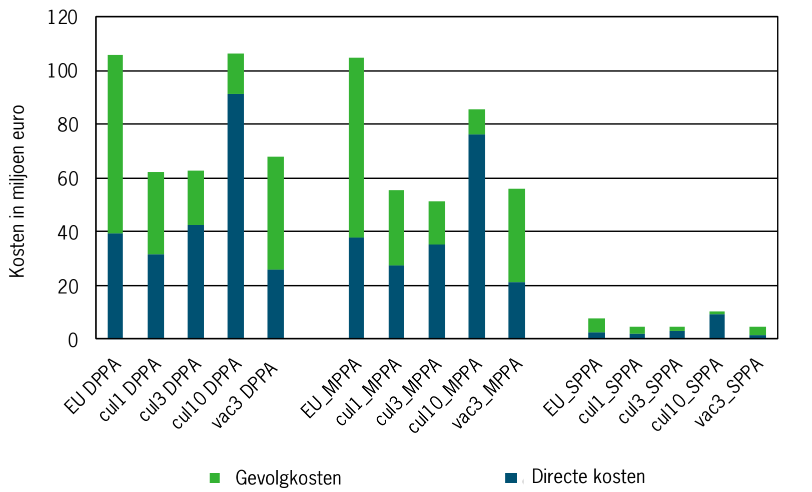
Alleen de kosten en opbrengsten waarvan verwacht werd dat ze substantieel afwijken tussen de geëvalueerde alternatieven zijn in de berekeningen meegenomen. Daarom zijn de volgende zaken bij de berekening buiten beoordeling gebleven:

- kosten die niet of slechts marginaal verschillen tussen de strategieën en daarom de volgorde van de strategieën niet veranderen;
- kosten die zijn gerelateerd aan de AI-epidemie op zich en niet afhankelijk zijn van de toegepaste bestrijdingsstrategieën, zoals de kosten van verstoring van de handel;
- kosten die kunnen voorkomen tijdens een AI-epidemie in niet-AI-gevoelige sectoren en kosten van de niet-agrarische sector zoals het toerisme.

S.3 Belangrijkste economische bevindingen

Vanuit economisch perspectief is het ruimen van besmette boerderijen in een straal van 1 of 3 km (cul1, cul3) de optimale strategie om AI te bestrijden. Van de andere geëvalueerde alternatieven brengt vaccinatie op legbedrijven in een straal van 3 km (vac3) aanzienlijk lagere kosten met zich mee dan het EU-minimumscenario (EU) of het ruimen in een straal van 10 km (cul10), maar het resulteert in een aanzienlijk grotere en langdurigere epidemie (Figuur S.1).

Figuur S.1 **Directe kosten en daaruit resulterende verliezen van verschillende bestrijdingsstrategieën (gemiddelde waarden)**



DPPA - dicht bevolkt pluimveegebied, MPPA = matig dicht bevolkt pluimveegebied, SPPA = dun bevolkt pluimveegebied, EU = EU-minimumstrategie (ruimen besmette boerderijen + surveillance en verplaatsings-restrictiezone), cul1 = EU + ruiming pluimveebedrijven in een straal van 1 km, cul3 = EU + ruiming in een straal van 3 km, cul10 = EU + ruiming in een straal van 10 km, vac3= EU + vaccinatie in een straal van 3 km.

S.4 Andere economische bevindingen

- In SPPA: vanuit economisch oogpunt zijn er geen aanzienlijke verschillen tussen de strategieën.
- De verdeling van de kosten varieert tussen de gekozen strategieën. De gevolgschade is het laagst als er meer dieren preventief worden geruimd.
- Met name de lagere prijs van eieren in het gebied met vervoersbeperkingen heeft een grote invloed op de totale kosten van de epidemie.
- Het voortijdig slachten van vleeskuikens in het gebied met vervoersbeperkingen om de dichtheid van het pluimvee in dat gebied te verlagen, heeft maar een klein effect op de totale kosten van de epidemie en zorgt voor een verhoging van de directe kosten. De boeren zijn economisch gezien beter af als de jonge vleeskuikens worden gedood, ook al wordt er voor de dieren geen compensatie uitgekeerd.

- Het uitsluiten van hobbypluimveekoppels van preventief ruimen wordt geacht geen invloed the hebben op het verloop van de epidemie in de commerciële veeteelt. Er moeten echter wel gepaste voorzorgsmaatregelen (zoals preventieve vaccinatie van hobbypluimveekoppels) worden genomen om de infectie van hun eigenaar te voorkomen.
- Een uitgebreide ruimingscapaciteit of vaccinatiecapaciteit heeft een substantieel positief effect op het verloop, de duur en de kosten van de epidemie.

1 Introduction

Avian Influenza is considered a serious threat to the health of both humans and animals, especially since the emergence of Highly Pathogenic Avian Influenza (HPAI) H5N1 in South-East Asia in 2003 (Sims et al., 2005). With migratory birds as a possible introduction route (Alexandersen, 2000, Chen et al., 2005), waterfowls as a possible virus reservoir (Sturm-Ramirez et al., 2005, Gilbert et al., 2006) and the possible transformation from an LPAI to an HPAI virus (Capua and Marangon, 2000), commercial poultry flocks are believed to be under a continuous risk of infection. HPAI epidemics have a major impact on animal welfare and the poultry industry, illustrated by the H7N1 epidemic in Italy in 1999-2000 (Mannelli et al., 2006) and the H7N7 epidemic in the Netherlands in 2003 (Stegeman et al., 2004).

Virus transmission from birds to humans occasionally occurs (Katz et al., 1999, Koopmans et al., 2004). It is therefore essential to control an AI epidemic in poultry to minimise risk for humans. For the same reason, hobby flocks should be critically considered. Even though infected hobby flocks are believed to play a minor role in the epidemic (Bavinck et al., 2009), they can still pose a considerable threat to their owners.

The last epidemic of Avian Influenza in the Netherlands in 2003 was caused by an H7N7 virus on 255 farms, resulting in the killing and destruction of 30m birds (Stegeman et al., 2004). An HPAI virus was isolated from 241 farms, but 1,349 commercial farms and 16,490 backyard farms were depopulated. The poultry industry in the affected areas suffered substantial economic losses: the total direct costs amounted to 270m Euro. These costs were mainly related to costs for compensation of culled animals and costs related to the infrastructure for the control of the epidemic. The costs associated with culling and destroying of infected and contact animals were substantially smaller (Dutch Ministry of Agriculture, 2003).

Not only the livestock sector was confronted with serious consequences and restrictions due to the Dutch epidemic, but it also had a large impact on society as a whole. The massive culling of backyard animals resulted in public unrest (Berenschot, 2004), the death of a veterinarian due to an AI infection and the conjunctivitis of people involved in the control of the epidemic confronted society with the zoonotic consequences of Avian Influenza.

The epidemic of HPAI caused by H5N1 in South-East Asia in 2003 and the threat of a human pandemic of HPAI confronted the world with the interrelatedness of human, animal, and ecosystem health. It further put a lot of emphasis on the control of Avian Influenza, especially after reporting estimated costs of USD3 trillion (according to raised estimates by the World Bank in a worst-case scenario) in the beginning of the epidemic, in case an HPAI should evolve into a relatively severe global human pandemic. This threat of a pandemic of H5N1 was also the rationale for some form of coordinated policy and action among agencies responsible for public health, medical science and veterinary services. From this, the broader concept of 'One World One Health' emerged, which is used to represent the inextricable links among human and animal health and the health of the ecosystems they inhabit (World Bank, 2010).

A new epidemic of AI in the Netherlands can have an equally large impact as the previous one in 2003. Controlling epidemics of notifiable diseases, in this case AI, by massive killing of mostly uninfected animals is criticised more and more, mainly on ethical grounds, and there is an increasing need for improvement of the current control measures (Thomas et al., 2005). In the Dutch contingency plans it is described how an outbreak of AI should be approached and which actions should be taken. In case of an outbreak timely action is needed to adequately contain the epidemic. This puts great challenges for the responsible authorities, especially in the beginning of an epidemic. Not only with respect to decision making but also to logistics, especially when a strategy is chosen that involves culling or vaccination of large numbers of farms. They are often confronted with limited availability of staff and equipment. At the moment it is not clear what the impact of this limited availability of staff and equipment on the size and duration of an epidemic will be. Therefore it is worthwhile to investigate socially acceptable control strategies that can limit the economic impact of new epidemics.

Epidemiological models have become increasingly more appreciated in the analysis and control of AI epidemics. Stegeman et al. (2010) emphasise the importance of thorough analysis of past epidemics, such as the estimation of the within-flock (Tiensin et al., 2007, Bos et al., 2009, 2010) or between-flock reproduction ratio (Stegeman et al., 2004, LeMenach et al., 2006, Manelli et al., 2007, Garske et al., 2007). These estimates of the transmission parameters can be used for predictive modelling. For instance, the effectiveness of control strategies has been evaluated for commercial poultry in the UK (Truscott et al., 2007, Sharkey et al., 2008).

Here we will evaluate different strategies for controlling an AI epidemic in the Netherlands, using a two-level epidemiological model that describes virus transmission within a flock and between flocks. The objective is to identify the most effective control strategy, in terms of epidemic duration and epidemic impact (i.e. total number of depopulated farms). We will study the basic control strategy as required by the EU (depopulation of infected farms, transport regulations, screening and tracing of dangerous contacts), as well as additional measures that aim to reduce the susceptible population, such as pre-emptive culling, vaccination or a combination of both. Which strategy will be the most effective will depend on the applied control radius and on the farm density of the affected area? Furthermore, the effect of a limited culling and vaccination capacity will be studied and an estimation will be made of the number of infected, culled and vaccinated hobby flocks.

The results of the epidemiological model will be input for an economic analysis. The following questions will be addressed:

- What is the optimal strategy to control and eradicate AI from an economic perspective?
- What is the distribution of costs between cost types?
- What is the effect of reduced prices of products in the movement restriction zone on the total costs of the epidemics?
- What is the effect of specific modifications of strategies?
    a. excluding hobby farms from preventive culling;
    b. premature slaughter of broilers in the movement restriction zone to lower the poultry density in an area; and
    c. unlimited culling and vaccination capacity.

2 Vaccination against Avian Influenza: epidemiological consequences

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2.1 Introduction: epidemiology

In this chapter we will evaluate different strategies for controlling an AI epidemic in the Netherlands, using a two-level model that describes virus transmission within a flock and between flocks. The objective is to identify the most effective control strategy, in terms of epidemic duration and epidemic impact (i.e. total number of depopulated farms). We will study the basic control strategy as required by the EU (depopulation of infected farms, transport regulations, screening and tracing of dangerous contacts), as well as additional measures that aim to reduce the susceptible population, such as pre-emptive culling, vaccination or a combination of both. Which strategy will be the most effective will depend on the applied control radius and on the farm density of the affected area? Furthermore, the effect of a limited culling and vaccination capacity will be studied and an estimation will be made of the number of infected, culled and vaccinated hobby flocks.

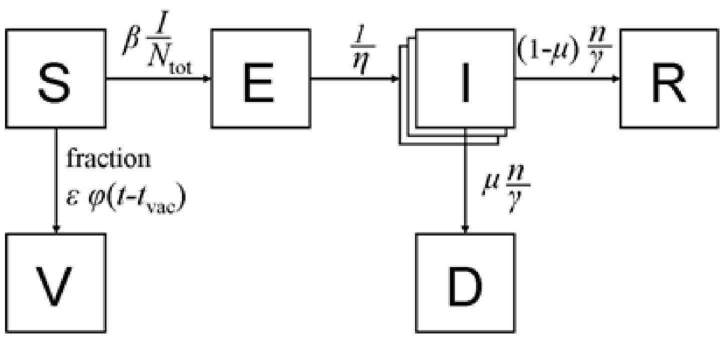
2.2 Transmission model

To evaluate different control strategies to combat an AI epidemic, we use a model that is similar in structure to previously developed models for Classical Swine Fever (Backer et al., 2009) and Foot and Mouth Disease (Backer et al., 2009b). It describes the transmission of HPAI on two distinct levels: the within-flock level that is formulated in terms of individual animals and the between-flock level that takes all flocks in the Netherlands into account. By coupling these two levels, we can extrapolate the effect of what happens to individual animals to entire poultry areas.

2.2.1 Within-flock transmission model

The infection from animal to animal is described by an SEIR compartmental model (Figure 2.1): when a susceptible animal (S) is infected, it will after a latent period (E) become infectious (I) until it either recovers (R) or dies (D). A part ε of the susceptible animals will be immunised by vaccination (V). The latent and infectious period, as well as the mortality μ and effect of vaccination are estimated from literature on transmission experiments. The transmission parameter β and the detection probability distribution are estimated from data on the 2003 AI epidemic in the Netherlands.

Figure 2.1 **Schematic representation of within-flock model, with susceptible (S), latently infected (E), infectious (I), recovered (R), dead (D) and vaccinated (V) animals a)**



a) The stacked squares denote that this I-compartment consists of multiple stages (resulting in a gamma-distributed residence time).

The parameters of the within-flock model are estimated from the results of transmission experiments with contact infected chickens (Bouma et al., 2009, Poetri et al., 2009, Van der Goot et al., 2003, Van der Goot et al., 2005), ducks (Beato et al., 2007, Van der Goot et al., 2008) and turkeys (Bos et al., 2008). We will not make a distinction between these species in the model, because the variability of the available transmission data between species is as large as the variability between virus strains.

