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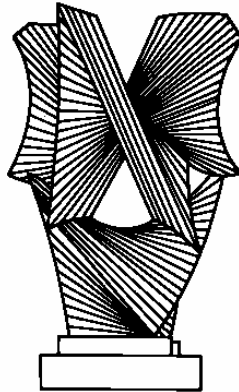
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Controlling Avian Influenza in Chickens

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Controlling Avian Influenza in Chickens

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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 [39]. Over 30 nations have experienced an outbreak of bird flu in their chicken populations and 285 humans[1] have been infected with H5N1. Although only 170 people have died from bird flu [40], 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 [26]. 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 [11, 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, however, many countries also pursue a policy of culling chickens once they discover an H5N1 outbreak among chickens. Indeed, since 2003 over 100 million chickens have been culled worldwide [38].[2]

In this paper we compare the relative merits of the basic policies that governments employ to procure chickens for culling. In many developing countries, due to weak institutions and limited social organization, the government cannot simply expect compliance with laws requiring farmers to surrender chickens for culling. The government must pursue policies that are narrowly incentive compatible to farmers. The most obvious of these policies to offer to purchase chickens ("buying chickens"). This is recommended by the World Bank and the Food and Agriculture Organization [37] and followed by numerous Southeast

[1]As of this writing.

[2]Some countries such as China, Vietnam and Indonesia have also pursued a policy of vaccinating chickens [25, 2, 10]. That policy is much less common than culling [37, p. iii]. We shall explore it, however, in a future version of this paper.

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Asian countries. A complementary policy is to ban private chicken production or sales and thereby lower the price at which the government can purchase chickens ("banning chick-

25 ens"). This is most notably practiced in Jakarta, Indonesia, the country with the highest number of human cases of H5N1 [1]. We also explore the procurement-related policies of dumping healthy imported chickens or exchanging healthy imported chickens for domestic chickens, though neither policy is currently practiced.

A cursory analysis reveals that the choice between simply buying chickens and banning

30 chickens to the price at which the government buys chickens depends on the prevailing market price of chickens and the cost of enforcing a ban. The problem, however, is more complex. Government policy may alter the market price and supply of chickens. It may also trigger changes in the ecology of flu among chickens and thus humans. Indeed, it can even alter the evolution of the influenza virus. Therefore, we take an interdisciplinary

35 approach to the problem. We employ a model of the ecology of flu in chickens and humans, a domestic and foreign market in chickens, and the evolution of influenza to compare socially-relevant equilibrium outcomes — namely the number of living, infected chickens and thus humans — under each policy.

This approach yields four interesting conclusions. First, purchasing chickens generates

40 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 completely offset by a greater absolute number of healthy chickens. Thus the net ecological effect is completely due to higher birth rates which increase the population of sick chickens

45 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 is an important source of flu among chickens in Africa [8].) Thus an important complement to a ban on chickens is a quarantine across regions if feasible. Third, a policy of importing healthy chickens may

50 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. Finally, any policy that alters infection control by farmers — whether it raises price and thus infection control or lowers price and thus infection control — will alter the evolution of the virus population. Depending on the ecology of flu in

55 chickens, mainly whether it is capable of coinfection or superinfection, greater infection control can lead to the evolution of greater or lower virulence. These effects change the relative merits of purchasing or banning chickens.

This paper has practical relevance beyond bird flu in chickens. For one thing, the problem of animal-to-human transmission of infection occurs in other contexts. Cows with

60 Bovine Spongiform Encephalopathy ("mad cow disease") cause Variant Creutzfeldt-Jakob disease in humans and cows spread tuberculosis to humans. The former threat triggered the mass culling of cattle in the UK in the 1990s [28] and the latter triggered mass slaughters

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in the first half of the 20th century [27]. In both cases governments resorted to some form of compensation to encourage farmers to cooperate with culling efforts [14, 4]. Moreover, the analysis of government procurement not just of animal stock but any product or service is – as our paper illustrates – complicated by the ability of the government to ban private market sales and thus lower the price it must pay. Often this strategy has important behavioral side effects [23]. In our case the result is a spread of infection to other regions.

This paper belongs in the literature on economic epidemiology [32] because it addresses the interaction between disease control and the economic behavior of humans. A formal distinction is that the host is an animal, but one that does not qualitatively alter the analysis because humans have an economic interest in the host. Nor is the introduction of incomplete information new, as previous papers have modeled incomplete information in the market for sexual partners [REF]. A minor distinction is that, whereas those papers examine demand for information on disease status, we examine the impact of incomplete information on government policy. A more important contribution of this paper is that it incorporates the interaction between disease control and evolution of disease. This paper also belongs to the economic literature on renewable resource management – specifically fisheries management. Like Kremer and Morcom [21] and Brown and Leyton [9, pp. 34-35], we account for storage and its qualitative equivalent, exports. Here incomplete information is important because government dumping of the natural resource may not discourage exploitation since it increases the average quality and thus price of those resources.

