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Free-Range Farming and the Optimal Public and Private Responses to a Possible Epidemic

By

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Abstract

We develop an optimizing model of a farm that is subject to invasion by an infectious disease such as bird flu, where the probability of invasion depends on the degree of free-ranging on the farm and post-invasion rate of spread on the farm depends on the farm size, the farmer's surveillance efforts, and the degree of free-ranging. We examine optimal policies for the farm and for the government, and analyze how these policies are affected by the degree of free-ranging. We find, *inter alia*, that when the farm size is endogenous fining an infected farm is superior as an instrument than providing it a rebate on costs, but when the farm size is exogenous the two instruments are equivalent. We also find that optimal surveillance effort, farm size, and fines are smaller for free-range farms when costs are sensitive to the degree of free-ranging.

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1 Introduction

With the increasing number of animal infections (OIE, 2008a) and recent cases of human infections (WHO, 2008) from highly pathogenic avian influenza (AI) virus, increased attention is being focused on AI as the world fears a recurrence of influenza pandemic at an even bigger scale than the pandemic of 1918 which killed 50 million people worldwide. Improving farm management both at the private level and at the public level is a centerpiece of the strategy to avoid the recurrence of a pandemic. In October 2005, the German government ordered poultry to be kept indoors (or in special shelters) for nearly two months to avoid possible avian influenza infection from migratory birds (USDA, 2005). Once AI is detected on a farm, the flock is usually culled. The United Kingdom culled 15,300 birds following the AI type H5N1 outbreak in Redgrave and Knettishall in November, 2007 (OIE, 2008b).

While AI is perhaps one of the most feared infections, other diseases that affect farm animals such as Bovine Spongiform Encephalopathy (BSE) commonly known as mad cow disease, and Aphtae epizooticae or foot-and-mouth disease (FMD) can also have devastating effects on farmers and economies, especially those that rely heavily on exports of cattle and poultry products. This is one of the reasons most countries employ stringent restrictions on imports of uncooked farm products by tourists, as any international traveler knows. If an infection among farm birds or animals is reported in a country, its exports of related meat products are often subjected to a blanket ban by other countries. The restrictions are imposed because of fear of transmission of disease to farm and nonfarm animals as well as humans.

When livestock is destroyed following an infection, compensation is often paid to the affected farmers. It is said that without compensation farmers may have little incentive to report an outbreak to authorities. It is also argued that since farmers have little control over the contracting of the initial infection, it is unfair to punish them. As a result, we find that in most cases of AI infections, farmers are indeed compensated. Compensation is often paid for culled birds at varying rates in different countries, though formal examination of optimal compensation levels is limited (World Bank, 2006).

However, it is not clear *a priori* why only compensation can provide the right incentives for the farmers. In fact, in the case of AI at the Bernard Mathew's Turkey farm in Suffolk, England, the government was criticized for compensating the farm and not imposing any penalties (Elliott, 2007). The farmers may have little control over the initial contracting of the disease, but the subsequent spread can to a large extent depend on the actions of the farmers. Efforts to detect and report AI in bird flocks have special significance for free-range farming that may allow poultry to come in contact with migratory birds (USGS, 2006; USDA, 2008). Vigilance and early reporting of any infections by farmers can be incentivized through an appropriately designed scheme of fines and/or compensation.

What type of policies should a government follow to induce effective farm behavior in the face of a potential invasion by an infectious disease? The question is at the heart of the present paper. We develop an optimizing model of a farm when there is an exogenous probability that a disease is introduced on the farm. Once the disease invasion takes place, its rate of spread within the farm depends on the size of the farm (livestock), and the level of efforts by the farmer. Although for the brevity of exposition, we shall refer to the infection as AI, the analysis may also apply to other farm diseases such as BSE and FMD. We consider two instruments for inducing the farmer to behave as a 'social planner' would want the farmer to. The instruments are a fine proportional to the incidence of infection on the farm and a compensation scheme proportional to the total cost of the farmer. We analyze how the farmer's behavior is affected by these instruments. We derive optimal levels for the instruments under two scenarios — short-run and long-run — depending on whether the size of the farm is exogenous or endogenous. We show that the fine is superior as an instrument when farm size is endogenous, but the two instruments are equivalent when farm size is exogenous.

The final aspect of our analysis deals with the effects of free-range farming. This type of farming increases the potential for livestock exposure to disease vectors. On the other hand, subsequent spread of infection may be slow due to lower stocking density under free-range farming compared with more intensive forms of farming.[1] We examine how the farmer's behavior and the optimal instrument level is affected by the degree of free-ranging.