Table 2.1	Parameters for within-flock HPAI model		
Parameter	**Value**	**5%-95%**	**Remarks**
latent period, $1/\eta$	1 day	0.05-3.0	exponential distribution
infectious period, n/γ	4 days	2.5-5.8	gamma distribution (with number of stages $n = 16$)
fraction mortality, μ	0.70		
vaccination coverage, ε	0.80		0.50 and 1.00 used as alternatives
start effect vaccination, t_1	7 dpv a)		
full effect vaccination, t_2	14 dpv		
transmission parameter, β	1.9 day^{-1}	0.61-8.1	estimated from outbreak data 2003, only median value used in model
cumulative fraction of dead animals at detection of farm	0.0061	0.0041-0.034	estimated from outbreak data 2003, empirical distribution used in model

a) dpv: days post vaccination.

The latent period is difficult to estimate due to the relatively large sampling intervals used in experiments. Latent periods are usually assumed to be between 0 and 2 days (Bos et al., 2008, Poetri et al., 2009, Van der Goot et al., 2003, Van der Goot et al., 2005, Van der Goot et al., 2008). We will assume an exponentially distributed period with a mean of 1 day, although a Bayesian analysis of transmission data has recently shown the actual latent period might be much shorter (Bouma et al., 2009).

The infectious period can vary for different virus strains. Reported virus shedding periods range from 1.5 days (Poetri et al., 2009) up to 6.8 days (Van der Goot et al., 2003). The infectious period is modelled by a gamma distribution with a mean of 4 days and a 90% interval of 2.5-5.8 days. This is equivalent to 16 consecutive infectious compartments with an exponential residence time distribution.

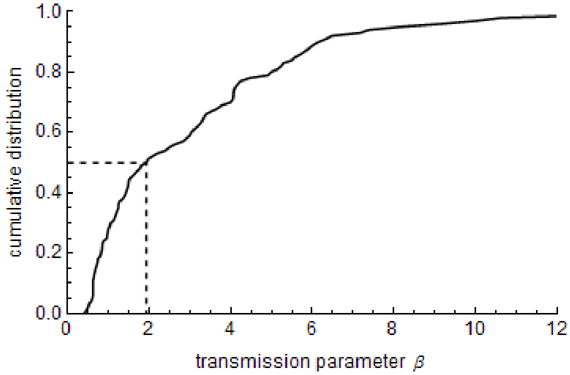
The reported mortality due to HPAI is 70%-100% in chickens and turkeys, but only 0%-20% in ducks. Nevertheless, we will assume a moderately high mortality of 70% for all species to simplify the detection model that is only based on mortality. Without mortality in ducks, this species would play an exaggerated role in the epidemic, which is not realistic in an outbreak situation when ducks are most probably detected by clinical examination and serological screening (*Beleidsdraaiboek Aviaire Influenza*, 2007) rather than mortality.

From the 2003 HPAI epidemic in the Netherlands mortality reports of infected farms prior to detection have been collected. These data have been previously analysed to estimate the time of introduction (Bos et al., 2007) and the transmission parameter (Bos et al., 2009). Here we have used the same data to estimate the transmission parameter β for each infected flock, using the experimental parameters discussed above. In total 174 flocks with at least two mortality reports were used in the analysis. No correlations between transmission parameter, mortality fraction at detection, herd size or species were found (in agreement with Bos et al., 2009) and therefore all data points are grouped. The resulting transmission parameter β varies widely over the different flocks (Figure 2.2a). The median value of 1.9 day^{-1} is lower than 4.3 day^{-1} as reported by Bos et al. (2009), because the latter is a mean value and because of different assumptions on the latent and infectious period distributions. In the model only the median value of 1.9 day^{-1} is used, which results in a reproduction number R_0 of 7.6.

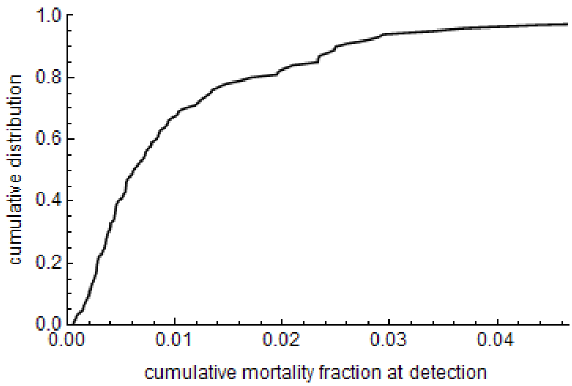
The detection of an infected flock is determined by the cumulative fraction of dead animals. From the mortality reports of the 2003 HPAI epidemic, an empirical distribution is derived (Figure 2.2b) with a median value of 0.0061, corresponding to 300 dead animals on an average broiler farm of 50,400 animals. This value is lower than the current Dutch monitoring threshold that requires AI notification at an observed mortality of 0.005 on two consecutive days (*Staatscourant* 204, 2005), or 0.01 as a cumulative mortality fraction. This is because the monitoring rule is designed for an AI-free period, while during an outbreak a higher alertness of farmers and veterinarians will lead to an earlier detection. For each infected flock in the model, a cumulative mortality fraction is drawn from the empirical distribution, at which detection will take place. Consequently, the period between infection and detection will vary between infected flocks.

Figure 2.2	Cumulative distributions of (a) transmission parameter β and (b) cumulative mortality fraction at detection for 174 analysed flocks that were infected during the 2003 AI epidemic in the Netherlands. The dotted line marks the median value of the transmission parameter β used in the model

a)



b)



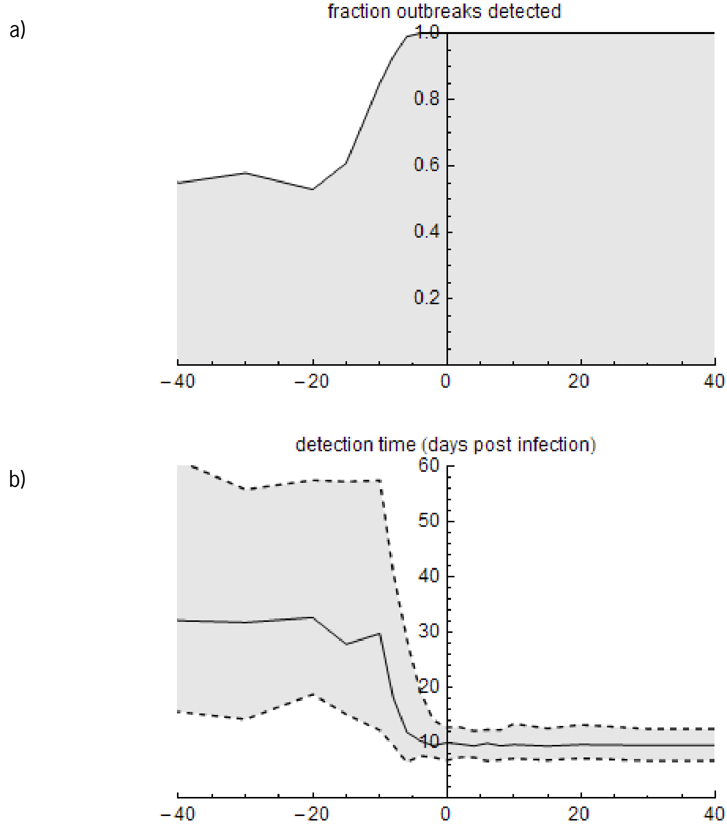
The efficacy of vaccines depends on the virus and vaccine strains used. Vaccination will affect the infectiousness and infectious period of infected vaccinated animals and the susceptibility of uninfected vaccinated animals. Because of the small number of vaccination-transmission experiments, we will limit the effect of vaccination to the effect on susceptibility. The build-up of immunity φ is a linearly increasing function of the time since vaccination τ.

$$\varphi(\tau)=\begin{cases}0 & \text{if } \tau<t_1\\ \dfrac{\tau-t_1}{t_2-t_1} & \text{if } t_1\le\tau<t_2\\ 1 & \text{if } \tau\ge t_2\end{cases} \qquad [2.1]$$
,

where t_1 is the time the immunity starts to build up after vaccination and t_2 is the time since vaccination when full immunity is reached. This immunity function can be considered as the probability that an animal is protected at a certain time since vaccination. When it is not protected at infection it will behave as an unvaccinated animal. Experiments have shown that infection can still occur at 7 days post vaccination (Van der Goot et al., 2005, Van der Goot et al., 2008), while all or almost all transmission is stopped at 14 days post vaccination (Bos et al., 2008, Poetri et al., 2009, Van der Goot et al., 2005, Van der Goot et al., 2008). For this reason we will use t_1 = 7 days and t_2 = 14 days in the model. Non-perfect vaccine response or failed vaccinations are captured in a reduced vaccine coverage. A moderately high coverage of 50% to 80% of the birds on a vaccinated farm is thought to be achievable in an outbreak situation. These two extremes as well as a perfect coverage of 100% will be studied in simulations.

The effect of vaccination time (relative to time of infection) is studied separately in a series of stochastic simulations. The results show that when a flock is vaccinated after infection (positive x-axes in Figure 2.3) all outbreaks are detected (Figure 2.3a) and the detection time distribution is the same as the unvaccinated detection time distribution (Figure 2.3b). For this reason we simulate flocks that are vaccinated after infection or not vaccinated *deterministically* by numerically solving the ODE system for unvaccinated flocks. Flocks that are vaccinated prior to infection however, are simulated *stochastically* to capture the variation in within-flock dynamics due to vaccination. The stochastic model is implemented by combining the method of Sellke (1983) with the 'τ-leap method' of Gillespie (2001).

Figure 2.3	Effect of vaccination as a function of time since vaccination on (a) the fraction of outbreaks that is detected and (b) the median time of detection (with the 5%-95% interval between dotted lines), with a vaccination coverage of 80%



2.2.2 Between-flock transmission model

The transmission between flocks depends on the distance between source and destination flock and the infection pressure generated at the source. The probability p_{ij} that a farm *i* will infect farm *j* during its entire infectious period T_i is:

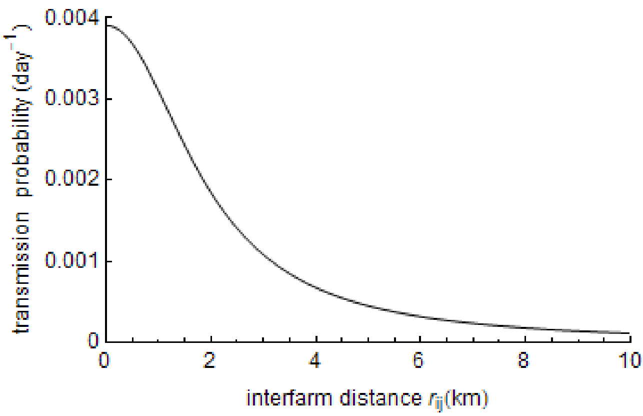
$$p_{ij} = 1 - \exp\left[-k(r_{ij}) \int_0^{T_i} q_i(t)dt \right], \qquad [2.2]$$

where q_i is the time-dependent infection pressure at the infectious farm and $k(r_{ij})$ the transmission kernel that describes the transmission probability depending on the distance r_{ij} between farms i and j. This kernel is assumed to follow a power law relation:

$$k(r_{ij}) = \frac{k_0}{1 + \left(\frac{r_{ij}}{r_0} \right)^{\alpha}}, \qquad [2.3]$$

where the parameters k_0, r_0 and α determine the height and the shape of the transmission kernel (see Figure 2.4).

Figure 2.4 **Between-flock transmission kernel: probability of infection per day as a function of distance between source and destination flock (Eq. 2.4)**



The kernel parameters were estimated for the 2003 HPAI epidemic in the Netherlands by Boender et al. (2007), assuming all infectious farms generate a constant infection pressure (q_i = 1 day^{-1} $\forall$ i) for a fixed infectious period (T_i = 7.5 days $\forall$ i). This resulted in r_0 = 1.9km, α = 2.1, and k_0 = 0.002 day^{-1}.

We will use the estimates for the shape parameters r_0 and α in our model. Because of the different model structure, the height of the kernel was used to match the number of 255 infected farms during the 2003 outbreak (Stegeman et al., 2004) in a total of 3567 commercial poultry farms at that time (*Land- en tuinbouwcijfers 2003*): k_0 = 0.004 day^{-1}. This translates into an infection probability of 3% at r_{ij}=0 during the entire infectious period of an average infected flock. The average cumulative infection pressure is normalised to the cumulative infection pressure of 7.5 'infectious farm days' used in the transmission kernel estimation.

In our between-flock simulations we will not distinguish between flocks of different bird species, due to the lack of information. No duck farms were infected during the 2003 AI epidemic and only a limited number of turkey farms. From the discussion of the transmission at the individual level there is no reason to assume that within-flock dynamics will significantly differ between species. Hobby flocks of a small number of chickens are taken into account by assigning them a passive role in the epidemic. This means they can get infected but they will not infect other flocks ('dead-end hosts'), supported by the results of a previous study on Foot-and-Mouth Disease (Backer et al., 2009b). A two-type SEIR model analysis of the 2003 HPAI outbreak data showed that hobby flocks have a reduced susceptibility of 0.014 (0.0071-0.023) compared to commercial flocks (Bavinck et al., 2009). By assuming the point estimate of 0.014, the expected number of infected hobby flocks is calculated from the simulation results. Depending on the applied control strategy, the number of vaccinated or culled hobby flocks is calculated.

2.3 Poultry farm data

The HPAI transmission model is applied to the Dutch situation in 2008. The poultry farm data set was obtained from the Business Economics Group (BEC) of Wageningen UR, where poultry data of the 'Dienst Regelingen' and the KIP database were analysed by Natasha Longworth. The data set contains the locations and farm sizes of in total 2,834 commercial poultry farms (see Table 2.5 and Figure 2.5). Broiler farms consist of animals for meat production and are fairly evenly distributed over the Netherlands (Figure 2.5a). The chicken broiler farms in particular have a short production cycle of 6 weeks, followed by 1 week of cleaning and disinfection. For this reason they will not be considered for vaccination as a possible control strategy. Layer farms produce eggs for either industry or consumers. They are concentrated in the centre part of the country, the 'Gelderse Vallei' (Figure 2.5b). Rearing and multiplier farms supply to broiler and layer farms. Hatcheries and slaughterers have no permanent bird population, and can therefore not be infected in the model. They will be taken into account though when they lie in a depopulation zone.

