Avian flu and the procurement of chickens for culling

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Highly pathogenic strains of the A/H5N1 subtype of influenza — the so-called bird flu which has been intermittently infecting humans since May 1997 — are thought to spread from migratory waterfowl to chickens and then to humans [21]. Over 30 nations have experienced an outbreak of bird flu in their chicken populations and 353 humans[1] have been infected with H5N1. Although only 212 people have died from bird flu [22], if the H5N1 subtype were to acquire the ability to spread from human to human, the ensuing pandemic could cause an estimated 62 million or more humans deaths [14]. It has also been predicted that a pandemic would have large economic costs, perhaps as much as a 4.7 percent reduction in U.S. gross domestic product alone [8, p. 12].

For most governments, the primary strategy against bird flu is the development and stockpiling of antivirals and vaccines to limit human infection. Until an effective treatment is developed and as a precaution against the possible failure of treatment, many countries also pursue a policy of culling chickens once they discover an H5N1 outbreak among poultry. Since 2003 over 100 million chickens have been culled worldwide [20].[2]

An important question is whether culling actually reduces the risk from bird flu. It has been suggested [9] that culling can have detrimental evolutionary consequences, reducing the resistance of chickens to flu and increasing the virulence of bird flu strains. But before the government can cull any chickens, it has to obtain those chickens. That procurement policy may have separate consequences for the spread of flu. In some locales, such as Jakarta [1], Indonesia, the government can expect compliance with laws requiring surrender of chickens or has the enforcement resources to simply seize chickens for culling. In other places, including the rest of Southeast Asia, the government cannot expect compliance or

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[1] As of November 12, 2007.

[2] Some countries such as China, Vietnam and Indonesia have also pursued a policy of vaccinating chickens [13, 2, 7]. That policy is much less common than culling [19, p. iii]. We shall explore it, however, in a future version of this paper.

has limited resources. There the World Bank and the Food and Agriculture Organization [19] recommend that governments compensate farmers for surrendering chickens. This paper examines the merits of different methods of procuring chickens for culling – focusing on purchasing or seizing chickens – and demonstrates that the government's procurement policy has its own, sometimes counterproductive, consequences for the spread of bird flu.

A purely economic analysis suggests that the choice between buying and simply seizing chickens should depend on the prevailing market price of chickens and the cost of enforcing a ban. The relatively higher is the price of chickens, the more likely one is to prefer seizure to purchase of chickens. The choice is, however, more complicated. Government policy may alter the market price and supply of chickens. More importantly, it may also trigger changes in the ecology of flu among chickens and thus humans. This paper takes an interdisciplinary approach to the problem. It combines models of the ecology of flu in chickens and humans with a model of trade in chickens to compare socially-relevant equilibrium outcomes — namely the number of living, infected chickens and thus humans — under each policy.

This approach yields three interesting conclusions. First, purchasing chickens generates an economic incentive for farmers to increase their chicken populations by raising birth rates and practicing infection control on their farms. Better infection control decreases the per capita probability that a healthy chicken becomes sick but this beneficial effect is can be offset by higher birth rates, which increase the population of sick chickens and consequently the risk of human infection. Second, banning chickens has the economic effect of encouraging farmers to export their chickens to neighboring regions. This has the side effect of spreading infection. (It has been alleged that this is an important source of flu among chickens in Africa [5].) Thus an important complement to a ban on chickens is a quarantine across regions if feasible. Third, a policy of importing healthy chickens may increase the average quality of chickens and thus the price of chickens. This would have the perverse economic effect of encouraging farmers to increase the population of chickens, including sick chickens.

The analysis herein makes two critical but reasonable assumptions. First, farmers, consumers and the government have an imperfect ability to detect sick chickens. Specifically, detection is subject to false negatives – some sick chickens are incorrectly thought to be healthy – but that all participants have a common and correct estimate of the rate of false negatives. This assumption, which may be described as symmetric partially incomplete information, is reasonable given that both formal and informal methods of diagnosing H5N1 in chickens have imperfect sensitivity and that influenza is a stable, asymptomatic infection in many birds [18, 11].[3] The assumption explains why the government culls even ostensibly

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[3] The argument against treating avian flu in chickens as a problem of fully incomplete information is that flu strains which are highly pathogenic – also known as HPAI strains – cause symptomatic and thus more observable infection in chickens, and strains that are more highly pathogenic to chickens are also thought to be more highly pathogenic in general ([11], but see the discussion in [10]). This is because all the HPAI

healthy chickens and implies that the price of ostensibly healthy chickens will depend on the average quality of these chickens. It is this last feature that complicates government procurement policy. The second assumption is that consumers value ostensibly sick chickens at zero price. This assumption implies that the government can easily procure all ostensibly sick chickens for culling, and allows the analysis to focus on the procurement of ostensibly healthy chickens for culling.

Part 1 presents a model of the ecology of flu in chickens. Part 2 describes the information structure that constrains trade in chickens. Part 3 presents a model of the supply of chickens. Part 4 describes the demand for chickens and the implied market equilibrium. Part 5 examines the government's optimal policy for procuring chickens for culling. Part 6 considers the effect of export markets, storage technology, and chicken imports. Part 7 concludes.