The literature on the economics of avian influenza has only recently started to emerge. Part of the literature has modeled farmer behavior, and part of it has focused on estimating the impacts of potential AI outbreaks. Elbakidze (2008) presents an epidemiological model for minimizing the cost from an avian influenza outbreak by controlling contact rates and the length of symptomatic and asymptomatic periods. The model is solved numerically to find cost minimizing policies under different parameter choices. Public versus private incentives to manage outbreaks are not modeled. Beach *et al.* (2007) model farmer behavior when facing a potential AI outbreak. They consider the impact of government provided compensation for culled birds on the private control measures by profit-maximizing farmers, and propose data and analyses for generating information to guide public policy for AI prevention. Optimal level of compensation or other instruments for public welfare-maximization is not derived. Paarlberg *et al.* (2007) empirically estimate the economic impacts of potential AI outbreaks in the United States under different regionalization scenarios. Brown *et al.* (2007) use the Food and Agricultural Policy Research Institute (FAPRI) model to estimate the impact of AI outbreaks on different US agricultural sectors. There is also substantial literature on other forms of farm infections, for example, Rich and Winter-Nelson (2007), Pendell *et al.* (2007), and Zhao *et al.* (2006), Dent *et al.* (2002) on FMD, Chi *et al.* (2002), Fox *et al.* (2005), Dnes (1996), and Mainland and Ashworth (1992), on BSE, and Bicknell *et al.* (1999) on farm infection in general, among many other important contributions.

The present paper distinguishes itself from the above literature in a number of ways. First, our focus is on public policy to induce appropriate farm behavior. Second, we model

[1] In the European Union, free-range bird density is set at 2,500 birds per hectare.

and compare two instruments to motivate optimal behavior by farmers. Third, we examine both short-run and long-run scenarios. Finally, we examine how optimal farm responses and public policy are affected by the degree of free ranging.

The layout of the paper is as follows. The following section (section 2) sets up the theoretical framework and analyzes the short-run and long-run scenarios in subsection 2.1 and 2.2. Section 3 provides concluding remarks.

2 The theoretical framework

We consider a representative farm facing a competitive market for its product. The product could be any animal, but for the sake of exposition we shall call it birds. Farming practice is modeled parametrically by the degree of free-ranging denoted by θ.[2] Since free-rage farm products typically attract a higher market price, we assume that the price p is an increasing function of θ:

$$p(\theta) = \theta^{\rho}, \quad \rho > 0. \tag{1}$$

The farm has a stock of n birds which shall be treated both exogenously and endogenously in the analyses that follow. There is a probability ϕ that a bird in the farm catches an infection from an invading bird. This probability is assumed to be an increasing function of the degree of free-ranging θ. In particular,

$$\phi(\theta) = \theta^{\psi}, \quad 1 > \psi > 0. \tag{2}$$

Since free-range farming allows birds to move around more freely, the probability of initial infection is larger in a farm with a higher degree of free-ranging. However, once the infection takes place, its rate of spread among other birds on the farm is likely to be smaller on a farm that allows more free-ranging due to lower bird density. We also assume that the farmer makes an effort e to detect and limit the spread of the infection within the farm by, for

[2] There can be many levels of free-ranging depending on, for example, the amount of time the animals are allowed to roam around.

example, keeping an eye on the health of the birds. Total number of infected birds s is assumed to be an increasing function of n, but decreasing in e and θ:

$$s(n,e,\theta) = n^{\alpha} e^{-\beta} \theta^{-\gamma}, \quad \alpha > 1,\ \beta > 0,\ \gamma > 0. \tag{3}$$

The assumption that $\alpha > 1$ captures the fact that the disease is infectious, and the proportion infected (s/n), *ceteris paribus*, increases with n.

The total cost of production, c, (including that of effort e) is assumed to be:

$$c(n,e,\theta) = n^{\delta} e^{\epsilon} \theta^{\lambda}, \quad \delta > 1, \epsilon > 1, \lambda > 1, \tag{4}$$

where the assumptions that the parameters are greater than unity is consistent with the standard assumption of convex cost functions. In addition to these costs, there are policy induced costs (and benefits). We consider two policy instruments for the government. When an infection is found on a farm, the government destroys the bird stock on the farm, and a rebate, y, is paid to the farm as a proportion of its total costs. In addition, a fine f is imposed on the farm per infected bird found on the farm. The *expected* net profit of the farm π is then

$$\pi(n,e,\theta,f,y) = (1-\phi(\theta))p(\theta)n - c(n,e,\theta)(1-y\phi(\theta)) - fs(n,e,\theta)\phi(\theta). \tag{5}$$

The first term is expected revenue from the sale of birds. The second term is the expected production cost, net of any rebate received. The final terms is the total expected fine.

