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# Is prevention better than cure? An empirical investigation for the case of Avian Influenza

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**Abstract-** The new EU Animal Health Strategy suggests a shift in emphasis away from control towards prevention and surveillance activities for the management of threats to animal health. The optimal combination of these actions will differ among diseases and depend on largely unknown and uncertain costs and benefits. This paper reports an empirical investigation of this issue for the case of Avian Influenza. The results suggest that the optimal combination of actions will be dependent on the objective of the decision maker and that conflict exists between an optimal strategy which minimises costs to the government and one which maximises producer profits or minimises negative effects on human health. From the perspective of minimising the effects on human health, prevention appears preferable to cure but the case is less clear for other objectives.

*Keywords-* avian influenza, prevention, control

## I. INTRODUCTION

In 2007, the European Commission published a new Animal Health Strategy (AHS) for the European Union (2007-2013) with the vision that “prevention is better than cure” [1]. The goals of this strategy are to ensure a high level of public health and food safety, to promote animal health thereby supporting farming and the rural economy, to improve economic growth, cohesion, and competitiveness, and to promote farming practises and animal welfare which prevent animal health related threats and minimise environmental impacts. Four areas of activity are outlined: prioritisation of EU intervention; a modern animal health framework; animal-related threat prevention, surveillance and preparedness; and science, innovation and research. With respect to the first area, threats to animal health will be assessed to determine their relevance to the goals of the AHS, the “acceptable level of risk” for the Community, and the relative priority for action to reduce the risk. For serious threats to human health and the rural economy, the goal is to reduce the risk to a negligible level.

An increasing number of outbreaks of Avian Influenza (AI) in domestic poultry have occurred worldwide in the last few decades; with large outbreaks also in EU member states, namely in the Netherlands and Italy. Similar to other epizootic diseases such as Foot and Mouth Disease (FMD) and Classical Swine Fever (CSF), outbreaks of AI can have serious impacts on animal health and welfare, producers, markets and trade. In contrast to FMD and CSF however, AI viruses also have implications for human health. AI viruses can be transmitted to humans causing a range of illness from no symptoms, through to conjunctivitis, serious influenza and fatalities [2, 3]. Additionally, AI viruses can either mutate or reassort to become a novel influenza virus in humans, potentially resulting in an influenza pandemic [3].

The risks to human health suggest that demand shocks may also be relevant, since consumers may perceive a health risk to be present from eating infected poultry meat. In 2006, consumption of poultry meat dropped severely in several EU member states, following reports of cases of AI in wild birds and backyard poultry [4]. However, this effect on consumption was not seen in 2007 [5]. It seems likely that outbreaks of AI will remain a threat in the foreseeable future. Considering the potential impact that AI could have on the achievement of the goals of the AHS, it would appear to be a high priority threat.

The AHS envisages a shift in emphasis away from control towards prevention and surveillance. In the management of epizootic animal diseases, three population states are distinguished. The normal state is disease-free where there is no disease present in the population. Once the disease is introduced, there is usually a period of delay before the disease is detected. During this state (called the high risk period, HRP), the disease can spread freely within the population. Once the disease is detected then the population enters the post-HRP state and control measures are implemented to eradicate the disease. Risk management of epizootic diseases aims to influence the occurrence and timing of the events of disease introduction (prevention), detection

(monitoring/surveillance) and eradication (control). The balance between these three actions will differ between diseases and depends on the uncertain (and often unknown) costs and benefits of each action.

The literature regarding the analysis of prevention versus mitigation options for threats to animal health is limited. In the context of epizootic animal diseases, Elbakidze and McCarl [6] examined the optimal balance between pre- and post-event actions with a specific application for FMD. The decision problem was to choose the level of surveillance and control that minimised expected costs, where surveillance and control had per unit costs and losses related to the value of culled herds. Their results suggest that the optimal level of investment in surveillance is increasing in the rate of disease spread, cost of control and probability of disease introduction; and decreasing in the effectiveness of control and cost of surveillance. In the context of diseases at farm level, Chi et al. [7] considered the optimal balance between prevention and treatment of disease. Much more attention has been given to these options individually, particularly regarding control strategies for epizootic animal diseases [e.g. 8, 9-11]. Analysis of prevention [12] and surveillance [13] options is less frequent and focuses on (stochastic) cost-effectiveness. In their welfare analysis of the effects of the CSF outbreak in the Netherlands in 1997, Mangen and Burrell [11] clearly showed that the concept of the economic losses associated with a disease outbreak is quite simplified. Total losses hides the differential effects on stakeholders where some stakeholders may actually gain from an outbreak. In the analysis of Mangen and Burrell [11], this differential effect was particularly noticeable for producers situated inside and outside the quarantine zone. The differential effect on stakeholders will be particularly complex when demand shocks may also play a role, such as in the case of AI.