1 Ecology of bird flu among chickens

Let x_h be the number of non-infected chickens ("healthy" chickens) and x_s be the number of chickens infected with bird flu ("sick" chickens). The dynamics of bird flu among chickens on an individual chicken farm can be described with the standard set of epidemiological equations [3]:

$$\begin{aligned} \dot{x}_h &= b - z\beta x_h x_s - \sigma x_h &(1)\\ \dot{x}_s &= z\beta x_h x_s - v x_s - \sigma x_s &(2) \end{aligned}$$

where dots represent time derivatives, b is the rate the birth rate of chickens, v is the disease-induced death rate (or virulence), z is the contact parameter among chickens (which can be controlled with infection control measures by individual farmers), and β is the transmissibility of flu among chickens via the oral-faecal route, and σ is the rate at which chickens are taken to market for sale. It is assumed that the birth rate is independent of the chicken population because the farmer controls the former through his disposal of fertilized eggs. Natural death rates can be ignored because chickens are raised solely for human consumption. Indeed, (1) and (2) are best viewed as describing the dynamics of healthy and sick chickens intended for human consumption.

The system above has a stable endemic equilibrium where

$$\hat{x}_h = \frac{v+\sigma}{\beta z} \text{ and } \hat{x}_s = \frac{b}{v+\sigma} - \frac{\sigma}{\beta z} \tag{3}$$

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strains have a sequence of basic amino acid residues at the HA cleavage site; this aa-sequence confers higher replication levels and more pathogenicity in humans, birds, possibly mice [**cite Hata**], and probably most animals that are capable of being infected by flu.

This paper examines how the implementation of culling affects, among other things, the practice of infection control (z) by farmers. For convenience, z is normalized to $[0, 1]$. Importantly, once z passes below the critical value $z_{crit} = \sigma (v + \sigma) / b\beta$, the the disease's basic reproduction ratio drops below one and it dies out. In that case, the stable equilibrium in (3) becomes

$$\hat{x}_h = \frac{b}{\sigma} \text{ and } \hat{x}_s = 0$$

Because there is no return to infection control below z_{crit}, farmers will not reduce z below this amount.

There are two relevant properties of this equilibrium. First, higher fertility does not affect the equilibrium population of healthy chickens. The absence of an effect is a result of higher birth rates increasing the number of new susceptibles per unit time which, in turn, increases the equilibrium number of sick chickens. A higher equilibrium number of sick chickens increases the per capita probability a healthy chicken will become infected, which exactly offsets the increased birth rate of healthy chickens. Second, increased virulence not only lowers the population of sick chickens, it increases the population of healthy chickens. Higher virulence decreases the number of sick chickens that can infect healthy chickens, thus increasing the numbers available for consumption.

2 Diagnostic technology and information

In order to model the farmer's behavior and the market in chickens, it is necessary to describe the ability of consumers and farmers to distinguish healthy from sick chickens. If consumers cannot perfectly identify sick chickens, the price of ostensibly healthy chickens will depend on the prevalence of undetected sick chickens. If farmers cannot perfectly identify sick chickens, they will have only an imperfect ability and thus incentive to control the population of sick chickens.

Consumers, farmers and the government are all assumed to have access to a common technology for diagnosing avian flu in chickens. This technology has sensitivity θ_s and specificity θ_h, and the values of (θ_s, θ_h) are common knowledge. In other words, the probability of a false negative, that is, a sick chicken being mistaken for a healthy chicken, is known to be $1 - \theta_s$, and the probability of a false positive, that is, a healthy chicken being mistaken for a sick chicken, is known to be $1 - \theta_h$. This implies that the number of ostensibly healthy and ostensibly sick chickens in a flock are $w_h = \theta_h x_h + (1 - \theta_s) x_s$ and $w_s = (1 - \theta_h) x_h + \theta_s x_s$, where (x_h, x_s) are actually healthy and sick chickens, respectively.

In order to focus the analysis on the factors most important to determining optimal procurement policy, two simplifying assumptions are made. First, there are no false positives diagnoses of flu in chickens.[4] This implies $\theta_h = 1$ and that ostensibly sick chickens are all

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[4] Healthy looking chickens have tested positive for strains of H5N1, but not for highly pathogenic versions

actually sick. It also implies that

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\begin{aligned}
w_h &= x_h + (1 - \theta_s)\, x_s && (4) \\
w_s &= \theta_s x_s && (5)
\end{aligned}
$$

Second, consumers value actually sick chickens and thus ostensibly sick chickens at zero price. This implies that the government can costlessly seize and cull all ostensibly sick chickens.