We consider a two stage game. In stage two, the farmer makes profit-maximizing choices for given fine and compensation levels. In stage one, the government decides on the optimal levels of the policy instrument f and y taking into account the farmer's reaction functions. In the following two subsections, we consider two cases depending on whether n is endogenous (long-run) or exogenous (short-run).

2.1 The case of endogenous n

We start with the case where n is endogenous, and the farm's optimization problem is to maximize (5) with respect to n and e. Using (1)-(4), the first order profit-maximizing conditions are:[3]

$$\pi_n = \frac{\partial \pi}{\partial n} = 0 \tag{6}$$

$$\Rightarrow \theta^{\rho}\left(1-\theta^{\psi}\right) = e^{\epsilon} n^{-1+\delta}\delta\theta^{\lambda}(1-y\theta^{\psi}) + e^{-\beta}n^{-1+\alpha} f\alpha\theta^{-\gamma+\psi} \tag{7}$$

$$\pi_e = \frac{\partial \pi}{\partial e} = 0 \tag{8}$$

$$\Rightarrow e^{-1-\beta}n^{\alpha} f\beta\theta^{-\gamma+\psi} = e^{-1+\epsilon}n^{\delta}\epsilon\theta^{\lambda}(1-y\theta^{\psi}). \tag{9}$$

The left hand side of (7) is the expected marginal benefit of expanding the size of the farm. The first term on the right hand side of (7) is the marginal production cost and the second term is the marginal increase in fine due to expected increase in infections associated with increasing farm size. The left hand side of (9) is the marginal benefits of effort in terms of reduced expected infections and thus fines; the right hand side represents the marginal cost of effort.

Solving (7) and (9) simultaneously, the resulting optimal n and e are:

$$n^*(\theta, f, r) = \left[A_n\ f^{-\epsilon}\ \theta^{(\gamma\epsilon-\beta\lambda+(\beta+\epsilon)\rho)}\ \left(-1+\theta^{-\psi}\right)^{(\beta+\epsilon)}\ \left(-y+\theta^{-\psi}\right)^{-\beta}\right]^{\frac{1}{\sigma}} \tag{10}$$

$$e^*(\theta, f, r) = \left[A_e\ f^{(-1+\delta)}\ \theta^{(\gamma-\gamma\delta+\lambda-\alpha\lambda+(\alpha-\delta)\rho)}\left(-1+\theta^{-\psi}\right)^{(\alpha-\delta)}\left(-y+\theta^{-\psi}\right)^{-(\alpha-1)}\right]^{\frac{1}{\sigma}}, \tag{11}$$

[3] The second order conditions, evaluated at the optimum, are satisfied.

$$\pi_{nn} = -e^{-\beta} f n^{-2+\alpha}(-1+\alpha)\alpha\theta^{-\gamma+\psi} - e^{\epsilon}n^{-2+\delta}(-1+\delta)\delta\theta^{\lambda}\left(1-y\theta^{\psi}\right) < 0,$$

$$\pi_{ee} = -e^{-2-\beta} f n^{\alpha}(1+\beta)\beta\theta^{-\gamma+\psi} - e^{-2+\epsilon}n^{\delta}(-1+\epsilon)\epsilon\theta^{\lambda}\left(1-y\theta^{\psi}\right) < 0,$$

$$\epsilon[\pi_{nn}\pi_{ee} - (\pi_{ne})^2] = e^{-2(1+\beta)} f^2 n^{-2+2\alpha}\beta(\beta(-1+\delta)+(-1+\alpha)\epsilon)(\beta\delta+\alpha\epsilon)\theta^{-2\gamma+2\psi} > 0.$$

where[4]

$$\sigma = \beta(-1+\delta) + (-1+\alpha)\epsilon > 0,$$

$$A_n = \beta^{\beta}\ \epsilon^{\epsilon}\ (\beta\delta + \alpha\epsilon)^{(\beta+\epsilon)} > 0,$$

$$A_e = \beta^{(-1+\alpha)}\ \epsilon^{(1-\delta)}\ (\beta\delta + \alpha\epsilon)^{(-\alpha+\delta)} > 0.$$

From (10) and (11), we obtain the following results.