The aim of this paper is to explore the issue of the optimal levels of prevention, monitoring (surveillance) and control for the management of AI outbreaks in domestic poultry. Particular attention is given to identifying situations where prevention may be preferred to cure. The approach is based on a national decision maker who is responsible for formulating risk management strategies for AI. It is assumed that the decision maker chooses the level of prevention, monitoring and control to optimise the expected value of an objective function across two states of nature; the normal (no-outbreak) and outbreak states. The

outbreak state in this model consists of the HRP and post-HRP states defined earlier (i.e. all states where the AI virus is present in the population). Different objective functions are explored relating to the economic impacts on stakeholders, the costs to the government and the effects on human health (infections with AI). This approach differs from standard economic welfare analyses and was chosen for two reasons. Firstly, the aim of this paper is an exploration of the issue and individual optimisation of objectives allows more insights regarding potential conflicts to be gained. Secondly, it is not clear how the different dimensions of risk (i.e. human health effects versus economic impact on producers) should be aggregated. The complexity of the objective functions makes numerical approaches attractive for exploring the optimal levels of prevention, monitoring and control. In this paper a stylised facts-based empirical application is developed which is based closely on the situation in the Netherlands.

The empirical application in this paper closely follows a theoretical framework developed by the authors (Longworth et al., submitted). Prevention is defined as activities aimed at reducing the likelihood of virus introduction (equivalent to the probability of the outbreak state occurring). Monitoring is defined as activities aimed at early detection of the virus once it is present in the poultry population. Control is defined as activities aimed at reducing virus spread and eliminating the virus from the population. Prevention and monitoring are implemented continuously (with the focus on implementation during the normal state of nature) while control only takes place in the outbreak state of nature. In terms of risk reduction, prevention reduces the likelihood of the adverse event while monitoring and control reduce the consequences (“cure”) of the event. In this paper, an intensity measure is used for the levels of each action which is a conceptual simplification of reality where each action consists of a number of discrete measures<sup>1</sup>. Such a simplification is currently necessary but has implications for the parameterisation of costs and efficacies of each action.

The outline of this paper is as follows. In section two, the empirical model is outlined in terms of the

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<sup>1</sup> In theory, all the possible combinations of measures (and their individual intensities) could be examined for their efficacy. This requires considerable modelling work which is currently unavailable for AI (for examples for CSF see [12] for prevention, [14] for surveillance and [15, 16] for control).

following components: epidemiological functions, effects on human health, the producers' profit maximisation problem, the consumers' utility maximisation problem and objectives of the decision maker. In section three the results of the empirical model are presented and discussed. Section four provides concluding remarks.

## II. THE MODEL

Three choice or management variables are considered in the framework: prevention,  $X^P$ , monitoring,  $X^M$ , and control,  $X^C$ , with  $0 \leq X^i \leq 100$ , for  $i=P, M, C$ ; where 0 represents a very low (almost non-existent) intensity and 100 represents the maximum technically feasible level. Some level of monitoring is still present at  $X^M=0$ , since producers still check their flocks everyday and will eventually notice and report a disease with very high mortality. This is taken into account in the epidemiological functions. Due to the complexity of the economic impacts, at this stage control excludes vaccination and is restricted to culling of infected flocks and preemptive culling of risk flocks.