3 A farmer's incentives

The typical chicken farm in the developing world is run by a small, price-taking farmer [16, 15, 17]. Let $p(\sigma)$ be the market price of ostensibly healthy chickens intended for human consumption,[5] $r(b)$ the cost of raising b chickens,[6] and $-c(z)$ be the cost of infection control. The price of chickens depends on the size of chickens, which is a direct function of their age and thus the rate at which they are taken to market. As is usual, it is assumed that costs are increasing and convex: $r' > 0$, $r'' > 0$, $c' < 0$, and $c'' > 0$. Because ostensibly sick chickens yield no revenue, the farmer only supplies ostensibly healthy chickens to the market. The farmer's profit during any interval T is given by

$$\int_0^T \left[p(\sigma)\,\sigma w_h - r(b) - c(z)\right] dt$$

where w_h is given by (4) and x_h and x_s are given by the ecological model in (1) and (2). The farmer maximizes this quantity over his choice of (b, z, σ) subject to the ecological model.[7]

The farmers problem may be simplified in two ways. First, it can reasonably be assumed that farmers will always wait until chickens are fully grown before sending them to market. This is demonstrated in the appendix which shows that the farmer's profit is a decreasing function of σ for a plausible piecewise linear version of the price function for biomass and for levels of virulence that might trigger a culling. Second, although the farmer faces a

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of that strain [21, 23].

[5] Chickens may be sold live in "wet" markets or slaughtered. Different parties in the two markets slaughter the chickens and slaughtering poses a risk of chicken-to-human contagion. This and other distinctions between the two markets are ignored here. This is justified if price adjusts for the cost and risks of slaughtering. In developing countries, most chickens are sold in wet markets because of the scarcity of refrigeration systems to preserve chicken meat.

[6] One could substitute a market for fertilized chicken eggs for $r(b)$. So long as the supply of eggs is upward sloping, this would not change this paper's analysis of the effect of government chicken procurement on the farmer's choice of fertility level. Even if supply is fixed, so long as heterogeneity in chicken farmer costs traces out a positive aggregate demand curve for eggs, the analysis would be unchanged.

[7] [Consider what happens if farmers care about health risk to themselves.]

dynamic optimization problem, the steady state of his solution coincides with the solution to the simpler problem of maximizing

$$\left[p\sigma w_h\left(b,z\right)-r\left(b\right)-c\left(z\right)\right]T \tag{6}$$

with respect to (b, z) subject to the steady state (3) of the ecological model.

The first-order condition for b is

$$r'(b)=\frac{p\sigma\left(1-\theta_s\right)}{v+\sigma}, \tag{7}$$

and the convexity of $r\left(b\right)$ ensures this is an internal maximum. A higher rate $\left(1-\theta_s\right)$ of false negatives increases the birth rate because the birth rate increases the population of sick chickens and greater false negatives increase the fraction of sick chickens that can be sold. Critical to this result is that the farmer is a price taker so that his selling more sick chickens to the market does not lower the price of chickens. The first-order condition for z is

$$-c'\left(z\right)=\frac{p\sigma\left[v+\theta_s\sigma\right]}{z^2\beta}, \tag{8}$$

If the second-order condition $c''(z) > 2p\sigma\left[v+\theta_s\sigma\right]/z^3\beta$ is satisfied, there will be an interior solution in $[z_{crit}, 1]$. If the cost of infection control is not that convex, so that the costs of infection control are small, then the farmer will practice maximum infection control. Because the population of sick chickens declines below $z_{crit} > 0$, there is no return to lowering z beyond this point and z_{crit} is the maximum infection control observed. Where there is an internal maximum, however, more sensitive diagnostic tests increase infection control because they the number of marketable and thus the return from sick chickens.

Consider the effect of price shocks on the price-taking farmer's choice of fertility and infection control. Differentiating the farmer's optimality conditions with respect to price reveals

$$\frac{\partial b}{\partial p} = \frac{1}{r''\left(b\right)}\cdot\frac{\sigma\left(1-\theta_s\right)}{v+\sigma} > 0 \tag{9}$$

$$\frac{\partial z}{\partial p} = \frac{\sigma z\left[v+\sigma\theta_s\right]}{2p\sigma\left[v+\sigma\theta_s\right]-z^3\beta c''\left(z\right)} \leq 0 \tag{10}$$

Note that $\partial z/\partial p = 0$ if the second order condition for an interior z^* is not met. Although lower p raises the odds that the second-order condition is met, the result is still that higher prices induce more infection control. Intuitively, if the price of chickens rises, the farmer will want to supply more chickens. One way to do this is to increase birth rates. Another is to reduce the number of sick chickens in his flock. The net effect on the number of healthy chickens and the supply of ostensibly healthy chickens is positive

$$\frac{\partial x_h}{\partial p} = -\frac{v+\sigma}{z^2\beta}\frac{\partial z}{\partial p} \geq 0 \qquad \frac{\partial \hat{w}_h}{\partial p} = -\left[\frac{v+\sigma\theta}{z^2\beta}\right]\frac{\partial z}{\partial p} + \left[\frac{1-\theta}{v+s}\right]\frac{\partial b}{\partial p} > 0 \tag{11}$$

The effect on the number of sick chickens, however, is ambiguous

$$\frac{\partial \hat{x}_s}{\partial p} = \left[\frac{1}{v+\sigma}\right]\frac{\partial b}{\partial p} + \left[\frac{\sigma}{z^2\beta}\right]\frac{\partial z}{\partial p} \tag{12}$$

unless the farmer is at a corner solution, in which case higher prices increase the number of sick chickens.