Lemma 1 *When n is endogenous,*

(i) the optimal value of n decreases with f, but increases with y,

(ii) the optimal value of e increases with f or y,

(iii) when the government uses only one instrument, viz., a fine per infected animal, an increase in θ (a) reduces the optimal size of the firm n if $\lambda > (\gamma\epsilon + (\beta+\epsilon)\rho + \psi\beta)/\beta$, and (b) reduces optimal effort level if $0 \leq \alpha - \delta \leq (\alpha-1)(\lambda-\psi) + \gamma(\delta-1)$.

The marginal cost (right hand side of (7)) of increasing the bird stock or the size of the farm is increasing in f and decreasing in y, while the marginal benefit (left hand side of (7)) does not depend on either. Therefore, when f increases or y decreases, the optimal value of n decreases. The marginal cost (right hand side of (9)) of increasing the effort level does not depend on f, and is decreasing in y, while the marginal benefit (L.H.S. of (9)) is increasing in f and does not depend on y. Thus, when either f or y increases, the optimal value of e increases. A change in the value of θ affects all components of marginal benefits and costs in both first order conditions above. In particular, an increase in θ increases the marginal costs of an additional bird (the first term on the of right hand side of (7)) and the magnitude of this effect depends on the size of the parameter λ. If λ is sufficiently high, this effect dominates all other effects and an increase in θ reduces the optimal value of n. An increase in θ has two opposing effects on the marginal cost of efforts; the magnitude

[4]Note that probability $\phi = \theta^{\psi} \in [0,1]$, and $y \leq 1$ otherwise (5) is monotonic increasing in e. Therefore, $-y + \theta^{-\psi} \geqslant 0$ and $-1 + \theta^{-\psi} \geqslant 0$.

on the increase (decrease) in marginal costs depends on the size of λ (ψ), and if $\lambda - \psi$ is sufficiently large, the net effect on the marginal costs of efforts is not only positive but it also dominates all other effects, reducing the optimal value of e. Let $\pi(n^*, e^*, f, y, r)$ represent the maximized farm profit (for given f, y).

In the first stage of the game, the government chooses the fine, f , and rebate, y,in order to maximize expected social welfare W given by

$$W = \mathrm{CS} + \pi(n^*, e^*, f, y, r) - \phi(\theta) H(s(n^*, e^*, \theta)) + \phi(\theta)[f s(n^*, e^*, \theta) - y c(n^*, e^*, \theta)], \quad (12)$$

where $H(s)$ represents the extent of public health externality associated with the epidemic, CS is consumers' surplus, and the last term is the net revenue for the government. We assume that

$$H(s) = s^{\eta}, \quad \eta > 1. \quad (13)$$

We assume that there is a sufficient number of domestic farmers to supply the market or the necessary demand is met with imports, so there is no disruption to consumption in the case of a bird flu outbreak. Therefore, consumers surplus is given by

$$CS = \frac{1}{2b} \left(D[\theta] \right)^2, \quad (14)$$

$$\text{where} \qquad D[\theta] = a - bp[\theta], \qquad\qquad a, b > 0. \quad (15)$$

Substituting (10) and (11) in (12), the first order conditions for the government's optimization problem are derived as:[5]

$$\begin{aligned} W_f &= \frac{\partial W}{\partial f} = 0 \\ &\Rightarrow \eta \beta^{\frac{\beta(\eta-1)}{\sigma}} \epsilon^{\frac{(\beta\delta+\alpha\epsilon)\eta}{\sigma}} (\beta(-1+\delta) + \alpha\epsilon)(\beta\delta + \alpha\epsilon)^{\frac{(\beta\delta+\alpha\epsilon)(1-\eta)}{\sigma}} \left(1 - \theta^{\psi}\right)^{\frac{(\beta\delta+\alpha\epsilon)(\eta-1)}{\sigma}} \\ &\theta^{\frac{(\eta-1)[\gamma\epsilon+\beta(\psi-\lambda)+(\alpha\epsilon+\beta\delta)(\rho-\psi)]}{\sigma}} \left(1 - y\theta^{\psi}\right)^{\frac{(\alpha-1)\epsilon+\beta(\delta-\eta)}{\sigma}} \\ &+ f^{\frac{\beta\eta(\delta-1)+\epsilon(-1+\alpha\eta)}{\sigma}} \epsilon^{\frac{\alpha\epsilon+\beta(-1+\delta+\eta)}{\sigma}} \left[\beta - (\beta\delta + \alpha\epsilon)\left(1 - y\theta^{\psi}\right)\right] = 0. \end{aligned} \quad (16)$$

[5]It can be verified that the second order conditions, evaluated at the optimal, are satisfied. Since the expressions are very large, they are omitted here for the sake of brevity.