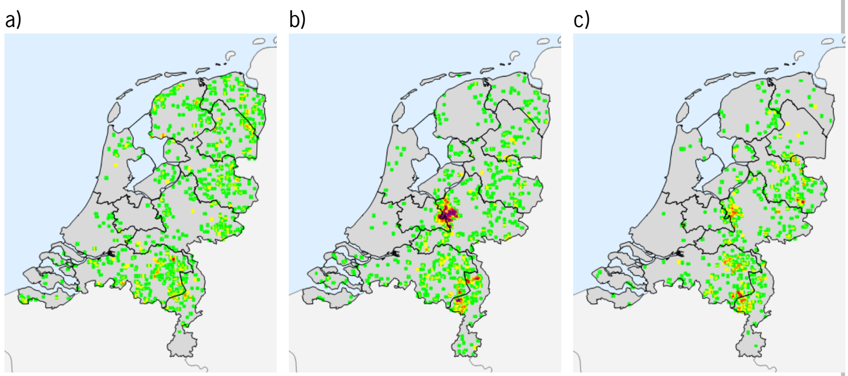
Besides the commercial farms, the number of hobby flocks is estimated at 110,000 (Treep et al., 2004). As the actual locations of these flocks are unknown, locations were generated by randomly scattering them over the Netherlands, independently of the locations of commercial farms. These flocks will not be explicitly modelled, but the locations serve to estimate the number of infected, culled and vaccinated hobby flocks.

Table 2.5 Poultry farm data in the Netherlands in 2008 a)

Farm type	Number of farms	Farm size ($x10^3$)		Total number of animals ($x10^6$)
		median	5%-95%	
Broilers (chicken)	887	50.4	10.8-132	52.4
Boilers (duck)	89	9.2	3.4-32.7	1.07
Broilers (turkey)	81	24.7	5.7-42	1.97
Layers	1,018	18.1	1.3-85.1	27.9
Rearing/multipliers	703	22.6	3.0-119	25.6
Hatcheries	32	-	-	-
Slaughterers	31	-	-	-
Total	2,834			109

a) Estimated from the KIP database by N.J. Longsworth.

Figure 2.5 **Density of (a) broiler, (b) layer and (c) rearing farms in the Netherlands (2008), with 0-0.2 (green), 0.2-0.4 (yellow), 0.4-0.6 (orange), 0.6-0.8 (red) and >0.8 (purple) farms/km²**



2.4 Simulations

2.4.1 Initialisation

To evaluate different control strategies, a realistic starting point is needed for the simulations. Before the disease is first detected, it can (silently) spread through the Netherlands. Our transmission model is not well conditioned to predict the infection chain during this high risk period (HRP), as the between-flock transmission kernel is estimated using data observed after the HRP. For this reason we have used the results of HRP simulations from the model 'Interspread Plus', as were obtained by Natasha Longworth (BEC of Wageningen UR, 2008). One hundred possible courses of HPAI spread in the Netherlands were simulated for three different areas of varying poultry farm density (densely, middle and sparsely populated poultry areas, see Figure 2.6), up to the moment of the first detection. At this time the number of infected farms differed largely: in a DPPA a median value of 27 (with a 5%-95% interval of 4-70) farms were infected, in an MPPA 7 (1-22) and in an SPPA 2 (1-6) (see also Figure 2.7). Each HRP simulation is continued after the HRP by our model in 10 simulations, so in total 1,000 simulations are carried out for each control strategy in each poultry area.

When the first farm is found to be infected with HPAI, a strategy needs to be chosen to mitigate the epidemic. The EU requires by directive that detected infected farms should be culled, that their dangerous contacts are traced and screened, that protection (3km around source flock) and surveillance (10km around source flock) zones are set up around detected farms and that transport is regulated in these zones. Additionally, national governments can decide to apply extra control measures, such as pre-emptive ring culling or emergency vaccination. For all these additional control strategies, we have assumed that in the first 5 days after the first detection pre-emptive culling will be applied in a ring of 1km around detected farms, with a culling capacity of 10 farms/day. This reflects the fact that the crisis control has to be organised and scaled up, and that-in the case of vaccination-the vaccine has to be formulated and produced, which takes about 5 days.

Figure 2.6	Positions (circles) of the layer farms where the epidemics are seeded in a densely (DPPA), medium (MPPA) and sparsely (SPPA) populated poultry area and the density of all poultry farms in the Netherlands (2008)(with 0-0.2 (green), 0.2-0.4 (yellow), 0.4-0.6 (orange), 0.6-0.8 (red) and >0.8 (purple) farms/km^2)

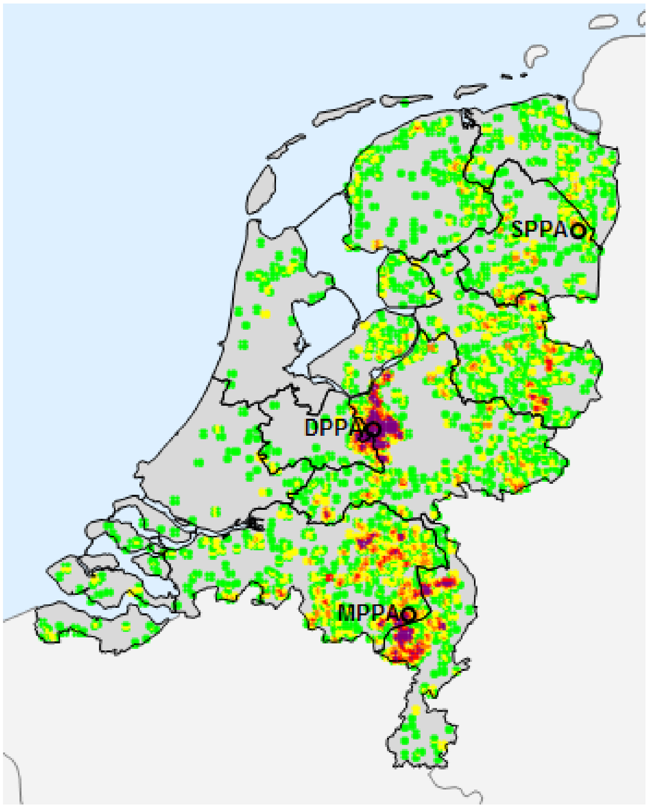
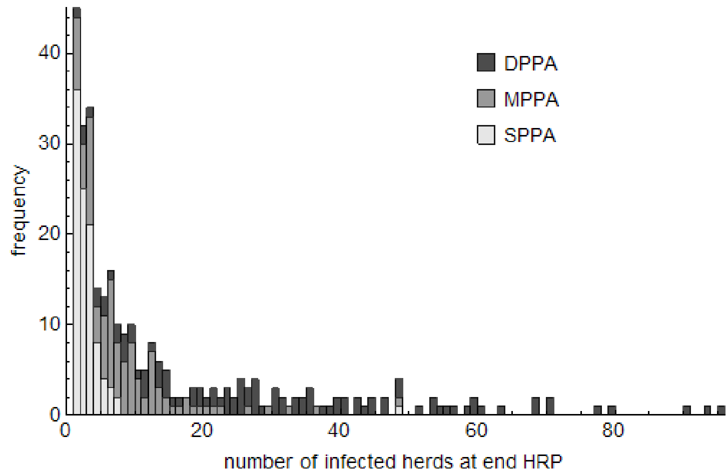


Figure 2.7	Distribution of the number of infected herds at the end of the HRP (high risk period) when the virus is introduced in a densely (DPPA, dark grey), medium (MPPA, grey) and sparsely (SPPA, light grey) populated poultry area



2.4.2 Outbreak scenarios

Our 'default' simulations will take place in the most densely populated poultry area (DPPA). For the first 5 days after the first detection a culling capacity of 10 farms/day is assumed, increasing to a capacity of 20 farms/day thereafter, for both culling and vaccination. For culling this is supported by the culling capacity of 750.000 birds/day that was reached in the later stages of the 2003 HPAI epidemic in the Netherlands (Stegeman et al., 2004). For vaccination, however, this is a very optimistic estimate, as with the current vaccine all birds need to be injected by hand. We will use a vaccination capacity of 20 farms/day though as an 'ideal' situation. Also, in the default situation the production cycle of broiler farms is taken into account. This production cycle of 7 weeks affects the epidemic in two ways. First, these farms are empty for one week, so the infection probability is also reduced by a factor 1/7. And second, when a broiler farm is located in a surveillance zone, it can't obtain eggs or chickens for production and will stay empty at the end of the production cycle until the surveillance zone restrictions are lifted, 40 days after the last detection in that area.

Table 2.6 lists all outbreak scenarios that are evaluated. First, a comparison is made between the EU strategy and several basic additional strategies. These are pre-emptive culling in 1km, 3km and 10km around detected farms (and emergency vaccination in 3km around detected farms. Second, these basic strategies are compared in areas of different poultry farm densities. Third, a comparison studies the effect of vaccination and culling capacity: simulations with the default limited culling and vaccination capacity are compared to simulations with unlimited capacities, where farms are instantly culled or vaccinated. Fourth, a comparison studies the strategy of premature slaughter in broiler farms in the surveillance zone. In this strategy, broilers younger than 21 days will be culled as soon as possible (given the culling capacity), while older broilers are allowed to complete the production cycle. This premature slaughter will more rapidly deplete affected areas of broiler farms. Last, the culling strategies are compared to strategies that combine culling with vaccination. Farms in a limited ring around detected farms will be culled, while farms in a ring around the culling ring will be vaccinated.

The vaccination-only strategies are studied in some more detail. The effect of emergency vaccination is mostly expected from the first vaccine dose. The second dose that most manufacturers recommend to be given four weeks after the first, will be too late to have an effect on the course of the epidemic. Although the second dose is important to gain better protection, it is not included in the simulations. So, an important parameter is the vaccination coverage, i.e. the proportion of animals that is effectively protected in two weeks after the first vaccine dose. The default vaccination coverage is an optimistic estimate of 80% that is compared to a pessimistic 50% and an ideal 100% coverage, to investigate the effect of vaccination coverage on the effectiveness of emergency vaccination. As vaccinated farms are simulated stochastically - allowing for minor outbreaks - the number of undetected infected animals that remain after an epidemic (before the final screening) can be determined for each simulation with varying vaccination coverage.

Finally, we will determine the expected number of infected, culled and vaccinated hobby flocks using the simulation results of the different control strategies. By assuming a reduced susceptibility of 0.014 relative to commercial flocks, the number of infected hobby flocks is calculated. The expected number of culled and/or vaccinated hobby flocks only depends on the applied control strategy.

Table 2.6	Overview of evaluated outbreak scenarios					
Strategy abbreviation	**Poultry area**	**Culling radius (km)**	**Vaccination radius (km)**	**Vaccination coverage**	**Culling and vaccination capacity (farms/day)**	**Premature slaughter**
EU	DPPA	0	0	0	20	no
EU_MPPA	MPPA	0	0	0	20	no
EU_SPPA	SPPA	0	0	0	20	no
EU_unl	DPPA	0	0	0	∞	no
EU_ps	DPPA	0	0	0	20	yes
cul1	DPPA	1	0	0	20	no
cul1_MPPA	MPPA	1	0	0	20	no
cul1_SPPA	SPPA	1	0	0	20	no
cul1_unl	DPPA	1	0	0	∞	no
cul1_ps	DPPA	1	0	0	20	yes
cul3	DPPA	3	0	0	20	no
cul3_MPPA	MPPA	3	0	0	20	no
cul3_SPPA	SPPA	3	0	0	20	no
cul3_unl	DPPA	3	0	0	∞	no
cul3_ps	DPPA	3	0	0	20	yes
cul10	DPPA	10	0	0	20	no
cul10_MPPA	MPPA	10	0	0	20	no
cul10_SPPA	SPPA	10	0	0	20	no
cul10_unl	DPPA	10	0	0	∞	no
cul10_ps	DPPA	10	0	0	20	yes
vac3	DPPA	0	3	0.8	20	no
vac3_MPPA	MPPA	0	3	0.8	20	no
vac3_SPPA	SPPA	0	3	0.8	20	no
vac3_unl	DPPA	0	3	0.8	∞	no
vac3_ps	DPPA	0	3	0.8	20	yes
vac3_50	DPPA	0	3	0.5	20	no
vac3_100	DPPA	0	3	1.0	20	no
cul1vac3	DPPA	1	1-3	0.8	20	no
cul1vac5	DPPA	1	1-5	0.8	20	no
cul3vac10	DPPA	3	3-10	0.8	20	no

2.5 Results and Discussion

Table 2.7 shows the key characteristics of all evaluated outbreak scenarios. The median values and 90% intervals are based on 1,000 simulations per control strategy. The epidemic duration is the time between first and last detection. The epidemic impact-the total number of culled farms-is a combination of the detected and pre-emptively culled farms. The vaccination strategies also involve a number of farms that were pre-emptively culled in the first 5 days after the first detection. Next, we will discuss specific questions in more detail and focus on the relevant results.