Define the quality of a farmer's supply of chickens to be the fraction of his ostensibly healthy – and thus marketable – flock that is actually healthy:

$$\hat{q} = \frac{\hat{x}_h}{\hat{w}_h} \tag{13}$$

Although higher prices increase infection control and thus the population of healthy chickens, their effect on quality is ambiguous, because they also encourage farmers to increase birth rates, which may raise the number of sick chickens:

$$\frac{\partial \hat{q}}{\partial p} = -\hat{q}^2\frac{z\beta\left(1-\theta_s\right)b}{\left(v+\sigma\right)^2}\left[\frac{1}{z}\frac{\partial z}{\partial p} + \frac{1}{b}\frac{\partial b}{\partial p}\right] \tag{14}$$

It is evident that $\varepsilon_q \propto -\left(\varepsilon_z + \varepsilon_b\right)$, where ε indicates elasticity with respect to price. This suggests that a higher price lowers the quality of a farmer's flock if the price elasticity of birth rates is greater than that of contact rates. These elasticities will in turn depend on the convexity of the cost functions r and c.

4 Competitive market equilibrium

To fully pin down the farmer's behavior, it is necessary to model market prices. For simplicity, it is assumed that the chicken market is supplied by N identical, price-taking farmers. Because there are known rates of false negatives in the diagnosis of flu in chickens, aggregate demand is a function of both the average quality of farmers' marketable chickens and price: $D\left(\hat{q}, p\right)$ where $\hat{q}$ is given by (13), $D_q > 0$ and $D_p < 0$. The equilibrium price is that which clears the market

$$N\hat{w}_h = D\left(\hat{q}, p\right)$$

that is, which equates aggregate supply and demand. Importantly, for the market to be in a stable equilibrium, demand must be falling in price after accounting for farmer behavior, specifically (14). This implies $N(\hat{w}_h)_p - D_q\hat{q}_p - D_p > 0$ where the subscript p indicates the derivative with respect to p.

Although the analysis below focuses on price-taking farmers, it is instructive to compare the behavior of the price-taking farmer with that of a monopolist farmer. Because the monopolist farmer can influence price, his problem is

$$\max_{b,z} p\left(\hat{q}\left(b,z\right)\right)\sigma\hat{w}_h\left(b,z\right) - r\left(b\right) - c\left(z\right)$$

The monopolist would set birth rate and infection control such that

$$\begin{aligned} r'\left(b^m\right) &= \frac{p\sigma\left(1-\theta_s\right)}{v+\sigma} + p_q q_b \sigma w_h < r'\left(b^c\right) \\ -c'\left(z^m\right) &= \frac{p\sigma\left[v+\theta_s\sigma\right]}{z^2\beta} - p_q q_b \sigma w_h > -c'\left(z^c\right) \end{aligned}$$

where superscripts m and c indicate the optimal choices of the monopolist and the price taker. Because costs are convex, these equations imply that the monopolist would maintain a smaller flock and practice more infection control than the price-taking farmer. The reason is that a higher birth rate increases only the number of sick chickens and thus lowers quality and price. Moreover, higher contact rates clearly reduce quality and price. Unlike the price-taker, the monopolist internalizes these costs. This constitutes an argument for corporate farms that differs from the standard claim that such farms by their production process reduce contact rates *between chickens and humans.* The model in this paper predicts that corporate farms would also reduce the extent of sickness *among chickens.* Because the average developing world chicken farmer is a price taker, however, the remainder of the paper focuses on the competitive case.

5 The government's problem

5.1 Justifying the government's objective

Although governments care directly about humans and not chickens, sick chickens may infect humans. To arrive at the government's objective function, it is reasonable to model the relationship between flu in chickens and flu in humans with the standard epidemiological equations:

$$\begin{aligned} \dot{Y}_h &= dY_h - \gamma w X_s Y_h - \mu Y_h & (15) \\ \dot{Y}_s &= \gamma w X_s Y_h - \left(\mu+\rho\right) Y_s & (16) \end{aligned}$$

where (Y_h, Y_s) are the total population of healthy humans and humans infected with bird flu, respectively; X_s is the aggregate population of sick chickens across all farms; d is the birth rate of humans; γ is the transmissibility from chickens to humans; w is the contact rate between chickens and humans; μ is the natural death rate of humans; and ρ is the incremental mortality rate among humans infected with bird flu.

Given that roughly 60 percent of human H5N1 infections result in mortality within weeks [22], ρ is presumably very very large. If one supposes that the government's goal is to maintain the existing population growth rate and that the government cannot alter fertility or non-flu mortality rates in the short-run, and until the government can find an antiviral or vaccine to lower γ, the government's problem reduces to minimizing wx_s. A policy of culling sick chickens, by reducing contact rates and the supply of sick chickens, furthers this end. Since culling is equivalent to reducing the number of non-culled chickens, it is reasonable to formulate the government's narrow objective as minimizing the number of chickens that it fails to cull, $X_s - X_{sg}$, where X_s is the total population of sick chickens and X_{sg} is number of sick chickens the government culls.