$$W_y = \frac{\partial W}{\partial y} = 0$$

$$\Rightarrow -\eta\beta^{\frac{\beta(\eta-1)}{\sigma}} \epsilon^{\frac{(\beta\eta(\delta-1)+(\alpha\eta-1)\epsilon}{\sigma}} (\beta\delta+\alpha\epsilon)^{\frac{(\beta\delta+\alpha\epsilon)(1-\eta)}{\sigma}}$$

$$\theta^{\frac{(\eta-1)[\gamma\epsilon+\beta(\psi-\lambda)+(\alpha\epsilon+\beta\delta)(\rho-\psi)]}{\sigma}} \left(1-\theta^{\psi}\right)^{\frac{(\beta\delta+\alpha\epsilon)(\eta-1)}{\sigma}} \left(1-y\theta^{\psi}\right)^{\frac{\beta(1-\eta)}{\sigma}} \tag{17}$$

$$- f^{\frac{\beta\eta(\delta-1)+\epsilon(-1+\alpha\eta)}{\sigma}} \Big([\beta\delta+(-1+\alpha)\epsilon] \left(1-y\theta^{\psi}\right)^{-1} - (\beta\delta+\alpha\epsilon) \Big) = 0.$$

Since an increase in f reduces the optimal value of n and increases that of e, it reduces the number of infections s and thus the disutility from public health hazard. A lower level of n and e also reduces production costs and thus rebate payments to the farmers. These are marginal benefits of an increase in f. An increase in f reduces the revenue received per unit fine, and this is the marginal social cost of an increase in f – the deadweight loss from taxation. These marginal benefits and costs are equalized in (16). The marginal effects of an increase in y on social welfare given in (17) can be similarly explained.

Simultaneously solving (16) and (17), we get the optimal values of the two policy instruments as:

$$f = \beta^{\frac{\beta(-1+\eta)}{\beta(-1+\delta)\eta+\epsilon(-1+\alpha\eta)}} \epsilon^{\frac{(\beta(-1+\delta)+\alpha\epsilon)(-1+\eta)}{\beta(-1+\delta)\eta+\epsilon(-1+\alpha\eta)}} (\beta\delta+\alpha\epsilon)^{-\frac{(\beta\delta+\alpha\epsilon)(-1+\eta)}{\beta(-1+\delta)\eta+\epsilon(-1+\alpha\eta)}} \tag{18}$$

$$\eta^{\frac{\beta(-1+\delta)+(-1+\alpha)\epsilon}{\beta(-1+\delta)\eta+\epsilon(-1+\alpha\eta)}} \theta^{\frac{(\eta-1)[\gamma\epsilon+\beta(\psi-\lambda)+(\alpha\epsilon+\beta\delta)(\rho-\psi)]}{\beta(-1+\delta)\eta+\epsilon(-1+\alpha\eta)}} \left(1-\theta^{\psi}\right)^{\frac{(\beta\delta+\alpha\epsilon)(-1+\eta)}{\beta(-1+\delta)\eta+\epsilon(-1+\alpha\eta)}}$$

$$y = 0. \tag{19}$$

The above characterization of the optimal policy instruments indiactes that the fine is a more appropriate measure to induce better farming practice than the rebate. The reason for this result is that while an increase in f reduces n and increases e and thus the level of potential infections, s, an increase in the level of the rebate y, while also increasing e, in fact increases the size of the bird stock n and thus has an opposite effect on potential infections s, as can be seen by taking appropriate derivatives of (10) and (11).

Proposition 1 *A fine per infection is a superior instrument to a rebate on costs for dealing with a potential bird flu epidemic.*

From (18), we also obtain the following results:

Proposition 2 *When the size of the firm is endogenous, an increase in the degree of free ranging reduces the optimal level of the fine if the cost of the firm is sufficiently sensitive to the degree of free ranging, i.e., the value of* λ *is sufficiently high. The optimal value of* y *remains unchanged.*

By 1, when the value of λ is high, an increase in θ decreases the optimal size of the farm, n^*, and the effort level, e^*, decreasing the net marginal benefit of increasing f.

Finally, we want to determine the total effect of θ on the optimal level of n and e. For this, note that

$$\frac{dn}{d\theta} = \frac{\partial n}{\partial \theta} + \underset{(+)}{\frac{\partial n}{\partial f}} \cdot \frac{df}{d\theta} + \frac{\partial n}{\partial y} \cdot \underset{(0)}{\frac{dy}{d\theta}}, \tag{20}$$

$$\frac{de}{d\theta} = \frac{\partial e}{\partial \theta} + \underset{(+)}{\frac{\partial e}{\partial f}} \cdot \frac{df}{d\theta} + \frac{\partial e}{\partial y} \cdot \underset{(0)}{\frac{dy}{d\theta}}. \tag{21}$$

The first terms on the right hand sides of (20) and (21) give the direct effects of an increase in θ. The second terms give the indirect effects via induced changes in the optimal levels of the policy instruments. Since the optimal value of y is always zero, the third terms on the right hand sides of (20) and (21) disappear. Then combining lemma 1 and proposition 2, we derive the following proposition.