Finally our paper relates to the evolutionary biology literature on niche construction [30, 31], which is the process by which a species alters its environment and thus affects the selection pressures exerted by that environment on either its own or another species' evolution. Pathogens, as it turns out, are classic niche constructors; they can alter host behavior [6], construct immunity [7], and enhance host susceptibility [15], to give just a few examples. In the analysis presented here, we study how government intervention can alter the evolution of avian influenza in chickens. The resulting evolved population of avian influenza viruses will most likely feed back into our preferences for infection control and thus procurement strategies.

We shall begin our analysis with the assumption that neither farmers, consumers nor the government can practicably distinguish chickens infected with H5N1 from non-infected chickens. (As is common in the economics literature, however, we shall assume all three know the proportion of all chickens in a market that are infected with H5N1.) This assumption, which defines what we call the "symmetric fully incomplete information" case, makes it difficult to identify and procure only sick chickens. This introduces average quality into the demand for chickens in a way that complicates procurement. Specifically, government purchases of chickens increases farmers' quantity supply but in a manner that alters the average quality of that supply, which has a distinct feedback effect on price. Moreover, government imports of healthy chickens increases the average quality and thus price in domestic chickens markets. We believe the assumption of fully incomplete information

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is justified for two reasons. First, influenza is a stable, asymptomatic infection in birds [36, 19]. Indeed, healthy looking chickens have tested positive for strains of H5N1 that are less virulent to chickens [39, 41]. Moreover, asymptomatic flu is a health threat because it has more access to humans [39, 41] and more time to mutate to survive and spread among humans. 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 ([19], but see the discussion in [18]).[3] Because identification of HPAI infections in chickens is less than perfect, we shall explore as an extension a model with "symmetric partially incomplete information." That case, it will be shown, has dynamics very similar to the fully incomplete information case.

Part 1 presents a model of the ecology of flu in chickens. Part 2 presents the profit maximization problem for chicken farmers and identifies optimal behavior by farmers given steady state infection rates among chickens. Part 3 justify the government's objective function based on a model of the ecology of flu in humans. It also compares the two basic policies – buying chickens or banning chicken sales – for procuring chickens. Part 4 introduces export markets and storage, chicken imports, disease evolution, and partially incomplete information to the analysis. Part 5 discusses our findings.

1 Ecology of flu among chickens

Let x_h be the number of non-infected chickens and x_s be the number of chickens infected with bird flu. We shall call the former healthy chickens and the latter sick chickens. On an individual chicken farm we can describe the dynamics of healthy and sick chickens with the standard set of dynamical equations [3]:

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

where the dots represent time derivative, b is the birth rate of chickens, v is 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 influenza in chickens via the oral-faecal route. We assume that birth rate is independent of the chicken population because the farmer controls birth rate through his disposal of fertilized eggs. We ignore natural death rates because in our model all chickens are raised

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[3]This is because all the HPAI 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 [REF], and probably most animals that are capable of being infected by flu.

for human consumption. Indeed, (1) and (2) are best viewed as describing the dynamics of healthy and sick chickens intended for human consumption.

The above system has a stable endemic equilibrium where

$$\hat{x}_h = v/\beta z \ \text{ and } \ \hat{x}_s = b/v \tag{3}$$

so the equilibrium number of total chickens is

$$\hat{x} = \frac{b\beta z + v^2}{\beta z v} \tag{4}$$

Let

$$\hat{q} = \frac{\hat{x}_h}{\hat{x}} = \frac{v^2}{b\beta z + v^2} \tag{5}$$

be the fraction of a farmer's chickens that are healthy. Going forward, we shall refer to this as the quality of chickens. (We shall also continue the practice of labeling ecological steady state values with hats.)

There are three 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, better infection control, which corresponds to lower contact rates, increases the population of healthy chickens, not sick chickens. Lower contact rates are exactly offset by an increase the number (and thus availability) of healthy chickens that sick chickens can infect. Nevertheless, and as expected, infection control does increase the total population of chickens for consumption, $\partial\hat{x}/\partial z = -v/\beta z^2 < 0$. (Note that, because they affect the flow equations identically, transmissibility and contact rates have the same effect on population.) Third, increased virulence not only lowers the population of sick chickens, it increases the population of healthy chickens. Lower virulence decreases the number of sick chickens that can infect healthy chickens, thus increasing the numbers available for consumption.