5.2 Constraints on the government

The problem is that many governments cannot simply mandate that farmers surrender their chickens for culling. Instead, the government must pursue incentive compatible policies to procure chickens. This section explores two such policies: (1) buying chickens and (2) seizing chickens. The latter is equivalent to a ban on chicken sales which lowers the price at which the government can purchase chickens.[8] One can compare these two policies by writing the government's loss function as

$$L = \varphi\left(X_s - X_{sg}\right) + k\left(f\right) + gW_{hg} \tag{17}$$

where φ is the monetary-equivalent value of the health risk from non-culled chickens, f is the sanction on chicken sales, k is the cost of administering that sanction, g is the price at which the government offers to purchase ostensibly healthy chickens from farmers, and W_{hg} is the number of ostensibly healthy chickens that the government purchases from farmers. It is assumed that $k' > 0$.[9]

Because consumers are assumed unwilling to purchase chickens diagnosed with bird flu, ostensibly sick chickens $\theta_s X_s$ have zero price and can be costlessly purchased by the

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[8] We shall assume the sanction on chicken sales is paid by the consumer rather than the farmer, though it shall make little difference to the analysis. A sanction on farmers would be implemented by changing the farmer's return from chicken sales to $p - s$ and removing the sanction from market demand, i.e., $\partial D / \partial s = 0$.

[9] If the government can enforce a tax on chicken sales, then it can raise revenues via a ban on sales. The cost of the sanction would be $-t\left(X_s - X_{gs}\right) + k\left(t\right)$. This would have the effect of lowering the cost of a ban. However, if the government also cares about raising revenue, a tax may have the perverse effect of lowering the incentive of the government to procure chickens. For simplicity we assume a non-tax sanction on chickens.

government. The question that remains is how many ostensibly healthy chickens W_{hg} to purchase. The reason to purchase and cull these chickens is that some may actually be sick. The government's yield on ostensibly healthy chickens is $(1-q)\,W_{hg}$. Therefore, one can write

$$X_s - X_{sg} = (1-\theta_s)\,X_s - (1-q)\,W_{hg}$$

and the government's problem is to minimize loss (17) by its choice of (f, g, W_{hg}).

The government's policy is subject to a number of constraints. The most important is the farmer's response to the government's offer to buy chickens. The farmer's best-response constraint may be written

$$\max_{\delta,b,z}\,[(1-\delta)\,p + \delta g]\,\sigma w_h\,(b,z) - r\,(b) - c\,(z) \tag{18}$$

This is identical to the profit function (6) except that the farmer has to decide the fraction δ of his flock to sell to the government at price g. Since the government can only purchase chickens that the farmer sells, government purchases are constrained by

$$W_{hg} = \delta N w_h \tag{19}$$

The left-hand side is the government's demand for chickens, and the right-hand side is farmers' supply to the government. Moreover, the government's offer is indirectly constrained by the market clearing condition

$$N w_h = D\,(q, f, W_{hg}, p) \tag{20}$$

where $D_f < 0$ and $D_{W_{hg}} > 0$. Finally, both the government and the farmer are constrained by the steady state of the ecological model in (1) and (2).

The government's problem can be simplified in three steps. First, one can derive the optimality conditions for the farmer's response (in the ecological steady state) and substitute them for (18). In particular, the optimality conditions for sales δ to the government is $g - p = 0$. This implies that the government cannot procure any chickens unless it matches the market price for chickens. (Offering any higher price is a waste of money.) When the government complies and offers $g = p$, the farmer will be indifferent between selling to the government and to private consumers. Therefore, the government can choose δ for the farmer, the optimality conditions for b and z simplify to their original form in (7) and (8), and the market clearing condition can be written

$$N w_h = D\,(q, f, \delta, p) \tag{21}$$

Plugging in the voluntary sales constraint (19) in the government's loss function allows the government's problem to be restated more concisely as

$$\min_{\delta,f} \varphi\left[(1-\theta_s)\, Nx_s - \{1-q\,(b,z)\}\,\delta N w_h\,(b,z)\right] + k\,(f) + p\delta N w_h\,(b,z) \tag{22}$$

subject to the farmer's optimality conditions (7) and (8), the market clearing condition (21), and the steady state of the ecological model in (1) and (2).

Second, one can substitute the steady values for (x_s, w_h, q) and simplify equation (22) to be

$$\min_{\delta,f} \varphi\left[(1-\theta_s)\,(1-\delta)\, N\hat{x}_s\,(b,z)\right] + k\,(f) + p\delta N\hat{w}_h\,(b,z) \tag{23}$$

This equation says that the loss is the sum of (1) the number of sick chickens among the fraction of ostensibly healthy chickens that the government fails to procure and (2) the cost of seizing or purchasing those chickens.

Third, one can reformulate all key parameters of (23) except the control variables as functions of price. The relationship between price and $(\hat{x}_s, \hat{w}_h)$ are given in (12) and (11). Moreover, totally differentiating the market clearing constraint (21) with respect to price yields

$$\frac{\partial p}{\partial \delta} = \frac{D_\delta}{N(\hat{w}_h)_p - D_q\hat{q}_p - D_p} > 0, \quad \frac{\partial p}{\partial f} = \frac{D_f}{N(\hat{w}_h)_p - D_q\hat{q}_p - D_p} < 0 \tag{24}$$

due to the stability of the market equilibrium. The government's problem then simplifies to

$$\min_{\delta,f} \varphi\left[(1-\theta_s)\,(1-\delta)\, N\hat{x}_s\,(p)\right] + k\,(f) + p\delta N\hat{w}_h\,(p) \tag{25}$$

subject to (12), (11) and (24). It become immediately apparent from this equation that greater sensitivity of diagnostic tests reduces the governments loss by lowering the number of ostensibly healthy but actually sick chickens.