2.5.1 Control strategies

The basic EU control strategy signifies the minimally required measures, such as the depopulation of detected farms and screening in the protection and surveillance zones. Additionally, control measures can be taken to reduce the density of susceptible farms in an area around a detected farm, by pre-emptive culling or vaccination. The first thing to notice when comparing these strategies (Table 2.8) is that the EU strategy yields the longest epidemics, involving the most infected farms. Additional measures are here (in the DPPA) required to bring the epidemic under control. Pre-emptive culling within a radius of 1km around detected farms almost halves the epidemic duration, while the total epidemic impact is comparable. Increasing the culling radius to 3km further reduces the length of the epidemic to only one month, but at the expense of a considerably higher epidemic impact. At the highest culling radius of 10km not much is gained in epidemic length or number of infected farms compared to 3-km culling; the number of pre-emptively culled farms almost doubles though. Vaccination within a 3-km radius around detected farms takes longer to be effective than all culling strategies. More farms are expected to be infected, but the total epidemic impact is even lower than the EU strategy. Of course a considerable number of farms are vaccinated, resulting in a longer period before the area can be declared free of infection. These results suggest that applying pre-emptive culling or vaccination is a choice between direct animal losses or a longer period of restrictions.

Table 2.7	Overview of results: the median values and 5%-95% interval (between brackets) of the epidemic duration and the number of detected, pre-emptively culled, culled and vaccinated farms for each control strategy a)									
Strategy	**Duration (days)**		**# Detected farms**		**# Pre-emptively culled farms**		**# Total culled farms**		**# Vaccinated farms**	
EU	88	(46-203)	278	(80-491)	0	(0-0)	278	(80-491)	0	(0-0)
EU_MPPA	91	(0-249)	131	(1-427)	0	(0-0)	131	(1-427)	0	(0-0)
EU_SPPA	8	(0-111)	3	(1-147)	0	(0-0)	3	(1-147)	0	(0-0)
EU_unl	85	(41-193)	259	(26-463)	0	(0-0)	259	(26-463)	0	(0-0)
EU_ps	80	(43-161)	244	(57-408)	117	(27-245)	361	(88-648)	0	(0-0)
cul1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
cul1_MPPA	46	(0-110)	32	(1-124)	74	(5-269)	106	(6-391)	0	(0-0)
cul1_SPPA	6	(0-56)	3	(1-30)	1	(0-72)	3	(1-102)	0	(0-0)
cul1_unl	47	(0-96)	76	(1-157)	204	(11-343)	281	(12-499)	0	(0-0)
cul1_ps	45	(0-90)	80	(1-233)	257	(11-479)	340	(12-708)	0	(0-0)
cul3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
cul3_MPPA	27	(0-55)	15	(1-73)	148	(5-472)	164	(6-519)	0	(0-0)
cul3_SPPA	6	(0-33)	3	(1-15)	2	(0-132)	5	(1-143)	0	(0-0)
cul3_unl	27	(0-50)	29	(1-70)	328	(11-573)	357	(12-641)	0	(0-0)
cul3_ps	29	(0-54)	43	(1-223)	386	(11-750)	437	(12-939)	0	(0-0)
cul10	26	(0-48)	40	(1-225)	630	(11-1350)	681	(12-1,541)	0	(0-0)
cul10_MPPA	18	(0-38)	8	(1-65)	366	(5-1,053)	374	(6-1,099)	0	(0-0)
cul10_SPPA	6	(0-28)	2	(1-10)	11	(0-452)	14	(1-464)	0	(0-0)
cul10_unl	16	(0-30)	14	(1-36)	493	(11-1,055)	508	(12-1,089)	0	(0-0)
cul10_ps	26	(0-50)	41	(1-225)	636	(11-1357)	687	(12-1,580)	0	(0-0)
vac3	67	(0-113)	140	(1-331)	23*	(11-54)	163	(12-374)	397	(0-678)
vac3_MPPA	59	(0-115)	43	(1-168)	6*	(5-25)	49	(6-185)	194	(0-580)
vac3_SPPA	6	(0-67)	3	(1-39)	0*	(0-4)	3	(1-39)	0	(0-198)
vac3_unl	64	(0-105)	114	(1-246)	23*	(11-57)	140	(12-298)	372	(0-619)
vac3_ps	64	(0-103)	131	(1-303)	98*	(11-248)	232	(12-545)	383	(0-625)
vac3_50	60	(0-114)	154	(1-334)	23*	(11-54)	180	(12-370)	400	(0-688)
vac3_100	45	(0-91)	129	(1-305)	23*	(11-54)	153	(12-346)	392	(0-665)
cul1vac3	47	(0-96)	75	(1-228)	199	(11-320)	274	(12-522)	288	(0-466)
cul1vac5	48	(0-85)	76	(1-231)	198	(11-315)	274	(12-518)	382	(0-650)
cul3vac10	29	(0-59)	43	(1-222)	358	(11-644)	406	(12-825)	372	(0-731)

a) For details about the control strategies, see Table 2.6

* Preemptively culled in the 5 days following the first detection.

Table 2.8	**Results for control strategies: median values and 5%-95% interval of epidemic duration and number of detected, pre-emptively culled, culled and vaccinated farms, for the EU strategy (EU), 1-km pre-emptive ring culling (cul1), 3-km pre-emptive ring culling (cul3), 10-km pre-emptive ring culling (cul10) and 3-km emergency vaccination (vac3)**									
Strat-egy	**Duration (days)**		**# Detected farms**		**# Pre-emptively culled farms**		**# Total culled farms**		**# Vaccinated farms**	
EU	88	(46-203)	278	(80-491)	0	(0-0)	278	(80-491)	0	(0-0)
cul1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
cul3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
cul10	26	(0-48)	40	(1-225)	630	(11-1350)	681	(12-1,541)	0	(0-0)
vac3	67	(0-113)	140	(1-331)	23 a)	(11-54)	163	(12-374)	397	(0-678)

a) Pre-emptively culled in the 5 days following the first detection.

2.5.2 Poultry areas of varying farm density

The effectiveness of the basic control strategies also depends on the poultry farm density of the affected area. When an epidemic occurs in an MPPA, it will take the same amount of time to control it as in a DPPA (Table 2.9). Also the numbers of detected and pre-emptively culled farms are ranked similarly to the DPPA results, but they are significantly smaller due to the lower farm density. Therefore the main conclusions still hold: the EU strategy is insufficient for effective control and vaccination as an additional measure is the most effective in limiting the epidemic impact, but the least effective in limiting the epidemic duration.

In an SPPA the basic strategies yield similar median results: an epidemic lasts less than a week, affecting only three farms. But when considering the upper bound of the results, the EU strategy yields a much higher epidemic duration and epidemic impact. These are caused by a jump to a poultry area with a higher farm density, where the epidemic was subsequently not controlled. Closer analysis of the simulations reveal that such a jump from the SPPA to the DPPA occurs in 3% of our simulations, irrespective of the control strategy in the SPPA. The EU strategy in the DPPA will not bring the epidemic under control, whereas the additional control measures can halt the epidemic there in an early stage. So, in an SPPA the EU control strategy is sufficient to bring an epidemic locally under control, and additional control measures do not reduce the (small) chance of the epidemic jumping to a poultry area of higher farm density.

Table 2.9	Results for poultry areas of varying farm density: median values and 5%-95% interval of epidemic duration and number of detected, pre-emptively culled, culled and vaccinated farms, for the basic control strategies in a densely populated poultry area (DPPA, default), a medium populated poultry area (MPPA) and a sparsely populated poultry area (SPPA)

Strategy	Duration (days)		# Detected farms		# Pre-emptively culled farms		# Total culled farms		# Vaccinated farms	
EU	88	(46-203)	278	(80-491)	0	(0-0)	278	(80-491)	0	(0-0)
cul1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
cul3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
cul10	26	(0-48)	40	(1-225)	630	(11-1,350)	681	(12-1,541)	0	(0-0)
vac3	67	(0-113)	140	(1-331)	23 a)	(11-54)	163	(12-374)	397	(0-678)
EU_MPPA	91	(0-249)	131	(1-427)	0	(0-0)	131	(1-427)	0	(0-0)
cul1_MPPA	46	(0-110)	32	(1-124)	74	(5-269)	106	(6-391)	0	(0-0)
cul3_MPPA	27	(0-55)	15	(1-73)	148	(5-472)	164	(6-519)	0	(0-0)
cul10_MPPA	18	(0-38)	8	(1-65)	366	(5-1,053)	374	(6-1,099)	0	(0-0)
vac3_MPPA	59	(0-115)	43	(1-168)	6 a)	(5-25)	49	(6-185)	194	(0-580)
EU_SPPA	8	(0-111)	3	(1-147)	0	(0-0)	3	(1-147)	0	(0-0)
cul1_SPPA	6	(0-56)	3	(1-30)	1	(0-72)	3	(1-102)	0	(0-0)
cul3_SPPA	6	(0-33)	3	(1-15)	2	(0-132)	5	(1-143)	0	(0-0)
cul10_SPPA	6	(0-28)	2	(1-10)	11	(0-452)	14	(1-464)	0	(0-0)
vac3_SPPA	6	(0-67)	3	(1-39)	0 a)	(0-4)	3	(1-39)	0	(0-198)

a) Pre-emptively culled in the 5 days following the first detection.

2.5.3 Culling and vaccination capacity

To study whether the culling and vaccination capacities (of 20 farms/day each) limit the effective control of an epidemic, the simulations were repeated with unlimited resources. When a farm is located in a control zone, it is instantaneously culled or vaccinated. The larger the difference between the results for limited and unlimited resources, the more the control of an epidemic is hampered by the limited culling and vaccination capacity. This effect will be largest for the 95th percentile results. The EU strategy is not much limited by the applied culling capacity (Table 2.10): both the duration and epidemic impact are only slightly lowered with an unlimited capacity. For 1-km pre-emptive culling the epidemic duration is not much affected but the number of detected farms is significantly lower with an unlimited culling capacity. The larger the pre-emptive culling ring (i.e. the more resources are needed), the more the epidemic duration and number of detected farms are reduced. Comparing 3- and 10-km pre-emptive culling shows that the small difference found earlier between these strategies (section 2.5.1) can be fully attributed to the limiting culling capacity. An unlimited vaccination capacity also affects the duration and size of epidemics controlled with 3-km ring vaccination, albeit not as much as its culling counterpart, 3-km ring culling. Most likely, the slow immune response is just as limiting for effective control as the vaccination capacity. It should also be kept in mind that the assumed vaccination capacity of 20 farms/day is not realistic for the current method of administration by injection. Feasible vaccination capacities are estimated to be 2 farms/day, which would disqualify vaccination as an emergency measure.

Table 2.10 **Results for culling and vaccination capacity: median values and 5%-95% interval of epidemic duration and number of detected, pre-emptively culled, culled and vaccinated farms, for the basic control strategies with a limited (default) and unlimited (unl) culling and vaccination capacity**

Strategy	Duration (days)		# Detected farms		# Pre-emptively culled farms		# Total culled farms		# Vaccinated farms	
EU	88	(46-203)	278	(80-491)	0	(0-0)	278	(80-491)	0	(0-0)
EU_unl	85	(41-193)	259	(26-463)	0	(0-0)	259	(26-463)	0	(0-0)
cul1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
cul1_unl	47	(0-96)	76	(1-157)	204	(11-343)	281	(12-499)	0	(0-0)
cul3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
cul3_unl	27	(0-50)	29	(1-70)	328	(11-573)	357	(12-641)	0	(0-0)
cul10	26	(0-48)	40	(1-225)	630	(11-1,350)	681	(12-1,541)	0	(0-0)
cul10_unl	16	(0-30)	14	(1-36)	493	(11-1,055)	508	(12-1,089)	0	(0-0)
vac3	67	(0-113)	140	(1-331)	23 a)	(11-54)	163	(12-374)	397	(0-678)
vac3_unl	64	(0-105)	114	(1-246)	23 a)	(11-57)	140	(12-298)	372	(0-619)

a Pre-emptively culled in the 5 days following the first detection.

Table 2.11 shows how the limited resources delay culling or vaccination. For culling a distinction is made between the culling of infected farms and pre-emptive culling. The first category is always culled within one day after detection, because these farm have the highest culling priority. The delay times for pre-emptive culling increase with larger culling radii, up to a median delay time of more than two weeks for 10-km culling, emphasising the severe limitations of the culling capacity. Also the median delay time for vaccination is more than a week. This is more than its culling counterpart of 3-km ring culling, because vaccination yields larger epidemics and thus a higher demand on the vaccination capacity.

Table 2.11 **Delay times for culling and vaccination at a capacity of 20 farms/day: median values and 5%-95% interval for the period between detection and culling, pre-emptive culling and vaccination for the basic control strategies**

Strategy	**Delay time (days) before**					
	culling infected farm		**pre-emptive culling**		**vaccination**	
EU	0.05	(0.05-0.3)				
cul1	0.06	(0.05-0.4)	0.3	(0.1-5.5)		
cul3	0.1	(0.05-0.6)	4.2	(0.2-18.2)		
cul10	0.1	(0.05-0.6)	16.0	(4.4-42.2)		
vac3	0.05	(0.05-0.3)			7.9	(0.6-28.7)

2.5.4 Premature slaughter

When a broiler farm is located in a surveillance zone, it is not allowed to receive chicks for production. The farm will stay empty after the production cycle has finished, depleting the susceptible farms in the affected area in a natural way. Premature slaughter is aimed at reducing the density of susceptible farms even further by depopulating the broiler farms with broilers younger than 21 days of age. As these young animals cannot be slaughtered in the regular way (because of size limitations in the slaughter houses), they will be slaughtered on farm by the same teams that are used for (pre-emptive) culling.