Proposition 3 *An increase in* θ *(a) reduces the optimal value of* n *(taking into account the indirect effect via changes in government policies) if* λ *is sufficiently large, and (b) reduces the optimal effort level* e *(taking into account the indirect effect via changes in government policies) if* $0 \leq \alpha - \delta \leq (\alpha - 1)(\lambda - \psi) + \gamma(\delta - 1)$.

Note that if λ is sufficiently large, the indirect effect (via changes in optimal policies) of an increase in the degree of free-ranging on the size of the farm and the effort level are both negative.

2.2 The case of exogenous n

In the preceding subsection we assumed that the farm optimally chooses the size of of the bird stock n. However, it may not be possible — at least in the short run — for a farm to do so. In this section therefore we consider n to be an exogenous parameter.

Since n is exogenous, here we ignore equation (7) (first-order condition for n) and from (9) the optimal solution for e is solved as:[6]

$$e^{**}[\theta, f, r] = \left(\frac{f\beta}{n^{-\alpha+\delta}\epsilon\theta^{\gamma+\lambda}\left(-y+\theta^{-\psi}\right)} \right)^{\frac{1}{\beta+\epsilon}} \tag{22}$$

From (22), we obtain the following results.

Lemma 2 *When n is exogenous, we have:*

(i) An increase in n raises the optimal value of e if and only if $\alpha > \delta$,

(ii) An increase in f or y unambiguously raises the optimal value of e,

(iii) $\partial e^{**}/\partial\theta < 0 \iff (\gamma+\lambda)(1 - y\phi^{\psi}) > \psi$.

The results with respect to f and y can be explained as in proposition 2. The effect of n on the optimal level of e can be explained as follows. An increase in n raises both the marginal benefits and marginal costs of efforts, and the magnitudes of the two depend respectively on the size of the parameters α and δ (see (9). Thus, an increase in n increases the optimal effeort level if and only if $\alpha > \delta$.

Turning to optimal policies, the expression for social welfare W is the same as in (12) with n^* replaced by the exogenous value of n. Maximizing welfare with respect to the two

[6] The second order condition, evaluated at the optimum, is satisfied since

$$e^2 \cdot v_{\text{ee}} = -e^{-\beta} f n^{\alpha}\beta(1+\beta)\theta^{-\gamma+\psi} - e^{\epsilon}n^{\delta}(-1+\epsilon)\epsilon\theta^{\lambda}\left(1 - y\theta^{\psi}\right) < 0.$$

instruments f and y gives us:[7]

$$W_f = \frac{\partial W}{\partial f} = 0 \;\Rightarrow$$

$$\epsilon f^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} n^{\frac{\beta\delta+\alpha\epsilon}{\beta+\epsilon}} \beta^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \theta^{\frac{\gamma\epsilon\eta+\beta\lambda+\beta\eta\psi}{\beta+\epsilon}} = \eta\beta n^{\frac{(\beta\delta+\alpha\epsilon)\eta}{\beta+\epsilon}} \epsilon^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \theta^{\frac{\gamma\epsilon+\beta\eta\lambda+\beta\psi}{\beta+\epsilon}} \left(1-y\theta^{\psi}\right)^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \tag{23}$$

$$W_y = \frac{\partial W}{\partial y} = 0 \;\Rightarrow$$

$$\epsilon f^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} n^{\frac{\beta\delta+\alpha\epsilon}{\beta+\epsilon}} \beta^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \theta^{\frac{\gamma\epsilon\eta+\beta\lambda+\beta\eta\psi}{\beta+\epsilon}} = \eta\beta n^{\frac{(\beta\delta+\alpha\epsilon)\eta}{\beta+\epsilon}} \epsilon^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \theta^{\frac{\gamma\epsilon+\beta\eta\lambda+\beta\psi}{\beta+\epsilon}} \left(1-y\theta^{\psi}\right)^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \tag{24}$$

The right hand sides of (24) and (24) give the marginal benefits of the policy instruments (via reductions in public health hazards) and the left hand sides are the marginal costs associated with changes in government revenues.