5.3 Optimality conditions

Government purchases and sanctions have direct effects on loss as well as indirect effects on loss through price. To understand the price effect, observe that an increase in price has three effects on the government's loss:

$$\frac{\partial L}{\partial p} = \varphi\,(1-\theta_s)\,(1-\delta)\, N\frac{\partial \hat{x}_s}{\partial p} + \delta N\hat{w}_h + p\delta N\frac{\partial \hat{w}_h}{\partial p} \tag{26}$$

First, it may increase or decrease the number of sick chickens that farmers produce. Second, it raises the amount the government pays for the fraction of ostensibly healthy chickens the government buys. Second, it raises the number of ostensibly healthy chickens farmers produce and the government buys holding constant the fraction δ the government buys.

The net effect is ambiguous: it could be negative if higher prices induce a large increase in infection control and thus decrease in the number of sick chickens.

Assuming the government's problem has an interior solution, the government should choose the fraction of chickens to purchase so that marginal benefit equals marginal cost:

$$\varphi \left(1-\theta_s\right) N \hat{x}_s = pN\hat{w}_h + \frac{\partial L}{\partial p}\frac{\partial p}{\partial \delta} \tag{27}$$

The direct benefit (on the left-hand side) of purchasing chickens is to reduce the number of sick chickens the government fails to purchase. The direct cost (on the right-hand side) of government purchases is simply the payment for chickens. The indirect effect through price depends on whether losses rise or fall in prices. If higher prices reduce the number of sick chickens, the indirect price effect is a marginal benefit that suggest the government should by a higher fraction of ostensibly healthy chickens. However, it can be verified that increasing this fraction causes the indirect price effect to become positive, and thus a marginal cost. This in turn discourages further purchases. Thus it is likely that at an internal optimum the marginal effect of price is to increase losses. The subsequent analysis assumes this is so.

The government should choose its sanction so that

$$-\frac{\partial L}{\partial p}\frac{\partial p}{\partial f} = k'\left(f\right) \tag{28}$$

The benefit of sanctions is that they reduce the price of chickens and the cost is simply that of implementation.

There are two further things to note about the government's optimal choices. First, because of the economic costs of procurement, the government may not want to purchase all chickens despite the ecological risks from these chickens. Though in other contexts an ecological argument such as herd immunity may be advanced to support this claim, it is inapt here because the specific ecology of flu in humans is such that the risk to humans is linear in the number of non-culled sick chickens.[10] Second, sanctions and purchases are complementary. Fines lower the price the government must pay and thus the cost of purchases. Unless the costs of sanctions are unbelievably prohibitive, it is tempting to conclude that a government should always couple a compensation program for farmers with at least a partial ban on private sales. The next section, however, considers extensions to the model that challenge these conclusions.

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[10] To be clear, there is no dispute that herd immunity may be possible among chickens in model described by (1) and (2). We are noting that the infection of humans described by (15) and (16) does not permit herd immunity as the infection is from chickens, not infected humans.

6 Extensions

6.1 Export markets and storage

The government's problem becomes more challenging when a farmer can either export chickens to other provinces or store chickens until a government ban on private sales expires. Because these two problems are mathematically similar, this section will first model export markets and then extrapolate to storage.

Suppose a farmer has access to an export market. Let superscript F designate foreign market variables and τ be the cost of transporting a chicken to the foreign market. The domestic farmer's problem (in ecological steady state) becomes

$$\max_{\alpha} \left[(1-\alpha) p + \alpha p^F \right] \hat{w}_h (b, z) - r (b) - c (z)$$

where α is the fraction of his flock a farmer exports. Although the individual farmer's optimality condition suggests he will either export all his flock (if $p^F - \tau > p$) or none of it, the market clearing conditions for the domestic and foreign markets

$$\begin{aligned} N (1-\alpha) \hat{w}_h &= D (\hat{q}, f, \delta, p) &(29)\\ N\alpha\hat{w}_h + N^F \hat{w}_h^F &= D^F \left(\hat{q}^F, p^F\right) &(30)\end{aligned}$$

will ensure that $p \geq p^F - \tau$ in equilibrium, though possibly after some chickens have been exported. (For simplicity, imports have been ignored in the market clearing conditions.) Exports will equilibrate markets both by reducing foreign price and increasing domestic price.

If the government cares about human infection in the export market, that market will complicate the government's problem by replacing the single market clearing condition (20) with dual conditions (29) and (30) or by adding the no-exports constraint

$$p > p^F - \tau \tag{31}$$

Let $\lambda \geq 0$ be the multiplier on this last constraint. Then the optimality condition (28) for sanctions becomes

$$-\frac{\partial L}{\partial p}\frac{\partial p}{\partial f} = \frac{k' (f)}{N} + \lambda$$

Thus the no-exports constraint increases the marginal costs of sanctions. Intuitively, domestic sanctions lower domestic price. If they lower prices such that $p < p^F - \tau$, farmers will export their chickens – sick and healthy – to other provinces, which spreads the infection.