For all strategies it is found that premature slaughter does not add much to the effectiveness of the basic control strategy. This result has two causes. The main reason is that in the studied DPPA area only a limited number of broiler farms is present (see Figure 2.5). Most of the infected farms are layer farms that are not targeted by the premature slaughter. Secondly, premature slaughter has the lowest priority in the use of the culling capacity, after the culling of the infected farms and pre-emptive culling. This means that a broiler farm may already have ended its production cycle by the time it can be prematurely slaughtered, especially in strategies with a large demand for pre-emptive culling (see delay times in Table 2.11).

Table 2.12	**Results for premature slaughter: median values and 5%-95% interval of epidemic duration and number of detected, pre-emptively culled, culled and vaccinated farms, for the basic control strategies without (default) and with premature slaughter (ps)**									
Strategy	**Duration (days)**		**# Detected farms**		**# Pre-emptively culled farms**		**# Total culled farms**		**# Vaccinated farms**	
EU	88	(46-203)	278	(80-491)	0	(0-0)	278	(80-491)	0	(0-0)
EU_ps	80	(43-161)	244	(57-408)	117	(27-245)	361	(88-648)	0	(0-0)
cul1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
cul1_ps	45	(0-90)	80	(1-233)	257	(11-479)	340	(12-708)	0	(0-0)
cul3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
cul3_ps	29	(0-54)	43	(1-223)	386	(11-750)	437	(12-939)	0	(0-0)
cul10	26	(0-48)	40	(1-225)	630	(11-1,350)	681	(12-1,541)	0	(0-0)
cul10_ps	26	(0-50)	41	(1-225)	636	(11-1,357)	687	(12-1,580)	0	(0-0)
vac3	67	(0-113)	140	(1-331)	23 a)	(11-54)	163	(12-374)	397	(0-678)
vac3_ps	64	(0-103)	131	(1-303)	98 a)	(11-248)	232	(12-545)	383	(0-625)
a) Pre-emptively culled in the 5 days following the first detection.										

2.5.5 Combination of pre-emptive culling and vaccination

The advantages of pre-emptive culling and vaccination can be combined, by applying fast pre-emptive culling in a small radius around a detected farm, while allowing more time for immunity build-up by vaccination in a larger radius around the culling zone. But even though the resources are almost doubled (20 culled farms/day and 20 vaccinated farms/day), the combination strategies yield similar epidemic durations and sizes as the pre-emptive culling only strategies (Table 2.13). The effect of pre-emptive culling is so much larger, that vaccination does not provide any added value. This is also caused by the logical result of the combination strategy that vaccinated farms will often (in approximately 25% of the cases) be pre-emptively culled later in the epidemic, when they are located in a culling zone because of a recent detection. In this way the vaccination protection is not used to its full potential.

Table 2.13	Results for combination strategies: median values and 5%-95% interval of epidemic duration and number of detected, pre-emptively culled, culled and vaccinated farms, for combining 1-km culling (cul1) with vaccination in 1-3km (cul1vac3) and 1-5km (cul1vac5) and combining 3-km culling (cul3) with vaccination in 3-10km (cul3vac10)

Strategy	Duration (days)		# Detected farms		# Pre-emptively culled farms		# Total culled farms		# Vaccinated farms	
cul1	47	(0-99)	84	(1-235)	214	(11-334)	297	(12-548)	0	(0-0)
cul1vac3	47	(0-96)	75	(1-228)	199	(11-320)	274	(12-522)	288	(0-466)
cul1vac5	48	(0-85)	76	(1-231)	198	(11-315)	274	(12-518)	382	(0-650)
cul3	30	(0-57)	44	(1-227)	362	(11-639)	412	(12-848)	0	(0-0)
cul3vac10	29	(0-59)	43	(1-222)	358	(11-644)	406	(12-825)	372	(0-731)

2.5.6 Vaccination coverage

In the default simulations an optimistic vaccination coverage of 80% of the birds on a vaccinated farm was assumed, accounting for the birds that are missed during vaccination and for the vaccinations that are not successful in inducing an immune response. These simulations are repeated with a pessimistic vaccination coverage of 50% and a perfect vaccination coverage of 100%. The number of detected and culled farms decreases when the vaccination coverage increases (Table 2.14). The number of vaccinated farms only slightly decreases due to the smaller epidemic size. The epidemic duration however, does not follow this trend; the 80% vaccination coverage yields the longest epidemics. This counterintuitive trend can be understood when we analyse the vaccinated farms in more detail.

Table 2.14	Results for vaccination coverage: median values and 5%-95% interval of epidemic duration and number of detected, pre-emptively culled, culled and vaccinated farms, for vaccination coverages of 50% (vac3_50), 80% (vac3, default) and 100% (vac3_100)										
Strategy	**Duration (days)**		**# Detected farms**		**# Pre-emptively culled farms**		**# Total culled farms**		**# Vaccinated farms**		
vac3_50	60	(0-114)	154	(1-334)	23 a)	(11-54)	180	(12-370)	400	(0-688)	
vac3	67	(0-113)	140	(1-331)	23 a)	(11-54)	163	(12-374)	397	(0-678)	
vac3_100	45	(0-91)	129	(1-305)	23 a)	(11-54)	153	(12-346)	392	(0-665)	

a) Pre-emptively culled in the 5 days following the first detection.

The time between infection and detection and the fraction of detected outbreaks are determined for all vaccinated infected farms (Table 2.15). Vaccinating only 50% of the animals is insufficient to halt an epidemic once a vaccinated farm is infected: all outbreaks are detected and the detection time is comparable to the unvaccinated detection time (see Figure 2.3b). The 50% vaccination coverage can still prevent an introduction on a farm though. The farms with an 80% vaccination coverage show a long tail in the detection time distribution (95th percentile of 32.4 days), which explains the longer epidemic times found in the simulation results. Apparently, the infection can simmer for a long time before being noticed. The 100% vaccination coverage will only allow detection in the early stages after vaccination when the population is not fully protected yet. Later infections will be effectively halted, but these within-flock outbreaks are not detected. For this reason one third of the outbreaks on fully vaccinated farms is missed. The number of undetected infected animals is high for this perfect vaccination coverage, while for the more realistic vaccination coverages of 50% and 80% the numbers of these animals are negligible.

Table 2.15	Results for vaccination coverage: median values and 5%-95% interval of detection time per farm, detection fraction and number of undetected animals per epidemic, for vaccination coverages of 50% (vac3_50), 80% (vac3, default) and 100% (vac3_100)					
Strategy	**Detection time vaccinated farm (days)**		**Detection fraction vaccinated farms**		**# Infected undetected animals**	
vac3_50	10.3	(7.0-16.1)	1.00	(0.96-1.00)	0	(0-1)
vac3	10.3	(6.9-32.4)	0.95	(0.86-1.00)	1	(0-10)
vac3_100	9.2	(6.9-12.7)	0.67	(0.48-0.82)	142	(0-583)

2.5.7 Hobby flocks

With the simulated results of the commercial farms, we can make an estimate for the number of infected, culled and vaccinated hobby flocks. For this we have generated random locations of an estimated number of 110,000 hobby flocks in the Netherlands, assuming a relative susceptibility of 0.014 (Bavinck et al., 2009) and a relative infectiousness of 0 (i.e. hobby flocks are dead-end hosts). In general, the number of infected hobby flocks follow the same trends as the commercial farms. The numbers are considerable because of the vast amount of hobby flocks in the Netherlands. Even though these infected flocks do not play a role in the epidemic, each of them poses a potential risk of infecting its owner. When for hobby flocks the same control strategies as for the commercial farms are followed, very large culling and vaccination capacities are required, even in an MPPA.

Table 2.16	Results for hobby flocks: median values and 5%-95% interval of expected number of infected, pre-emptively culled and vaccinated hobby flocks, for basic control strategies in a densely populated poultry area (DPPA, default), a medium populated poultry area (MPPA) and a sparsely populated poultry area (SPPA)					
Strategy	**# Infected hobby flocks**		**# Pre-emptively culled hobby flocks**		**# Vaccinated hobby flocks**	
EU	235	(108-403)	0	(0-0)	0	(0-0)
cul1	89	(2-268)	687	(16-1,646)	0	(0-0)
cul3	57	(2-243)	2,024	(100-6,846)	0	(0-0)
cul10	55	(2-244)	8,200	(1,008-27,808)	0	(0-0)
vac3	147	(2-328)	0	(0-0)	3,026	(100-7,327)
EU_MPPA	96	(1-332)	0	(0-0)	0	(0-0)
cul1_MPPA	31	(1-121)	323	(7-1,083)	0	(0-0)
cul3_MPPA	16	(1-80)	1,129	(91-3,549)	0	(0-0)
cul10_MPPA	11	(1-75)	4362	(1,017-12,805)	0	(0-0)
vac3_MPPA	40	(1-163)	0	(0-0)	2,042	(91-5,697)
EU_SPPA	3	(1-119)	0	(0-0)	0	(0-0)
cul1_SPPA	3	(1-25)	25	(12-270)	0	(0-0)
cul3_SPPA	2	(1-21)	188	(96-1,614)	0	(0-0)
cul10_SPPA	3	(1-13)	1,740	(990-7,490)	0	(0-0)
vac3_SPPA	3	(1-35)	0	(0-0)	188	(96-1,513)

3 Socio-economic consequences of different control strategies against Avian Influenza in the Netherlands

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3.1 Introduction

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

- What is the optimal strategy to control and eradicate AI from an economic perspective?
- What is the distribution of costs between cost types?
- What is the effect of reduced prices of products in the movement restriction zone on the total costs of the epidemics?
- What is the effect of specific modifications of strategies?
    a. excluding hobby farms from preventive culling;
    b. premature slaughter of broilers in the movement restriction zone to lower the poultry density in an area;
    c. unlimited culling and vaccination capacity.

This chapter is structured as follows: paragraph 3.2 describes the material and methods, paragraph 3.3 gives the most important results, which will be discussed in paragraph 3.4, and paragraph 3.5 gives the conclusions and recommendations of the economic analysis.

3.2 Material and Methods

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 AI free, according to OIE standards.[1] Costs originating after this period are not calculated.

Epidemiological input

The epidemiological data as presented in chapter 2 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;
- the compartments with infected farms;
- the duration of the epidemic.

Method used for the economic analysis

When evaluating the costs of an epidemic of a contagious disease like HPAI, 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 costs associated with culling and destroying of infected and contact animals, the costs associated with destruction of feed and eggs on detected farms, and the compensation and vaccination costs.
- *Costs 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 AI will result in trade restrictions that are mostly 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*[2]
  The effects from outbreaks of AI that are felt upstream and downstream

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

[2] In case of a very large epidemic (in more than one major poultry producing country) there might be an undersupply of poultry product in the market. Due to the small price elasticity of agricultural

along the livestock value chain: breeding, feed production, input supply, slaughter, processing, final sale and consumption.

- *Spill-over effects*
  The effects from outbreaks of AI 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.

Table 3.1 **Summary table of the main epidemiological results (mean and 5-95% ranges)**

Strategy	Duration (days)		# Detected farms		# Pre-emptively culled farms		# Total culled farms		# Vaccinated farms	
DPPA										
EU	**88**	(46-203)	**278**	(80-491)	**0**	(0-0)	**278**	(80-491)	**0**	**(0-0)**
cul1	**47**	(0-99)	**84**	(1-235)	**214**	(11-334)	**297**	(12-548)	**0**	**(0-0)**
cul3	**30**	(0-57)	**44**	(1-227)	**362**	(11-639)	**412**	(12-848)	**0**	**(0-0)**
cul10	**26**	(0-48)	**40**	(1-225)	**630**	(11-1,350)	**681**	(12-1,541)	**0**	**(0-0)**
vac3	**67**	(0-113)	**140**	(1-331)	**23**	(11-54)	**163**	(12-374)	**397**	**(0-678)**
MPPA										
EU_	**91**	(0-249)	**131**	(1-427)	**0**	(0-0)	**131**	(1-427)	**0**	**(0-0)**
cul1_	**46**	(0-110)	**32**	(1-124)	**74**	(5-269)	**106**	(6-391)	**0**	**(0-0)**
cul3_	**27**	(0-55)	**15**	(1-73)	**148**	(5-472)	**164**	(6-519)	**0**	**(0-0)**
cul10_	**18**	(0-38)	**8**	(1-65)	**366**	(5-1,053)	**374**	(6-1,099)	**0**	**(0-0)**
vac3_	**59**	(0-115)	**43**	(1-168)	**6**	(5-25)	**49**	(6-185)	**194**	**(0-580)**
SPPA										
EU	**8**	(0-111)	**3**	(1-147)	**0**	(0-0)	**3**	(1-147)	**0**	**(0-0)**
cul1	**6**	(0-56)	**3**	(1-30)	**1**	(0-72)	**3**	(1-102)	**0**	**(0-0)**
cul3	**6**	(0-33)	**3**	(1-15)	**2**	(0-132)	**5**	(1-143)	**0**	**(0-0)**
cul10	**6**	(0-28)	**2**	(1-10)	**11**	(0-452)	**14**	(1-464)	**0**	**(0-0)**
vac3	**6**	(0-67)	**3**	(1-39)	**0**	(0-4)	**3**	(1-39)	**0**	**(0-198)**

products, this may lead to a large increase of the price of poultry products that are not affected by trade restrictions. And as such might compensate for the poultry sector as a whole part of the loses. However, society as a whole is confronted with a negative effect due to higher food prices.

To evaluate the economic consequences of the different control and eradication strategies presented in Table 2.6 a model in SPSS was developed (Longworth, forthcoming). Since the main objective of this research was to compare the effects of different control strategies, in this study only those costs and benefits that were expected to differ substantially between the evaluated alternatives are included. Therefore, those types of costs effects that do not or only marginally differ between strategies and therefore do not alter the order of the strategies, were excluded from the calculations. Also those costs that were related to the epidemic of AI per se and do not depend on the control strategies applied, such as trade distortions costs were excluded. Costs that can occur during an epidemic of AI in not primary affected branches as horses, pig and cattle farming and arable land and the costs of non-agricultural industry as tourism were also not analysed.