Table 1: Base year data<sup>a</sup> used to calibrate the model

<sup>a</sup> Unless otherwise specified, base year refers to the year 2005

<sup>b</sup> Anonymous [17]

<sup>c</sup> Verbeke and Ward [18]

<sup>d</sup> Huishoudelijke aankopen pluimveevlees Nederland, 2005 4de kwartal. Retrieved 10-01-2008, 2007, from <https://bedrijfsnet.pve.agro.nl/>.

<sup>1</sup> Calculated from feed conversion rates in b

<sup>2</sup> Calculated from delivery weights and mortality rates in base year. Data from b.

<sup>3</sup> Estimated per person consumption based on total consumption in d.

Variable	Value	Source
Length of production cycle in days	53	b
Price of poultry stock (€/thousand birds), $w_N$	270.5	b
Price of feed (€/tonne), $w_F$	233	b
Feed per cycle (tonne), $F$	279	b <sup>1</sup>
Poultry stock per cycle (thousand birds), $N$	75	b
Producer price of output (€/tonne), $p$	750	b
Output in base year (tonne), $q_S$	155.61	b <sup>2</sup>
Number of producer households, $s$	2800	
Number of consumer households (million), $t$	10.6	d
Poultry consumed (kg), $q_D$	13.42	d <sup>3</sup>
Consumer price (€/kg)	5.4	d
Price elasticity of demand for poultry meat	-0.47	c

The epidemiological population under consideration is the domestic commercial poultry population within a country.

Prices are currently modelled exogenously. The impact of price changes in the normal and outbreak states of nature is explored using price scenarios.

Base year data used to calibrate the model is presented in Table 1. This data represents the situation in the Netherlands in 2005. The equations in the model and the value of parameters are presented in Table 2.

Table 2: Functional forms and values of parameters used in the model

Eq.	Function and Parameters
1	$in(X^P) = a_1 e^{(-a_2 X^P)}$ $a_1 = 0.5; a_2 = 0.018$
2	$eps(X^M, X^C) = s \cdot c_1 \cdot e^{\left(\frac{-c_2 X^C}{c_3}\right)}$ $c_2 = 0.5$
3a	$c_1 = 1 - e^{-R_0 c_1}$ <span style="float: right;"><math>c_1 = 0.94; R_0 = 3</math></span>
3b	$c_3 = b_1 e^{-b_2 X^M}$ <span style="float: right;"><math>b_1 = 30; b_2 = 0.025</math></span>
4	$epl(X^M, X^C) = MIN\left(365, d_1 + 365 e^{\frac{-1}{d_2 eps}}\right)$ $d_1 = 35; d_2 = 0.01$
5	$qz(eps, X^M) = MIN\left(s, eps + f X^C\right)$ $f = 0.3$ $h^{lm} = h_0^{lm} + h_1^{lm} eps, \text{ for } m = n, o, k$
6	$h_0^{ln} = 0.1; h_1^{ln} = 0.0; h_0^{lo} = 1E^{-04};$ $h_1^{lo} = 1E^{-05}; h_0^{lk} = 0.0; h_1^{lk} = 1E^{-09}$
7a	$cf(X^P, X^M) = k_1 + k_2 X^{P^3} + k_3 X^{M^3}$ $k_1 = 430000; k_2 = 5; k_3 = 5$
7b	$cv(X^M, X^C) = l_1 + l_2 qz^2 + l_3 epl^2 + l_4 qz \cdot epl$ $l_1 = 23500000; l_2 = 10; l_3 = 150; l_4 = 50$
8	$q_S = AN^\alpha F^\beta K^{1-\alpha-\beta}$ $A = 4.845; \alpha = 0.278; \beta = 0.403$
9	$g(X^P, X^M) = g_1 X^{P^2} + g_2 X^{M^2}$ $g_1 = g_2 = 1E^{-05}$
10	$u = f_1 q_D - 0.5 f_2 q_D^2 - \theta q_D + z$ $f_1 = 16.86; f_2 = 0.85;$
11	$q_D^* = \frac{f_1 - p - \theta}{f_2}$
12	$\theta^1 = \alpha + \lambda eps$ $\alpha = 0.0; \lambda = 0.0044$

### A. Efficacy of prevention, monitoring and control

The key epidemiological processes of virus introduction into a population and virus spread are captured using three functions. One function captures the effect of prevention on the expected annual likelihood of virus introduction into the domestic poultry population. The other two functions capture the effect of monitoring and control on the expected length and size of an epidemic. The specification is designed to capture the main effects without detailing the underlying biological processes.