There are three additional things to note about exports. First, although the risk of exports is perhaps intuitive to economists, it highlights for ecologists an important risk from trade. Not only does trade provide a physical pathway for the spread of disease, but the economic pressures that generate trade tend to spread disease. To see this more clearly, note that an increase in the initial quality of chickens in foreign markets increases p^F and that the higher is p^F the more constraining is (31). This implies that farmers with relatively sicker chickens seek out markets with relatively healthier chickens when it is not possible for consumers to distinguish sick from healthy chickens. Second, a natural solution to exports is a quarantine, enforced either as a ban on exports by the domestic market or a ban on imports by the foreign market. Or, if imports cannot be distinguished from exports (perhaps due to domestic farmers' ability to mask their exports), a solution is sanctions on all private chicken sales in the foreign market. Of course a quarantine or additional ban requires additional enforcement, which will again increase the costs of sanctions. Third, offering a higher price for domestic chickens is a form of economic quarantine. This is evident from the optimality condition (27) for δ, which becomes

$$\varphi\left(1-\theta_s\right) N\hat{x}_s + \lambda = pN\hat{w}_h + \frac{\partial L}{\partial p}\frac{\partial p}{\partial \delta}$$

with the no-exports constraint. Offering a higher price for chickens reduces λ, a proxy for the incentive of domestic farmers to export their chickens.

Finally, our analysis of exports can be extended to storage. In the farmer's problem (6), storage is equivalent to reducing σ so that chickens are sent to market well after they are fully grown or attain maximum biomass. If culling is a temporary policy, storage operates like an export market except that the target is a future domestic market. (The cost of transportation τ can be re-interpreted as the cost of delaying sale of a fully grown chicken, which includes the cost of feeding the chicken and of deferring revenue form the chicken.) Like the export market, storage is a method of evading current domestic sanctions. The social cost is that sick chickens contaminate future flocks. The implication for the government's optimization problem is that current domestic price is constrained to be less that the discounted future price minus the cost of storage, i.e., $p\left(t\right) < e^{-rj}p\left(t+j\right) - \tau$. The way to relax this constraint is to extend the duration of sanctions, the analogue to extending the geographic scope of sanctions in the case of exports.

6.2 Chicken imports and exchanges

In a seminal paper on the management of elephant populations when poachers can store tusks, Kremer and Morcom [12] recommend that governments stock up on tusks and threaten to dump them if tusk prices rise to a level that makes poaching profitable. The idea is that the government's supply will drive down prices and make both poaching and the storage of tusks unprofitable again.[11] The analogous proposal for the chickens problem is that the government purchase foreign chickens and dump them in the domestic market.

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[11] A similar idea is found in [4, pp. 173-175] and [6, pp. 34-35].

If dumping drove down chicken prices, it would lower the government's cost of purchasing chickens. There is an important complication. Because of imperfect diagnostic technology, price depends on the average quality of chickens. If the government purchases and dumps healthy foreign chickens, it may raise the domestic price of chickens because the foreign chickens will increase the average quality of chickens in the local market.[12]

This dynamic is captured in the formal model by modifying the government's objective in (25) to be

$$\max_{\delta,f,g} \varphi\left(1-\theta_s\right)\left(1-\delta\right)N\hat{x}_s\left(p\right)+k\left(f\right)+p\delta N\hat{w}_h\left(p\right)+p^F X_{gh}^F$$

where p^F is the market price in the foreign market in which the government buys chickens, X_{gh}^F is the number of ostensibly healthy chickens the government buys in that market. With no loss in insight, it is assumed that the government does not sell the healthy chickens but simply gives them away, and exports are ignored. The new domestic market clearing condition is $N\hat{w}_h+\hat{W}_h^F=D\left(\hat{q},f,\delta,p\right)$, where quality is now

$$\hat{q}=\frac{N\hat{x}_h+\hat{X}_h^F}{N\hat{w}_h+\hat{W}_h^F}$$

$\hat{W}_h^F$ is the number of ostensibly healthy chickens imported from the foreign market, and $\hat{X}_h^F$ is the number of healthy chickens among the imported chickens. Totally differentiating the market clearing condition with respect to price yields

$$\frac{\partial p}{\partial \hat{X}_{gh}^F}=\frac{D_q\left(\partial\hat{q}/\partial X_{gh}^F\right)-1}{N(\hat{w}_h)_p+(\hat{W}_h^F)_p-D_q\hat{q}_p-D_p}$$

Downward sloping demand implies the denominator is negative. Therefore the effect of the government's imports on price depends on which is greater: the positive effect on quality (the first term in the numerator) or the negative effect from additional supply (the second term in the numerator). Although at some point government imports will reduce price, it is possible that over a large range they only raise price. In that case, optimal government imports are zero as they have no benefit, only costs. This can be verified by examination of the optimality condition

$$-\frac{\partial L}{\partial p}\frac{\partial p}{\partial X_{gh}^F}=\hat{X}_{gh}^F\frac{\partial p^F}{\partial X_{gh}^F}+p^F$$

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[12] The government can avoid this problem if it can clearly label the imported chickens as healthy, keep those chickens healthy even after they are imported, and stop domestic farmers from masking their chickens as imported. All three are big "if's."