In this evaluation the occurrence of the *first* outbreak in a densely (DPPA), or a medium (MPPA) or a sparsely (SPPA) populated poultry area were distinguished. The EU strategy was used as benchmark to compare the effects of the alternative strategies that involved culling and/or vaccination in different circles around infected farms. In the next section the costs that were included or excluded in the model are addressed. Also the assumed values are given.

3.2.1 Control costs

Included in the economic analysis are:
- compensation for depopulated poultry;
- depopulation (taxation, culling, transport & destruction, cleansing & disinfection);
- tracing;
- screening
- vaccination;
- additional surveillance in vaccination zone when the vaccination zone is larger than the BT zone;
- monitoring of vaccination efficacy (sampling and testing);
- compensation for welfare slaughter of reared pullets.

Table 3.2	Compensation values for slaughtered poultry used in the calculation of control costs							
	Broiler chickens	Ducks	Turkeys a)	Inside layers b)	Outside layers b)	Ready-to-lay layers c)	Ready-to-lay breeders c)	Breeders (parent stock) d)
Value €/bird	0.98	2.09	10.63	1.98	2.14	2.00	5.84	7.00

a) For turkey flocks, a weighted average of values for hens and cocks was used. Weights were equivalent to the proportion of movements of cocks versus hens in the KIP database; b) Values for inside layers were a weighted average of values for caged and barn housed layers, while values for outside layers were a weighted average of values for free range and organic layers. Weights were equivalent to the proportion of each type of housing in the total layer flock according to statistics of the PVE; c) Also the ready-to-lay layers and breeders that are slaughtered for welfare reasons are compensated by these amounts; d) 4 For breeders, the value of parent stock was used.

Excluded in the economic analysis are:

- the costs relating to the operation of the crisis centre and enforcement of regulations (in the 2004 outbreak these were approximately 4% of the total costs of the epidemic). These costs are not expected to differ much between the different control strategies.

Costs that were included in the calculations are:

- costs for to the operation of the crisis centre and enforcement of regulations. Included are costs for culling and disinfection (and when appropriate costs for vaccination);
- compensation for culled poultry flocks is calculated per culled bird;
- the value of culled birds was based on value tables prepared by the Agricultural Economics Research Institute (LEI), which are regularly updated. Values were calculated as averages over all ages, since the stage in the production cycle is unknown for individual farms. Besides the pre-emptive culled poultry flocks also reared pullets which face welfare problems are compensated, but below the value of the pullets on the day of slaughter. The difference between this value and the compensated value is attributed to the consequential losses (see below), the compensated value to the control costs.
- the per unit costs used to calculate the control costs are given in Tables 3.2 and 3.3;

Table 3.3	Organisational cost parameters used in the calculation of control costs				
Control cost category	**Unit**	**Value**	**Control cost category**	**Unit**	**Value**
Taxation a)	€/farm	0.10	Vaccination b)	€/dose	0.05
Culling a)	€/bird	1.90	Labour costs for application c)	€/bird	0.28
Transport and destruction a)	€/bird	0.66	Other materials d)	€/farm	45.40
Cleaning and disinfection a)	€/farm	459.60	Labour costs for preparation d)	€/farm	230.10
Depopulation total a)	€/bird	2.56	Vaccination total	€/bird	0.20
	€/farm	459.70		€/farm	275.50
Tracing a)	€/farm	501.68	Monitoring vaccination b)	€/farm	152.50
Screening a)	€/farm	541.33	Surveillance in vaccination zone b)	€/farm	152.50

a) Based on historical costs during the 2003 HPAI epidemic. These costs were divided by either the number of farm visits (screening, tracing, taxation), the number of poultry culled (costs of taxation, culling, transport and destruction) or the number of farms culled (cleansing and disinfection). Quantity estimates of the number of farm visits and farms and animals culled were based on the 2003 Annual Report of the Dutch authority (VWA) responsible for controlling the 2003 epidemic; b) Based on costs in Tacken et al. (2003); c) Assumed that a vaccination team (consisting of two veterinarians and four assistants could vaccinate 4,000 birds per day (assuming one vaccination day is equal to four hours due to the intensive nature of the work). Based on experience with free range layer farm in NL (VWA). Labour costs as in Tacken et al. (2003); d) From Mangen (2002).

3.2.2 Consequential losses/Indirect costs

These losses are calculated for each individual farm and then aggregated. In order to work at individual farm level we make two underlying assumptions:

- Farms produce average number of poultry per day (total number of poultry divided by length of the production period);
- Where necessary, farms are assumed to be halfway through the production cycle.

Poultry

Farms which are depopulated are assumed to be empty until the end of the epidemic (calculated as day of last detection + 40 days). Farms within a Movement Restriction Zone (MRZ) may run into welfare problems if an MRZ lasts longer than the production cycle (given our assumption, if MRZ > half the production cycle).

We assume the following:

- Farms which are located inside an MRZ for longer than half the production cycle are ready to deliver poultry and will face welfare problems;
- Farms containing poultry for slaughter (broiler, layer, breeder farms) will send poultry to slaughter under strict conditions and thereafter remain empty until the end of the epidemic;
- Farms containing reared pullets (rearing layer and rearing breeder farms) will be unable to deliver live poultry. These farms will be depopulated/ slaughtered at time period (begin MRZ + half production cycle) and remain empty until the end of the epidemic. Slaughtered poultry will be compensated, but below the value of the pullets on the day of slaughter. The difference between this value and the compensated value is attributed to the consequential losses, the compensated value to the control costs.

Three scenarios are calculated to determine the consequential losses or indirect costs. A best case a most likely and a worst case scenario. In all scenarios for reared pullets the losses are equal to the value at the day of slaughter minus the compensation for culled animals in all scenarios. For other poultry the losses are zero in the best case scenario and equal to the value at the day of slaughter in the worst case scenario. In the medium case scenario farms can deliver poultry to slaughterhouses at a price 30% below the normal value. The value at the day of welfare slaughter is given in Table 3.4.

Table 3.4 **Value of slaughtered poultry for welfare reasons used in the calculation of consequential losses**

	Broiler chickens	Ducks	Turkeys a)	Inside layers b)	Outside layers b)	Ready-to-lay layers c)	Ready-to-lay breeders c)	Breeders (parent stock) d)
Value €/bird	1.50	3.43	12.17	1.15	1.47	1.14	2.84	5.42

a) For turkey flocks, a weighted average of values for hens and cocks was used. Weights were equivalent to the proportion of movements of cocks versus hens in the KIP database; b) Values for inside layers were a weighted average of values for caged and barn housed layers, while values for outside layers were a weighted average of values for free range and organic layers. Weights were equivalent to the proportion of each type of housing in the total layer flock according to statistics of the PVE; c) Ready-to-lay layers and breeders are partly compensated (see Table 3.2). The values in this table are the values derived from the value tables minus this compensation;
4) For breeders, the value of parent stock was used.

Eggs

Layer and breeder farms located inside a MRZ which are not empty are assumed to continue production, but they are unable to deliver eggs. The assumption in the best case scenario is that all these eggs can still be delivered at the normal price. In the worst case scenario all eggs are destructed and not compensated for. In the medium case scenario all eggs can be delivered to the egg product industry at a lower price (industrial value), resulting in a loss of revenue.

Consequential losses for hatcheries located within a movement restriction zone were calculated separately. Upon entering a movement restriction zone, the hatching eggs currently within the hatchery cannot be delivered as day old chicks. It is assumed that the variable costs for the hatching eggs in the hatchery have already been made. In the best case scenario all eggs can be delivered to the egg industry for a lower revenue. In the worst case scenario the production must be destroyed in the medium case scenario half the production must be destroyed while half the production can be delivered to the egg industry for a lower revenue. For the period of the movement restriction zone, the hatchery is considered to be empty and the losses associated with idle production factors are calculated as gross margin per hatching egg per day.

For losses pertaining to lost revenue for egg delivery, this was calculated as a standard number of eggs per layer/breeder per day (based on KWIN data) multiplied by the reduction in per unit price received for eggs.

Table 3.5 **Value of normal and industrial eggs (Euro/egg)**

	Inside layers	**Outside layers**	**Breeders (parent stock)**	**Hatching eggs**
normal value	0.05	0.07	0.16	0.27
industrial value	0.03	0.03	0.03	0.03

Empty farms

For farms with the empty status, the value (per bird per day) of the loss due to idle production factors was calculated as the gross margin per bird per day. Gross margins were calculated from standard information pertaining to gross margins and length of production cycles (KWIN). Consequential losses pertaining to idle production factors were calculated for each farm and then aggregated. Farms which are empty are assumed to be empty until the end of the epidemic.

NOT included in calculating the economic consequences are:

- consequential losses for slaughterhouses and egg packing stations affected by control measures;

- extra costs (mainly at slaughterhouse/packing station level) associated with separating products from the MRZ or from vaccinated poultry;
- any potential losses for farms located inside a vaccination zone and not a MRZ (only relevant for the preventive vaccination strategy in our calculations). These farms will also face some movement restrictions.

3.2.3 Additional calculations

To evaluate the impact of a number of the assumptions additional calculations were performed to assess the impact of these assumptions.

Price level of products within the MRZ
Given the continuous production process a poultry production unit which is getting into a MRZ will have serious consequences for the marketing of the products in such a zone. Additional restrictions are foreseen. As a consequence the price paid for these products is expected to be lower than the price for products produced outside the MRZ. Experts defined a 'most likely' scenario for this. They assume a 30% lower price for poultry. Eggs produced in the MRZ have to be sold to industry and the price is expected to be 3 ct€/egg instead of 6 or 7 ct€/egg.

To get insight into the impact of this assumption for a number a scenarios the economic effect of two additional scenarios was calculated:
- a *best case* scenario in which product is sold for normal market value; and
- a *worst case* scenario in which the product value is zero.

Unlimited culling capacity and premature slaughter
To study whether the culling and vaccination capacities (of 20 farms/day each) limit the effective control of an epidemic, the simulations were repeated with unlimited resources. When a farm is located in a control zone, it is instantaneously (within 24 hours) culled or vaccinated. The larger the difference between the results for limited and unlimited resources, the more the control of an epidemic is hampered by the limited culling and vaccination capacity.

Slaughter and the role of depopulation of broilers
Stegeman et al. (2004) concluded that the containment of the epidemic in 2003 was most likely the result of depletion of susceptible flock by depopulation rather than the reduction of the transmission rate through bio-containment measures. To study the effect of reducing the density of susceptible farms and reduction of infectiousness premature slaughter was evaluated. Premature

slaughter is aimed at reducing the density of susceptible farms even further by depopulating the broiler farms with broilers younger than 4 weeks of age. As these young animals can't be slaughtered in the regular way (because of size limitations in the slaughterhouses), they will be culled on farm by the same teams that are used for (pre-emptive) culling.

The following results of the calculations are presented:

- not only the mean results but also the 5% percentile and the 95% percentile (5% of the results have a value that is lower/higher than the presented value). These two values give an indication of the distribution of the simulated outcomes. The mean can be considered an average outcome, whereas the 5% percentile can be considered an optimistic and the 95% percentile a pessimistic outcome;
- the strategies EU scenario (EU), cull in 1km (cul1), 3km (cul3) and 10km (cul10) and vaccinate in 3km (vac3) around infected farms are evaluated into detail for the starting in one of the 3 evaluated areas;
- the Gelderse Vallei as Densely Populated Poultry Area (DPPA), Northern Limburg as a Medium Populated poultry Area (MPPA) and in Drenthe as Sparsely Populated Poultry Area ((SPPA). In Table 3.6 the total and direct costs and consequential losses are presented;
- two alternative strategies Premature slaughter of broilers in the MRZ and of Unlimited culling or vaccinating capacity were evaluated for the strategy cul3 in DPPA.

3.3 Results and discussion

3.3.1 Total losses

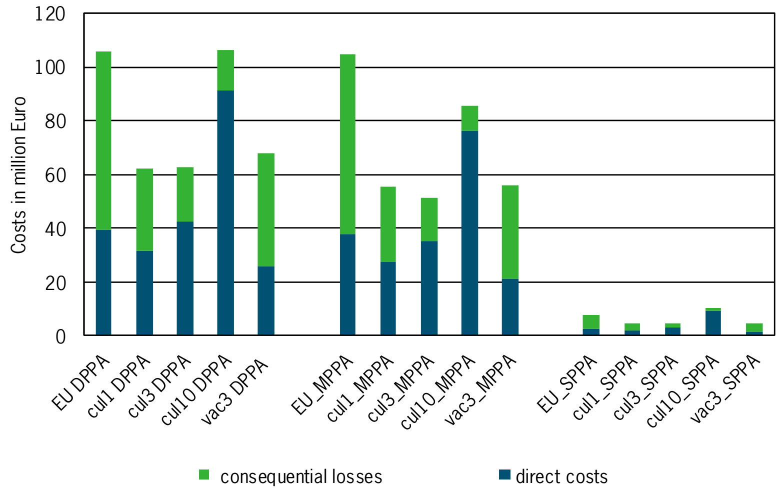
As already shown in the previous chapter there are large differences between the different areas in which an epidemics starts: in number of farms infected, culled or having movement restrictions, as well as even larger differences in the duration of the epidemic. These differences have their impact on the economic consequences of the different strategies.