The likelihood of introduction is modelled using a similar functional form to that adopted by Leung et al. [19] and Finnoff et al. [20] to model the probability of invasion for a highly mobile invasive species with numerous introduction pathways. The likelihood of introduction is specified in equation (1), where  $a_1$  represents some base probability of introduction and the parameter  $a_2$  represents the efficacy of prevention efforts. The function in equation (1) is parameterised by assuming that at an average level of prevention ( $X^p=50$ ), the expected likelihood of introduction is once every five years [21] and that the base probability is equal to one outbreak every two years.

No modelling studies were available which could be used to estimate the effects of increases in intensity of monitoring and control on the expected final size and length of an AI epidemic. Functional forms were chosen to represent realistic relationships<sup>2</sup>. The effect of monitoring and control on the final size and length of an epidemic is modelled using the function given in equations (2) and (3a-3b); where the variable  $c_1$  is the final size equation<sup>3</sup>, the variable  $R_0$  is the basic reproduction ratio<sup>4</sup>,  $b_1$  is the maximum number of

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<sup>2</sup> Standard mathematical epidemiological models [22, 23] detailing the dynamics of infection in a population and transmission between individuals could have been used. However the problem of estimating the effect of monitoring and control on transmission would remain. Given the complexity of all the equations in the model, the approach adopted in this paper has been to use this theory to inform the choice of a relatively simple functional form for the expected size and length of an epidemic.

<sup>3</sup> The final size equation from a simple mathematical epidemiological model assuming a closed population and a large number of infected and susceptible individuals [24]. The final size is the fraction of the total population which would have been infected at the end of an epidemic.

<sup>4</sup> The basic reproduction ratio is the average number of new infections caused by one average infected individual in a

infected premises at first detection when  $X^M=0$ ,  $b_2$  is an efficacy parameter for monitoring,  $c_2$  is an efficacy parameter for control,  $c_3$  is the number of expected infected premises at first detection, and  $s$  is the total number of premises (producers) in the population. Estimates of  $R_0$  for HPAI outbreaks in industrialised countries range from 0.9 to 3.6 [25]. In simulation studies, a high correlation is often found between the length and size of an epidemic [26, 27].

Equation (4) gives the functional form for the length of an epidemic as a function of the size of the epidemic (and therefore also monitoring and control), where  $d_1$  is the minimum length of the epidemic (the minimum expected HRP plus the number of days after the last infected farm is detected before the quarantine zone is lifted) and  $d_2$  is a parameter that relates the length of an epidemic to its size.

The size of the quarantine zone (i.e. the number of producers facing production restrictions) is an important variable determining the economic impact of an animal disease epidemic. Control has a two-sided effect on the size of the quarantine zone. On the one hand, culling of infected and at-risk premises reduces the number of infected premises (and therefore the quarantine zone) while on the other hand the quarantine zone increases because more at-risk premises are inside the zone. The functional form chosen to capture these effects on the number of producers inside the quarantine zone is given in equation (5), where  $f$  is a parameter reflecting the magnitude of the direct effect of control on the quarantine zone.

### B. Effects on human health

Although it is known that humans can become infected with AI, the relationship between exposure and likelihood of infection and illness is unknown. To capture some form of exposure, the likelihood of infection is modelled as a function of the expected epidemic size. Although a major simplification, such an approach seems reasonable from the perspective of a national decision maker. Given that poultry producers will generally have more intense contact with poultry, this stakeholder group is assumed to have a higher likelihood of infection. Within this stakeholder group, producers on infected farms will be more at risk than those on uninfected farms. Simple linear functions are chosen. No information is

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population of susceptibles. This measure is an important indicator of the rate of spread of an epidemic.

available to parameterise this effect with any accuracy. The health effects for the three stakeholder groups,  $m=n,o,k$ , (producer  $n$  inside the quarantine zone, producer  $o$  outside the quarantine zone and consumer  $k$ ) are given in equation (6).