From (23) and (24) are not independent equations, and therefore unique values of both cannot be endogenously determined. From the equation below, we can either determine the optimal value of f for a given value of y or determine the optimal value of y for given value of f.

$$f = n^{\frac{(\beta\delta+\alpha\epsilon)(-1+\eta)}{\epsilon+\beta\eta}} \beta^{-1+\frac{\beta+\epsilon}{\epsilon+\beta\eta}} \epsilon^{\frac{\beta(-1+\eta)}{\epsilon+\beta\eta}} \eta^{\frac{\beta+\epsilon}{\epsilon+\beta\eta}} \theta^{-\frac{(-1+\eta)(\gamma\epsilon+\beta(-\lambda+\psi))}{\epsilon+\beta\eta}} \left(1-y\theta^{\psi}\right). \tag{25}$$

The above result can be stated formally as

Proposition 4 *When n is exogenous, the two instruments f and y are equivalent.*

When n is endogenous, the instrument f is superior to y (proposition 1) since an increase in y (but not f) increases n and thus exposing the society to more potential pub-

[7]The second order conditions are satisfied since.

$$(\beta+\epsilon)^2\, W_{ff} = -f^{-2-\frac{\beta\eta}{\beta+\epsilon}} \beta^{1-\frac{\beta\eta}{\beta+\epsilon}} \epsilon^{-\frac{\epsilon}{\beta+\epsilon}} \theta^{-\frac{\gamma\epsilon(1+\eta)-\epsilon\psi+\beta\eta\psi}{\beta+\epsilon}} \left(1-y\theta^{\psi}\right)^{-\frac{\epsilon}{\beta+\epsilon}} n^{\frac{(\beta\delta+\alpha\epsilon)\eta}{\beta+\epsilon}} \epsilon^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \eta(\epsilon+\beta\eta)$$
$$\theta^{\frac{\gamma\epsilon+\beta\eta\lambda+\beta\psi}{\beta+\epsilon}} \left(1-y\theta^{\psi}\right)^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} < 0,$$
$$(\beta+\epsilon)^2\, W_{yy} = -f^{-\frac{\beta\eta}{\beta+\epsilon}} \beta^{-\frac{\beta\eta}{\beta+\epsilon}} \epsilon^{-\frac{\epsilon}{\beta+\epsilon}} \theta^{-\frac{\gamma\epsilon(1+\eta)+(-3\epsilon+\beta(-2+\eta))\psi}{\beta+\epsilon}} \left(1-y\theta^{\psi}\right)^{-3+\frac{\beta}{\beta+\epsilon}}$$
$$f^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} n^{\frac{\beta\delta+\alpha\epsilon}{\beta+\epsilon}} \beta^{\frac{\epsilon+\beta\eta}{\beta+\epsilon}} \epsilon(\beta\eta+\epsilon)\theta^{\frac{\gamma\epsilon\eta+\beta\lambda+\beta\eta\psi}{\beta+\epsilon}} < 0.$$

lic health hazards. Here, since n is exogenous this negative property of the instrument y disappears and both instruments become equivalent.

In particular, when $y = 0$ the optimal value of f is given by

$$f = n^{\frac{(\beta\delta+\alpha\epsilon)(-1+\eta)}{\epsilon+\beta\eta}} \beta^{-1+\frac{\beta+\epsilon}{\epsilon+\beta\eta}} \epsilon^{\frac{\beta(-1+\eta)}{\epsilon+\beta\eta}} \eta^{\frac{\beta+\epsilon}{\epsilon+\beta\eta}} \theta^{-\frac{(-1+\eta)(\gamma\epsilon+\beta(-\lambda+\psi))}{\epsilon+\beta\eta}}. \tag{26}$$

Since $1 > \psi > 0$ and $\lambda > 1$, from (26), the following result follows

Proposition 5 *When the government uses only one instrument, viz., a fine per infected animal, and the the size of the firm n is exogenous, we have the following results:*
(i) An increase in n unambiguously increases the optimal value of the fine, and
(ii) An increase in the degree of free-ranging unambiguously decreases the optimal level of fine.

An increase in n increases both the marginal costs and benefits of f, but the magnitude of the gain in benefits is larger than that in costs, raising the optimal value of f. A rise in the value of θ also increases both the marginal costs and benefits of f, but this time the magnitude of the gain in costs is larger than that in benefits, lowering the optimal value of f.