If imports lower the price of chickens, the left-hand side is the positive marginal benefit (driving down domestic price) of importing chickens and the right-hand side is the marginal financial costs importing chickens. If instead imports raise the quality and hence price of chickens the left-hand side becomes negative and there are no benefits to importing chickens.

There are three important notes to this observation. First, an alternative strategy that always lowers domestic price is importing sick chickens – or at least chickens as sick as the typical chicken in the domestic market.[13] The obvious and controlling risk of this policy, however, is that it increases the risk of human infection and, in any event, is politically unpalatable. Second, an alternative to merely dumping healthy foreign chickens is to exchange them with farmers for the farmers' lower quality domestic chickens. Although exchange will not reduce domestic quantity supply and thus price, it will replace sick chickens with healthy chickens. If farmers anticipate this policy, however, they will increase birthrates and reduce infection control before it is implemented because the policy portends an increase in price due to an increase in the quality of chickens. After all, the exchange is equivalent to "curing" each sick chicken and making it healthy. This increase in birth rates and reduction in infection control will increase the risk of human infection in the periods leading up to the policy.

Third, and most importantly, the price of foreign healthy chickens is likely to be greater than the price of lower quality domestic chickens. Unless the price elasticity of the competing foreign market supply is much less than the price elasticity of the domestic market supply, it will surely be less expensive to simply purchase more domestic chickens and reduce domestic sanctions.

7 Discussion

This paper attempts a systematic analysis of optimal procurement policy for a government seeking to cull chickens infected with bird flu. It accounts for the ecology of flu in chickens and the effect of government intervention on market supply and demand. It also examines the challenge posed by exports and the limited policy value of imports.

Nevertheless, the paper has more than a few notable omissions. First, it fails to account for differences between large and small chicken farmers. The cost of enforcing sanctions on large farmers may be smaller than those on small farmers. Moreover, larger farmers may be more likely to change their infection control activities in response to price. If that is the case, the government may want to adopt different procurement policies for, that is, price discriminate between, large and small farmers. Second, the model in this paper does not account for farmers' anticipation of government purchases. If, for example, the government did not simply purchase chickens but rather announced that it would purchase chickens

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[13] This is similar to Brown and Layton's (2001) proposal to dump lower quality but indistinguishable white rhino horns to drive down the price of black rhino horms.

when it discovered a flu outbreak among chickens, then farmers may have an incentive to practice lax infection control to trigger government purchases, which raise price. This contrasts with the finding in this draft that government purchases simply raise price and thus infection control. Third, an important policy that governments might employ to prevent outbreaks among chickens is vaccination of chickens. This will have important effects on the evolution of the virus and thus the probability that the vaccine will fail. It will also alter the supply of chickens, and thus the costs of an outbreak should vaccination fail. Finally, the paper examines the effect of interventions given steady state in the ecology and evolution of flu. If the time scale for economic dynamics is much shorter than the time scale for ecological and evolutionary dynamics, then it may be necessary to examine the non-steady state impacts of government policy. These and other complications will be addressed in future drafts.

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8 Appendix: maximizing over σ

The price-taking farmer's profit is

$$\pi(\sigma, b, z) \;=\; \left[\, p(\sigma) : \sigma \left(\frac{(1-\theta_s)b}{v+\sigma} + \frac{v+\theta_s\sigma}{\beta z} \right) - r(b) - c(z) \,\right] T : . \qquad (32)$$

The market price of a chicken depends on σ since the earlier chickens are sent to market, the smaller they are and the less money the farmer gets. The price function can be approximated with the following piecewise linear function:

$$p(\sigma) \;=\; \begin{cases} \frac{p_{\text{fg}}}{g}\left(\sigma^{-1} - d\right) & \text{for } d \leq \sigma^{-1} \leq g + d \\ p_{\text{fg}} & \text{for } \sigma^{-1} > g + d \\ 0 & \text{for } \sigma^{-1} < d. \end{cases}$$

where p_{fg} is the price of a fully-grown chicken, d is the number of days before a chick reaches a large enough size to be sold, and g is the number of days for a small chicken (just large enough to be sold) to grow into a fully mature chicken. This function states that chicks cannot be sold for positive net revenue until it reaches age d, then its value rises linearly due to increases in biomass until it is fully grown at age $d+g$, and then its value remains constant.

The first order condition for σ yields

$$-\left[d\left(v+\sigma\right) + \left(1 - d\sigma\right)\right] z\beta \left(1-\theta\right) b + \left[\theta\left(1 - d\sigma\right) - dv\right]\left(v+\sigma\right)^2$$

The second term is negative if either $\sigma^{-1} < 2d$ or $v^{-1} < d$. The former condition places a lower bound of $2d$ – twice the age of barely saleable chicks – on the age of marketed chickens. The latter condition is satisfied if bird flu is sufficiently virulent. A reasonable estimate for d is 40. This converts the condition to $v > 0.025$, which is a reasonable assumption for disease that is serious enough to be noticed by authorities and for consumers to be weary of buying sick chickens.