### C. Government costs

Government costs are split into an annual and a periodic component. Annual costs refer to the costs of continuous implementation of prevention and monitoring. Periodic costs relate to the costs of control and are only relevant in the outbreak state. The government cost function for annual costs is represented with a cubic function. High levels of prevention and control are assumed to be very costly. The periodic cost function is represented with a quadratic function. The functional forms for the two cost functions are given in equations (7a) and (7b). Given the lack of data surrounding costs, these functions have been parameterised with plausible guesstimates based on the costs of current monitoring and prevention programmes in the Netherlands and the costs of controlling the 2003 HPAI outbreak.

### D. Producer problem

The representative producer is assumed to be profit maximising taking the state of nature as given. Production technology is represented using a Cobb-Douglas functional form with constant returns to scale, defined over three inputs: poultry stock,  $N$ , feed,  $F$ , and a fixed capital input,  $K$ . This function is given in equation (8) where the fixed capital input is used in index form with  $K=1$ . Output,  $q_S$  has a per unit price of  $p$ , poultry stock has a per unit price of  $w_N$ , feed a per unit price of  $w_F$  and capital a price of  $w_K$ . In addition producers face per stock unit costs associated with the level of prevention and monitoring chosen by the national decision maker,  $g(X^P, X^M)$ . A quadratic functional form is chosen for the function,  $g$ , as represented in equation (9), where it is assumed that prevention and monitoring carry the same costs for producers ( $g_1 = g_2$ ). In the outbreak state, poultry flocks within the quarantine zone are assumed to be culled and thereafter unable to produce until the end of the epidemic. 95 per cent of the market price of the culled flock is compensated; no compensation is paid for the period that production is stopped. Producers outside the quarantine zone are assumed to face no restrictions on production and may respond to price changes.

Using the production function in equation (8), the corresponding factor demand equations and data from 2005, the parameters  $A$ ,  $\alpha$  and  $\beta$  were calibrated.

### E. Consumer problem

The utility maximisation problem for the representative consumer is based on the classical approach of Mussa and Rosen [28] to model consumer demand for differentiated products. This approach has been used to model perceived quality differences of products, including the case of hormone treated beef [see 29].

The representative consumer is assumed to derive utility from consumption of poultry products,  $q_D$ , and of a composite consumption good,  $z$ , with a perfectly elastic supply. Utility is represented by a quasi-linear utility function such that  $u = v(q_D) - \theta q_D + z$ . Consumers perceive that consumption of AI-infected poultry products may lead to infection with AI virus. These preferences regarding potential risks of AI for human health (via consumption of poultry products) are represented by the term  $\theta$ . The preferences represented by  $\theta$  are potentially different in the outbreak and no-outbreak states of nature. A quadratic form was chosen for the utility function,  $v$ . The utility function is given in equation (10) and the corresponding demand function in equation (11).

In the no-outbreak situation,  $\theta$  is given by  $\theta = \alpha$ , and in the outbreak situation by  $\theta = \alpha + \lambda(\text{eps})$  (equation 12). The parameters  $f_1$  and  $f_2$  are calibrated using base year data on average consumption and price of poultry products in 2005 and an own-price elasticity of -0.47 [18].  $\lambda$  was chosen such that when the expected epidemic size is at its maximum, demand from the representative consumer is zero.

### F. Objectives of the decision maker

Four separate objectives are considered for the decision maker. It is assumed that the decision maker wishes to maximise the expected profits and utility of the representative producer and consumer, to minimise the expected costs for the government and to minimise the expected number of annual human infections with AI virus. Hereafter, these objectives are referred to as the profit, utility, cost and health objectives respectively. Prices in the no-outbreak and outbreak states of nature are denoted as  $p^0$  and  $p^1$  respectively.

The health objective is presented in equation (13).

$$\min_{X^P, X^M, X^C} \left\{ in(X^P) \cdot [eps \cdot h^{1n} + (s - eps) \cdot h^{1o}(eps) + t \cdot h^{1,m}(eps)] \right\} \quad (13)$$

This objective can be interpreted as the number of stakeholders in each group multiplied by their individual likelihood of infection, multiplied by the probability of the outbreak state.