Finally, we want to determine the total effect of θ and n on the optimal level of e, assuming $y = 0$. For this note that

$$\frac{de}{d\theta} = \frac{\partial e}{\partial \theta} + \underset{(+)}{\frac{\partial e}{\partial f}} \cdot \underset{(-)}{\frac{df}{d\theta}}, \tag{27}$$

$$\frac{de}{dn} = \frac{\partial e}{\partial n} + \underset{(+)}{\frac{\partial e}{\partial f}} \cdot \underset{(+)}{\frac{df}{dn}}. \tag{28}$$

The first terms on the right hand sides of (27) and (28) show the direct effects of changes in θ and n respectively. The second terms show the indirect effects via induced changes in the optimal level of f.

When $y = 0$, combining lemma 2 and proposition 5, we derive the following results.

Proposition 6 *When $y = 0$, (a) an increase in the value of θ decreases the optimal level of efforts (taking into effect the indirect effect via a change in policy) if $(\gamma + \lambda)(1 - y\phi^{\psi}) > \psi$, and (b) an increase in the size of the firm increases the optimal level of efforts if $\alpha > \delta$.*

Note that while the indirect effect of a change in θ on e is negative, that of a change in n on e is positive. This is because while an increase in θ reduces the optimal value of f, a rise in n does just the opposite.

3 Conclusion

The fear of a possible bird flu pandemic has forced many governments and international institutions such as the World Health Organization to take measures to minimize the threat of possible public health disaster in the future. Over the past few years, many sporadic instances of this invasive influenza have been observed in different parts of the world among poultry birds and occaisonally among humans in close contact with infected poultry. In each case, the relevant governments, sometimes with the help of the WHO, acted swiftly culling large numbers of infected and potentially infected birds. What sort of policies should governments have toward individual farms? Should they be fined if infections are found in their farms or should they be compensated for the loss of their stock of poultry? Should the policy be dependent on the degree of free-ranging of the farms? These are some of the questions that we address in this paper.

We develop an optimizing model of a poultry farm with a given degree of free-ranging. There is an exogenous probability that an infectious disease invades the farm. Once the invasion takes place, its rate of spread within the farm depends on the size of the farm (bird stock), the level of surveillance and prevention effort by the farmer, and on the degree of free-ranging in the farm. Once an infection is detected, the entire stock is destroyed, and the farm receives a cost rebate from and pays a fine per sick bird to the government. Within this framework, we examine the optimal response of the farm and of the government and analyze how these responses are affected by the degree of free-ranging in the farm.

We consider two scenarios depending on whether the perspectives of the problem is short-run or long-run. In the short-run, the size of the farm is assumed to be exogenous, but in the long-run it is optimally chosen by the farmer. We find that both the nature of optimal policy and its responsiveness to farming practices are quite different in the two scenarios. In the short-run, a fine per infected animal and a rebate on costs are equivalent and either instrument can be used to induce optimal behavior by the farmers. In the long-run, a fine is superior to rebate as a policy instrument.

In the short-run, we find that the farmer chooses to exert more effort in surveillance and prevention of disease when compensation is increased. Similar impact is seen for an increase in fine as well. The optimal effort level can increase or decrease with farm size. If the elasticity of sick population to farm size is greater than the elasticity of farm cost to farm size, then an increase in farm size causes an increase in effort. The effort level decreases with the degree of free-ranging if the elasticity of cost to the degree of free-ranging is high and the elasticity of sick population to the degree of free-ranging is low. In addition, the optimal fine increases with farm size and decreases with the degree of free-ranging.

In the long-run, when the farmer can choose farm size or bird stock, we find that a larger bird stock is chosen when compensation is increased or fine is decreased. The optimal effort level increases with an increase in compensation or fine. The farm size decreases, the effort level increases, and the optimal fine decreases with the degree of free-ranging if the elasticity of cost to the degree of free-ranging is high. The results indicate that small free-range farms, particularly those with cost sensitivity to free-ranging, would require smaller fines in case of an outbreak compared with larger and traditional farms.

Further work is needed in a number of directions. The public impact of an avian influenza or other similar outbreak may consist of multiple components, including not only the health impact considered in this paper, but also temporary or permanent changes in food consumption patterns and changes in farmland usage driven by profitability. Management of these impacts in a unified framework needs to be examined. In addition, while surveillance and detection efforts help identify an outbreak when a relatively small number of birds have been infected, prevention efforts such as limiting inter-farm livestock contact may also help reduce the probability of a disease outbreak on the farm. A farmer can also reduce the probability of a disease outbreak on the farm by choosing the degree of free-ranging. Such efforts by the farmer can be allowed by extending the model in this paper. Finally, the government can use advertising and outreach programs to educate farmers in better disease detection and prevention practices. This would result in improved effectiveness of efforts by farmers, decreasing the marginal cost of reducing expected infections.

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