Table 3.6	Economic effects of the most important strategies: most likely scenarios (in million Euro) (mean and ranges)								
Strategy	Total costs			Direct costs			Consequential losses		
		5%	95%		5%	95%		5%	95%
EU DPPA	106	52	281	39	19	39	67	32	67
cul1 DPPA	62	11	173	31	3	31	31	8	31
cul3 DPPA	63	12	175	43	6	43	20	6	20
cul10 DPPA	106	26	269	91	22	91	15	4	15
vac3 DPPA	68	10	196	26	3	26	42	8	42
EU_MPPA	105	6	223	38	0	79	67	5	147
cul1_MPPA	56	2	127	27	1	67	28	0	64
cul3_MPPA	51	2	115	35	1	82	16	0	35
cul10_MPPA	85	2	190	76	1	164	9	0	25
vac3_MPPA	56	2	121	21	1	50	35	0	75
EU_SPPA	8	1	25	2	0	6	6	1	21
cul1_SPPA	5	0	21	2	0	6	3	0	13
cul3_SPPA	5	0	21	3	0	12	2	0	9
cul10_SPPA	10	0	49	9	0	44	1	0	5
vac3_SPPA	5	0	23	2	0	7	3	0	17

As Table 3.6 and Figure 3.1 show:

- There is a large variation in costs due to differences in regions in which the first outbreak occurs. The mean total costs are 10 to 12 times higher when the epidemics starts in a DPPA and MPPA compared to an epidemic that starts in a SPPA;
- Also there is a large variation in the range of expected outcomes as indicated by the 5%-95% interval of the different strategies;
- For all the areas DPPA, MPPA and SPPA the mean total costs of the strategies cul1, cul3 and vac3 are substantially lower than the EU strategy and the cul10 strategies. The total costs of the strategies cul1, cul3 and vac3 differ only marginally.

Figure 3.1	Mean direct costs and consequential losses of different control strategies



DPPA = densly populated poultry area, MPPA = medium populated poultry area, SPPA = sparsely populated poultry area, EU = EU minimum strategy (culling infected farms + surveillance and movement restriction zone), cul1 = EU +culling poultry farms in 1-km radius, cul3 = EU + culling in 3-km radius, cul10 = EU + culling in 10-km radius, vac3 = EU + vaccination in 3-km radius.

3.3.2 Fraction direct costs compared to consequential losses.

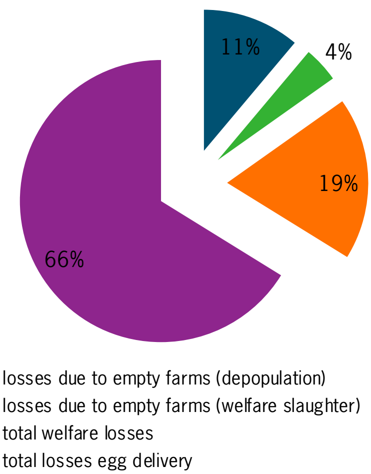
Not only total costs differ between different strategies also the distribution between direct and indirect losses differ. For example in the DPPA area the EU minimum strategy the fraction of the direct costs is 37% of the total costs whereas in the cul10 strategy this fraction is 85%. Please note that indirect costs are not reimbursed by EU or Animal Health Fund (Diergezondheidsfonds) and have to be borne by affected farmers themselves. I.e. although the total costs are more or less similar, the distribution of costs between stakeholders differs considerably.

This holds also for the evaluated strategies cul1, cul3 and vac3. For the DPPA region the fraction of direct costs as part of the total costa are for cul1 51% for cul3 31% and for vac3 62% respectively. The reason for this difference is that if the strategy involves more compulsory culling (and animal compensated) less animals are present in an area that suffer production losses. As illustrated by the fact that the lowest consequential losses (€15m) are calculated in the cul10 scenario.

3.3.3 Structure of consequential losses

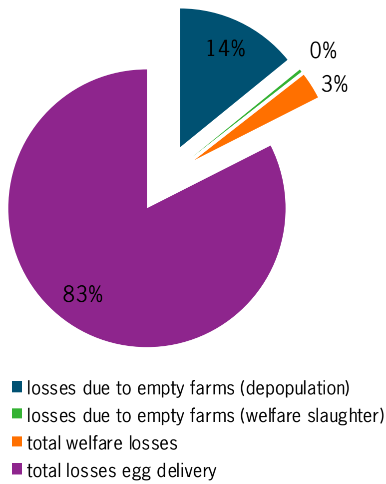
In Figures 3.2 and 3.3 the breakdown of the consequential losses into its' components is given for the EU scenario and the cul3 scenario in the DPPA region.[1]

Figure 3.2 **Structure of consequential losses DPPA and EU scenario (most likely)**



[1] The number of strategies evaluated (5) and the number of areas in which an epidemic can start (3) results in 15 different costs breakdowns. To prevent an information overload for the reader we choose for presenting only the most illustrative. Further details on the other calculations are available on request from the first author.

Figure 3.3	Structure of consequential losses DPPA and cul3 scenario (most likely)



As can be seen from these figures the largest part of the consequential losses originate from the losses in egg delivery. The reason for this is that especially during an epidemic layers stay in the affected region and maintain producing eggs that have to be delived to the egg-processsing industry at a much lower price than in case of delivering of the eggs as table egg. Given the duration of the simulated epidemics broilers are likely to be slaughtered within a few weeks to avoid welfare problems, which results in lower losses. In case preventive culling is applied in a larger area around infected farms (see cul10) the fraction of costs due to welfare slaughter (total welfare losses) is substantially reduced (3% in cul3 compared to 19% in EU).

3.3.4 Evaluation of the considered strategies

- When an epidemic occurs in an SPPA, the strategy chosen has a limited impact on the economic consequences of the epidemic.
- If an epidemic occurs in a DPPA or an MPPA the total costs of EU strategy or cul10 strategy are much larger than the cull1, cull3 en vacc3 strategies.
- Although the total cost of cull1, cull3 en vacc3 are more or less equal, the distributions between the direct and indirect costs differ substantially amongst the strategies. The indirect costs are smaller for cul3 than cul1 or

vac3. Since these indirect costs have to be borne by farmers and sector and are not compensated either by Animal Health Fund (Diergezondheidsfonds) or EU, poultry farmers might have a preference for this strategy.
- Compared to cul1 and cul3, the duration of the vac3 strategy exceeds the other strategy. This is less preferred given the negative effects within the MRZ and outside the MRZ (e.g. welfare problems, disturbed export).

3.3.5 Additional calculations

To evaluate the impact of a number of assumptions, additional calculations were performed to assess the impact of these assumptions.

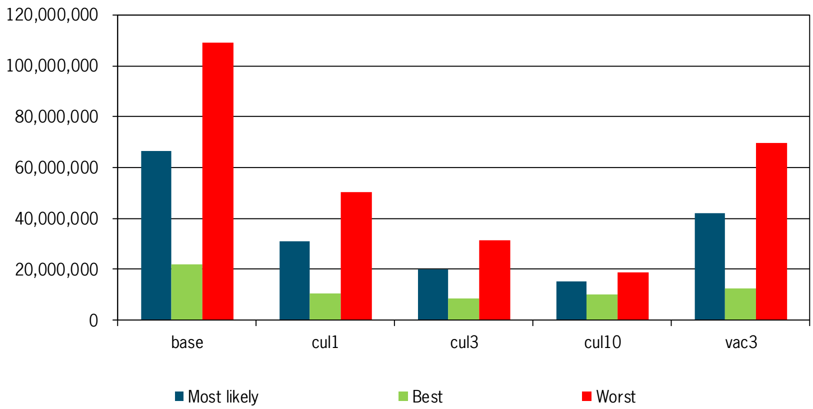
Price level of products within the MRZ
Given the continuous production process of poultry production, getting into an MRZ will have serious consequences for the marketing of the products of farms in such a zone. Additional restrictions (movement control and logistic processing) are foreseen. As a consequence the price paid for the products within the MRZ is expected to be lower than the price for products outside the MRZ. Experts defined a 'most likely' scenario for the price difference of prices for poultry products between inside or an MRZ. They assume a 30% lower price for broilers. Eggs produced in the MRZ have to be sold to industry and the price is expected to be 3 ct€/egg instead of 6 or 7 ct€/egg.

To evaluate the effect of different price scenarios, two additional price levels were evaluated: a best case and a worst case scenario. The assumption in the *best case* scenario is that all these eggs can still be delivered at the normal price. In the *worst case* scenario all eggs are destructed and not compensated for. For broilers, prices are equal to the value at day of slaughter in the *best case* scenario and zero in the *worst case* scenario. Table 3.7 and Figure 3.4 show the effect of the different scenarios on the total consequential losses.

Table 3.7 **Total consequential losses of AI in DPPA (in million Euro) for 3 different price scenarios**

	EU base	cul1	cul3	cul10	vac3
Most likely	67	31	20	15	42
Best case	22	11	8	10	12
Worst case scenario	109	50	31	19	70

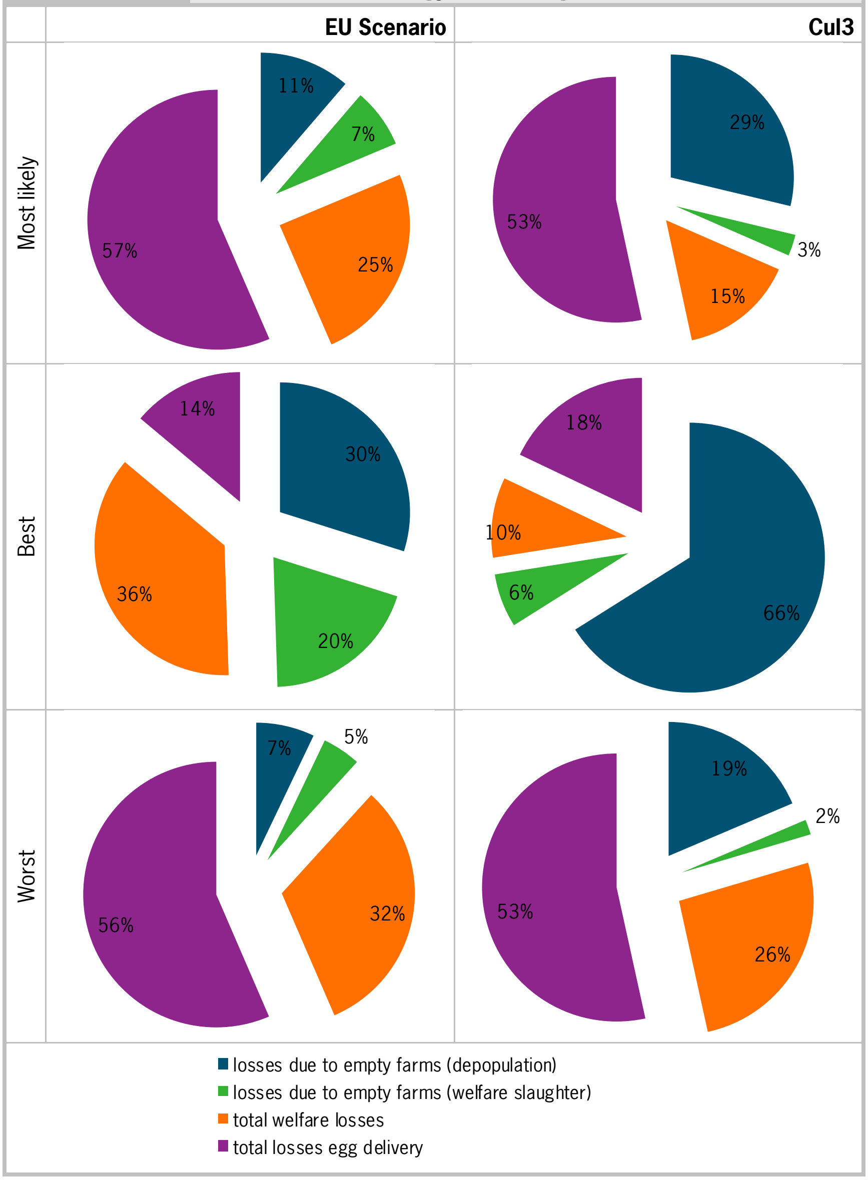
Figure 3.4 **Consequential losses for 5 different control strategies when an epidemic starts in DPPA under different price scenarios**



When evaluating the different price scenarios in all the evaluated control strategies, a large difference in consequential losses between the best case, most likely and worst case scenarios can be observed. In the best case scenarios the consequential losses vary from €8m in the cul3 strategy to €22m in the EU minimal strategy and are between 2.5 to 3 times lower for EU, cul1 and cul3. For cul10 this difference is only 2/3 of the most likely scenario. The reason for this is that a large portion of the animals are culled and not in the area present during the duration of the epidemic, i.e. direct costs are the largest part of the total costs.

In the worst case scenario the total consequential losses are 1.2 (cul10) to 1.6 (vac3 and EU) times higher than the most likely scenario. As Figure 3.5 shows the differences mainly originate from the fraction of the total losses due to egg delivery. The higher the prices paid for products originating from zones with restrictions the lower the overall consequential losses. The losses due to depopulation remain the same in the different scenarios and therefore its fraction in the best case scenario increases.

Figure 3.5 **Distribution of different consequential losses for epidemics in DPPA for EU strategy and culling in 3-km radius**



Slaughter and the role of depopulation of broilers

Stegeman et al. (2004) concluded that the containment of the epidemic in 2003 was most likely the result of depletion of susceptible flocks by depopulation rather than the reduction of the transmission rate through bio-containment measures. To study the effect of reducing the density of susceptible farms premature slaughter was evaluated. Premature slaughter is aimed at reducing the density of susceptible farms even further by depopulating the broiler farms in the MRZ with broilers younger than 3 weeks of age. As these young animals cannot be slaughtered in the regular way (because of size limitations in the slaughterhouses), they will be culled on farm by the same teams that are used for (pre-emptive) culling.