The cost objective is presented in equation (14), which is the annual costs plus the periodic costs multiplied by the probability of the outbreak state.

$$\min_{X^P, X^M, X^C} \left\{ cf(X^P, X^M) + in(X^P) \cdot cv(eps, qz) \right\} \quad (14)$$

The profit objective is presented in equation (15). This is the expected profit in the outbreak and no-outbreak states of nature. In the outbreak states of nature, two additional sub-states are distinguished relating to whether the producer is inside or outside the quarantine zone. The likelihood of being inside the quarantine zone is equal to the proportion of producers expected to be within the quarantine zone,  $\frac{qz}{s}$ .

$$\max_{X^P, X^M, X^C} \left\{ [1 - in(X^P)] \pi^{0j} + in(X^P) \left[ \frac{qz}{s} \pi^{1k} + \left(1 - \frac{qz}{s}\right) \pi^{1l} \right] \right\} \quad (15)$$

where  $\pi^{0j}$  refer to profits in the normal state of nature,  $\pi^{1k}$  refers to profits in the outbreak state of nature for producers inside the quarantine zone and  $\pi^{1l}$  refers to profits in the outbreak state for producers outside the quarantine zone.

Finally, the utility objective is presented in equation (16).

$$\max_{X^P, X^M, X^C} \left\{ [1 - in(X^P)] \mu^*(p^0, \theta^0, z) + in(X^P) \mu^*(p^1, \theta^1, z) \right\} \quad (16)$$

### III. RESULTS AND DISCUSSION

Optimising each objective separately indicates the level of conflict that exists between the objectives. The degree of conflict can be shown in a payoff matrix as presented in Table 3. This payoff matrix is for the scenario where prices do not change. The objective which is optimised is shown in the first column. In the rows, the corresponding levels of the other objectives

and the optimal levels of each action ( $X^P$ ,  $X^M$ ,  $X^C$ ) are presented. The numbers in bold represent the best achievable values for each objective while those in italics are the worst achievable values. Table 2 shows that there is no conflict (for this price scenario) between the health and utility objectives while there is quite some conflict between the health and cost objectives in terms of minimising health effects and between the profit and cost objectives in terms of minimising costs.

The health objective is minimised when  $X^P$  and  $X^M$  are at their maximum levels (100) and  $X^C=34$ . These levels correspond to the levels which minimise the expected size of the epidemic, hereafter termed epidemiologically optimal levels. At these levels, utility is also maximised. For these two objectives, these results suggest that prevention (as referred to in the AHS to include monitoring) is preferable to cure. In contrast, the profit objective stands out because this represents a situation of no prevention and maximum control. This is due to the assumption that producers face annual costs associated with the level of prevention and control, but not directly for control. A different cost sharing arrangement could reduce the conflict between objectives.

Table 3: Payoff matrix for the four objectives when prices do not change

- <sup>a</sup> Annual expected number of human infections with AI virus
- <sup>b</sup> Annual expected cost for the government, in million €
- <sup>c</sup> Annual expected profit for a representative producer, in thousand €
- <sup>d</sup> Annual expected utility for a representative consumer, in utils

Obj.	Health <sup>a</sup>	Cost <sup>b</sup>	Profit <sup>c</sup>	Utility <sup>d</sup>	$X^P$	$X^M$	$X^C$
Health	<b>0.05</b>	14.00	<i>133.71</i>	<b>150.24</b>	100	100	34
Cost	1.53	<b>10.32</b>	153.92	149.34	75	85	25
Profit	<i>1.61</i>	<i>603.25</i>	<b>206.16</b>	<i>149.35</i>	0	42	100
Utility	<b>0.05</b>	14.00	<i>133.71</i>	<b>150.24</b>	100	100	34

The payoff matrix in Table 3 reflects the price scenario when prices are unaffected by the outbreak state. The magnitude and direction of price changes in an outbreak depend on the size of supply and demand shocks and the nature of any potential trade bans. In the EU, both price decreases and increases have occurred in response to AI outbreaks. The large outbreak in the Netherlands in 2003 resulted in a large increase in egg prices (mainly layers were affected); while sporadic, small outbreaks in EU member states in 2006 resulted in short term decreases in poultry meat prices. The first case was consistent with a large supply shock (with little or no demand shock) while

the latter was consistent with demand shocks. Price changes have no effect on the optimal levels of actions for the cost and health objectives. For the utility objective, the optimal levels of  $X^M$  and  $X^C$  remain the same for all price scenarios while  $X^P = 0$  for all price decrease scenarios and  $X^P = 100$  for all price increase scenarios. The effect of price changes on the optimal levels of each action for the profit objective are shown in Table 4.

Table 4: Optimal levels of  $X^P$ ,  $X^M$  and  $X^C$  for the profit objective under different price scenarios

	Price scenario for the outbreak state, percentage change from $p^0$						
	-50	-25	-10	0	+10	+25	+50
$X^P$	67	50	30	0	0	0	0
$X^M$	3	37	40	42	43	43	43
$X^C$	100	100	100	100	100	100	100

The level of  $X^C$  which maximises the profit objective is the same regardless of the price scenario.  $X^P$  and  $X^M$  remain similar for all price increase scenarios but differ dramatically for price decreases. The larger the expected price decrease the higher the optimal level of  $X^P$  and the lower the level of  $X^M$ . When prices decrease, producers collectively lose in the outbreak situation so a high level of prevention is optimal. However prevention and monitoring are costly for producers and it is optimal to reduce the level of monitoring (the expected epidemic length becomes longer but has a smaller impact on expected profits because the likelihood of the outbreak state occurring is lower).

These results suggest that the effect of epidemic length on profits is more important than the size of the quarantine zone (at  $X^C=100$  all producers are inside the quarantine zone), but this is dependent on the assumption that producers face direct annual costs for prevention and monitoring but not for control. If the epidemic is short (especially if it is shorter than the average production cycle), then economic losses for producers in the quarantine zone remain small and the size of the quarantine zone is less important. The impact of different cost sharing arrangements requires further investigation, since the results here are dependent on the assumptions regarding cost sharing. A cost sharing arrangement where the costs of prevention and monitoring are spread over all stakeholders and where producers also share in control costs could reduce the conflict between objectives and

provide a strategy which is acceptable for all objectives and stakeholders.

If the economic impact on stakeholders is considered, then the case for prevention preferable to cure is less clear cut. In our analysis, an outbreak does not always lead to welfare losses for producers and consumers. A similar result was found by Mangen et al. [11] for CSF. These welfare effects are heavily dependent on price changes. In the current analysis prices are exogenous and the effect of price changes has been explored through potential price scenarios. Endogenising price and trade effects would allow a more thorough analysis of this aspect and should be addressed in further research.

Given the difference in approaches it is difficult to compare our results with those of Elbakidze and McCarl [6] for FMD. Considering the objective of cost minimisation (this is closest to their objective function), first sensitivity analysis (results not shown) suggests similar findings: optimal levels of prevention and monitoring increase as the base likelihood of introduction increases, the efficacy of control decreases, and the costs of prevention and control fall. However the effects are different for prevention and monitoring. Although prevention and monitoring are both pre-event actions, prevention reduces the likelihood of the adverse event while monitoring reduces the consequences (cure). This is not captured by the approach of Elbakidze and McCarl [6].

#### IV. CONCLUDING REMARKS

From the perspective of minimising effects on human health or minimising government costs, our results indeed suggest that prevention is preferable to cure, although these two objectives imply a different balance between prevention and monitoring. The case is less clear cut when considering the economic impacts on stakeholders, which are largely dependent on price effects. Endogenising prices in the model would better capture these effects. The four objectives considered in this paper show different degrees of conflict. Different cost sharing arrangement may provide an opportunity to reduce the conflict between the objectives pertaining to the economic impact on stakeholders and those pertaining to human health and government costs. However, any overall risk management strategy will entail a compromise in achieving these objectives. Further research should address issues regarding integration/aggregation of the objectives.



These results are indicative only and dependent on the functional forms and parameters chosen. A more thorough analysis of the sensitivity of results to the functional forms and parameters chosen is required. As integrated epidemiological and economic studies regarding the efficacies and costs of prevention, monitoring and control actions become available, this empirical application can be further improved.

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