In Table 3.8 the effect of depopulation of broilers younger than 21 days in a DPPA region and a cul3 strategy. On average in the situation of premature slaughter the number of depopulated farms is 34 farms higher than in the basic situation. As a consequence of this the costs for depopulation increase. These costs are not outweighed by the lower consequential losses. This may be partly due to the fact that in the DPPA region the number of broiler farms is rather limited (as can be seen from the only small increase in number of depopulated farms). For regions like the MPPA region the effect may be different, because in this region the broilers are a much larger fraction of the total poultry population. The effect on the course of the epidemic is very limited.

For an individual farmer however there might be an incentive for premature culling since from an economic perspective it does not make sense to continue feeding animals if the expected revenues of the broilers at moment of slaughter (here 70% of the normal revenues) do not outweigh the additional costs that have to be made in the remaining part of the rearing period. For broilers older than approximately 20 days the loss per animal is less when the animals are raised until 42 days and slaughtered compared to immediate culling. For animals younger than 20 days the loss is lower if the animals are immediately culled, the additional costs that have to be made to fully raise the animals do not outweigh the expected revenues, even if no compensation is paid for the animals.

Unlimited culling capacity

To study whether the culling and vaccination capacities (of 20 farms/day each) limit the effective control of an epidemic, the simulations were repeated with unlimited resources. When a farm is located in a control zone, it is instantaneously culled or vaccinated.

Table 3.8	**Effect of depopulation of broilers younger than 21 days in a DPPA region and a cul3 strategy (mean and 95% range)**					
	Basic situation		**Premature slaughter**		**Difference**	
	mean	**95%**	**mean**	**95%**	**mean**	**95%**
# farms INFECTED	104	274	104	270	0	4
# farms infected in HRP	32	77	32	77	0	0
# farms DETECTED	61	200	61	197	0	3
# farms DEPOPULATED	416	766	449	875	-34	-109
# farms SCREENED	741	1,393	701	1,307	41	86
# farms TRACED	122	400	122	394	1	6
# farms in SURZone	761	1,428	757	1,420	5	8
day of last detection	31	51	30	49	1	2
length of epidemic	71	91	70	89	1	2
	0	0			0	0
COSTS in million Euro						
TOTAL COSTS in million Euro	63	148	69	170	-6	-22
TOTAL DIRECT COSTS	43	104	50	124	-8	-21
depopulation	42	100	49	122	-8	-22
screening and tracing	0	1	0	1	0	0
total compensation welfare	0	2	0	2	0	0
TOTAL CONSEQUENTIAL LOSSES	20	46	19	43	1	3
total losses of empty farms	6	15	6	15	0	0
empty farms (depopulation)	6	14	6	14	0	0
empty farms (welfare slaughter)	1	2	0	1	0	1
total welfare losses	3	9	2	5	1	3
total losses egg delivery	11	24	11	24	0	0

Table 3.9	Effect of unlimited culling capacity DPPA an cul3 strategy (mean and 95% range)					
	Basic situation		Unlimited capacity		Difference	
	mean	95%	mean	95%	mean	95%
# farms INFECTED on	104	274	75	167	-29	-107
# farms infected in HRP	32	77	32	77	0	0
# farms DETECTED on	61	200	31	64	-30	-136
# farms DEPOPULATED on	416	766	349	588	-67	-178
# farms SCREENED	741	1,393	652	1,178	-90	-215
# farms TRACED	122	400	62	128	-60	-272
# farms in SURZone	761	1,428	671	1,209	-90	-219
day of last detection	31	51	27	45	-3	-6
length of epidemic	71	91	67	85	-3	-6
COSTS in million Euro						
TOTAL COSTS in million Euro	63	148	50	109	-13	-38
TOTAL DIRECT COSTS	43	104	34	77	-9	-27
depopulation	42	100	34	75	-8	-25
screening and tracing	0	1	0	1	0	0
total compensation welfare	0	2	0	1	0	-1
TOTAL CONSEQUENTIAL LOSSES	20	46	16	35	-4	-11
total losses of empty farms	6	15	5	12	-1	-4
empty farms (depopulation)	6	14	5	11	-1	-3
empty farms (welfare slaughter)	1	2	0	1	0	-1
welfare losses	3	9	2	7	-1	-2
total losses egg delivery	11	24	9	18	-2	-6

In Table 3.9 the effect of unlimited culling capacity DPPA an cul3 strategy is given. As the table shows unlimited culling capacity (due to its effect on number of infected farms and duration of the epidemic) substantially lowers the costs of an epidemic. This holds true for direct costs as well as indirect costs. These results indicate that it might be worthwhile to invest in preparedness and in resources that enable an adequate response. For example in training and maintaining a basic infrastructure for a quick response. On average the difference is €13m.

Experts estimate the risk of introduction of HPAI in the Netherlands at once in every 5 years (Elbers, pers. comm.) and the probability that this will occur in a DPPA, MPPA or SPPA equally high. This means that per year a substantial sum (for an average epidemic €866,000) can be invested in maintaining the preparedness.

3.3.6 Other aspects

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 HPAI. These input data were based on reasoned assumptions. The results should thus be seen as the best possible estimates 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 AI in the Netherlands.

It is difficult to predict the effect of a specific AI 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 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 minimising the chance on unpleasant outcomes (Hardaker, Huirne 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 avoiding 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 actually 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' (Ge, 2008).

Adjustments during the epidemic

The epidemiological and economic results suggest that several control measures themselves incur high costs. Also there is a large variation in possible outcomes. Since fighting the epidemic is a dynamic process in which decisions can be and have to be adjusted when new information arrives, a decision maker can decide to apply a control strategy with measures which has relatively low costs at the start of an epidemic, while he/she can take additional more costly measures during the epidemic when appropriate. This might result in a more economyically 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.

In addition to the 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 AI that are felt upstream and downstream along the livestock value chain-breeding, feed production, input supply, slaughter, processing, final sale and consumption.

Due to an epidemic the market access for products of susceptible species is seriously restricted. An epidemic of AI 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. Part of these especially apply for the infected areas, but also Dutch poultry farmers outside the infected compartments can be faced with consequences since trade bans might occur for. Especially for the Dutch poultry sector, an epidemic of AI can have high consequences, because of the export of large numbers of breeding eggs and one day old chicken. 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 to the situation before the initial outbreak.

Hobby flocks
As the results of the previous chapter show in case of applying the same culling strategies on hobby flocks a considerable number of flocks have to be culled because of the vast amount of hobby flocks in The Netherlands. Even though these infected flocks do not play a role in the epidemic, each of them poses a potential risk of infecting its owner. To prevent infection of the owners it should be considered to preventively vaccinate hobby flocks. A public awareness campaign might help to increase the cooperation in this voluntary campaign.

Zoonotic aspects
Avian influenza has proven to be a lethal zoonotic. In case of an outbreak of H5N1 other than veterinary or economic arguments will have a role in the discussion. This might lead to other more drastic (and costly) strategies than when only the consequences for the poultry sector have to be taken into consideration. Collaboration between veterinary and human health authorities is vital for an adequate response.

4 Conclusions

4.1 Epidemiological consequences

Using model calculations, we have assessed different strategies to control an HPAI epidemic in different regions of the Netherlands, with a special focus on resources for culling and vaccination and on the expected consequences for hobby flocks. Numbers mentioned below are median values with the 5%-95% interval between brackets.

4.1.1 EU control strategy

The EU requires a minimal control strategy of depopulating infected farms, regulating transports in affected areas, screening in protection and surveillance zones and tracing dangerous contacts. In densely populated poultry areas (DPPA) this strategy is not sufficient to mitigate an epidemic effectively. The epidemic is predicted to last for 88 (46-203) days, infecting 278 (80-491) commercial poultry farms. When the epidemic starts in a medium populated poultry area (MPPA), the epidemic durations are similar to the results in the DPPA, but the epidemic sizes are much smaller due to the lower farm densities. In sparsely populated poultry areas (SPPA), the EU strategy suffices. Still, a small chance exists that the epidemic jumps to a denser area (in approximately 3% of the simulations), but this is not influenced by additional control measures taken in the SPPA.

4.1.2 Pre-emptive culling

Pre-emptive culling in a DPPA reduces the epidemic duration and the number of infected farms, but the total number of culled farms-the epidemic impact-increases with increasing culling radius. Culling in a 1-km radius around each detected farm limits the epidemic to 47 (0-99) days and 84 (1-235) infected farms, but the epidemic impact of 297 (12-548) culled farms is comparable to the EU strategy. A larger culling radius of 3km reduces the epidemic duration even further to 30 (0-57) days, but at the expense of culling 412 (12-848) farms in total. Enlarging the culling radius from 3km to 10km does not lead to smaller or shorter epidemics, due to the limited culling capacity of 20 farms/day. The only effect is increasing the median delay time between detection of the source farm and pre-emptive culling of the neighbouring farm from 4 to 16 days, making the extra culling effort pointless. The 1-km culling strategy and the EU strategy are not or to a lesser extent limited by the available culling capacity. The infected farms in all strategies are depopulated within one day after detection, because they are culled with the highest priority. Rapid depletion of an affected area by premature slaughter of broiler farms, does not lead to substantially smaller or shorter epidemics, because the DPPA contains a relatively small number of broiler farms in the Netherlands and because premature slaughter has the lowest culling priority.

4.1.3 Emergency vaccination

Emergency vaccination in a 3-km radius around detected farms in the DPPA yields epidemics of 67 (0-113) days, shorter than the EU strategy but longer than any culling strategy. However, the total number of 163 (12-374) culled farms is the smallest epidemic impact of all basic control strategies. While the assumed vaccination capacity of 20 farms/day already delays the vaccination to 8 days after detecting a source farm, it is not a realistic capacity for the current vaccination method by injection. Until a more efficient way of administration is developed, emergency vaccination seems ineffective in bringing an epidemic under control. Also the attainable vaccination coverage in a bird population affects the effectiveness of vaccination. A 'pessimistic' vaccination coverage of 50% can prevent a farm from being infected (in maximally half of the attempts), but once infected the population is insufficiently protected to stop virus transmission in the flock. With the 'optimistic' vaccination coverage of 80%-used as default-most outbreaks are still detected, but some can take a long time (up to a month) before being noticed. A perfect vaccination coverage of 100% does not allow an outbreak to simmer but effectively halts it once immunity has built up. As a result, one third of the outbreaks is not detected at all, which leads to the considerable number of 142 (0-583) undetected infected animals per epidemic (in the entire country, before final screening). The numbers of these animals for the more realistic vaccination coverages of 50% and 80% are negligible.

4.1.4 Combination strategies

Combining pre-emptive culling in an inner circle with vaccination in an outer circle does not yield substantially smaller or shorter epidemics. The control of the epidemic is driven by the pre-emptive culling, because of its instantaneous effect and because a part of the vaccinated farms will still be pre-emptively culled (when in a culling zone of another detected farm) before vaccination can take effect.

4.1.5 Hobby flocks

With an estimated number of 110,000 hobby flocks in the Netherlands, some of them are inevitably infected during an epidemic, even though they are expected to be less susceptible to infection than commercial poultry farms. When additional control measures are taken in a DPPA, approximately 50-150 hobby flocks are expected to be infected, posing a potential risk to their owners. Pre-emptive culling or vaccination of hobby flocks during an epidemic requires a vast expansion of the currently available capacities.

In conclusion, the EU strategy must be extended with additional measures to bring an HPAI epidemic under control in all but sparsely populated poultry areas. The choice between pre-emptive culling or vaccination depends on accepting direct animal losses or a longer period of restrictions, provided that a large vaccination capacity is available. Due to the non-perfect vaccination the risk of missing infected vaccinated farms and animals is negligible.

4.2 Economic consequences

4.2.1 Economic optimal strategy

In Densely Populated Poultry Areas (DPPA), both culling around infected farms in a radius of 1 or 3km (cul1, cul3) and vaccination of layer farms in a 3-km radius (vac3) yield substantially lower costs than the EU minimum scenario (EU) or culling in a radius of 10km (cul10). However, vaccination in a 3-km radius results in a substantially larger and longer epidemic. Extended capacity for culling or vaccination has substantial positive effects on the course and duration of the epidemic. From an economic point of view, in Sparsely Populated Poultry Areas (SPPA) no considerable difference between the evaluated strategies were observed.

4.2.2 Costs of the epidemics

The distribution of costs between direct costs and consequential losses varies between the evaluated strategies. Direct costs are highest and consequential losses are lowest when more animals are pre-emptively culled (cul3 and cul10 versus cul1 or vac3).

Layer flocks remain present and productive in an area with movement restrictions also during longer epidemics, whereas broilers are slaughtered when welfare problems tend to occur. It shows that especially lower egg prices (due to the fact that they cannot be used as table eggs) in the movement restriction zone has a large impact on the total costs of the epidemic.

4.2.3 Hobby flocks

Excluding hobby flocks from pre-emptive culling is assumed not to affect the course of the epidemic in commercial livestock. Therefore abolishing pre-emptive culling of animals on hobby farms should be seriously considered. Pre-emptive culling of these hobby flocks contributes a lot to the negative perception of the public towards needed interventions. However, since the fact that hobby flocks can get infected (without spreading to commercial livestock), adequate precautions such as preventive vaccination of the hobby flocks have to be taken to prevent infection of their owners.

4.2.4 Premature slaughter

Premature slaughter of broilers in the movement restriction zone to lower the poultry density in that area has only minor effects on the total costs of the epidemic and increases the direct costs. However, farmers are economically better off when the young broilers are killed even if no compensation is paid for the animals, since the expected revenues are lower than additional costs that have to be made to raise the animals to slaughter weight. To prevent moral hazards premature slaughter should be seriously considered as a policy option.

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