2 A farmer's incentives

The typical chicken farm in the developing world is run by a small, price-taking farmer [34, 33, 35]. Let p be the market price of chickens for human consumption,[4] $r(b)$ the cost

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[4]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. We ignore this and

of raising b chickens,[5] and $-c(z)$ be the cost of infection control. As is usual, we assume costs are increasing and convex, that is, $r' > 0$, $r'' > 0$, $c' < 0$, and $c'' > 0$. The farmer's objective is to choose birth rate and infection control to maximize profits from sales of chickens:

$$\max_{b,z} p_h x_h(b,z) + p_s x_s(b,z) - r(b) - c(z)$$

subject to the ecological conditions (1) and (2).[6] Because we assume that neither farmers nor consumers can distinguish sick chickens, both types of chickens earn the same price p and the farmer's objective can be written

$$\max_{b,z} px(b,z) - r(b) - c(z)$$

Because we shall focus on steady state results, the ecological conditions reduce to their endemic equilibrium value (4).[7]

The farmer will choose fertility such that

$$r'(b) = p \cdot (1/v) \tag{6}$$

that is, the marginal cost of a fertilized egg equals the marginal value of that egg. The value of the egg is price of each chicken it yields times the expected number of chickens it yields. Since in steady state birth rates only affect the number of sick chickens, which die at a rate v, the marginal number of chickens each egg yields is $1/v$. If the cost of infection control satisfies the second order condition $c''(z) > 2pv/\beta z^3$, then the farmer's will choose a level of infection control such that

$$-c'(z) = p \cdot (v/\beta z^2) \tag{7}$$

that is, the marginal cost of control is equal to the monetary value of the marginal benefit to his total flock of chickens. If the second order condition is not satisfied, then it is optimal for the farmer to practice maximal infection control. The ecological dynamics are such

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other distinctions between the two markets. 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.

[5] 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 the our prediction 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, our prediction would be unchanged.

[6] Because we assume all farms are identical, we can account for farm-to-farm spread of flu among chickens [39] without modifying the ecological model. All that is required is that $c'(z) = \infty$.

[7] Although we present this problem as a static maximization problem subject to constraints implied by the steady state of the ecological model, the results are identical to the steady state solution to a dynamic optimization problem with an infinite horizon.

that this does not require the farmer to drive z down to zero. Once z gets below some critical level $z_{\text{crit}} = v/\beta x_h > 0$, the population of sick chickens will decline ($\dot{x}_s < 0$) and the pathogenic strains of the disease will disappear from the chicken population. We shall proceed, however, assuming the second order condition for z is satisfied.

Because it will be relevant to our policy analysis, let us examine the effect of price shocks on the farmer's choice of fertility and infection control. Differentiating the farmer's optimality conditions with respect to price reveals

$$\frac{\partial b}{\partial p} = \frac{1}{vr''(b)} > 0 \tag{8}$$

$$\frac{\partial z}{\partial p} = \frac{vz}{2pv - \beta z^3 c''(z)} < 0 \tag{9}$$

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 infection, which may kill chickens before they reach the market. While it should be obvious that $\partial \hat{x}_s/\partial p > 0$ and $\partial \hat{x}/\partial p > 0$, it is interesting to note that

$$\frac{\partial \hat{q}}{\partial p} = \hat{q}(1 - \hat{q}) \left[-\frac{1}{z}\frac{\partial z}{\partial p} - \frac{1}{b}\frac{\partial b}{\partial p} \right] \tag{10}$$

is ambiguous in sign because a price shock causes farmers to increase birth rates (which raises the number of sick chickens) but decrease the contact rates (which raises the number of healthy chickens). Writing this last equation more succinctly as $\varepsilon_q = (1 - \hat{q})(-\varepsilon_z - \varepsilon_b)$, where ε indicates elasticity with respect to price, it is evident that a higher price might lower 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.

To fully identify the farmer's decision, we must determine how prices are set. We shall assume for simplicity that the chicken market is supplied by N identical farmers. Because we assume consumers cannot distinguish a sick chicken from a healthy one but know the fraction of chickens that are sick, aggregate demand is a function of both the average quality of farmers' chickens and price: $D(\hat{q}, p)$ where $D_q > 0$ and $D_p < 0$. The equilibrium price is that which clears the market

$$N\hat{x} = D(\hat{q}, p)$$

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 (10). This implies $N\hat{x}_p - D_q\hat{q}_p - D_p > 0$.

Although it is not strictly relevant to our policy analysis, it is instructive to compare the behavior of the price-taking farmer with that of a monopolist farmer. Because the monopolist can influence price, his problem is

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

The monopolist will set birth rate and infection control such that

$$
\begin{aligned}
r'\left(b\right) &= p \cdot \frac{1}{v} - \frac{p_q v}{\beta bz + v^2} < p \cdot \frac{1}{v} \\
-c'\left(z\right) &= p \cdot \frac{v}{\beta z^2} + \frac{p_q vb}{z\left(\beta bz + v^2\right)} > p \cdot \frac{v}{\beta z^2}
\end{aligned}
$$

Because costs are convex, this implies that the monopolist will 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. It is obvious that higher contact rates also reduce quality and price. Unlike the price-taker, the monopolist internalizes these costs. Indeed, 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.* Our prediction is that corporate farms may also reduce the extent of sickness *among chickens.* Yet the average developing world chicken farmer is a price taker, therefore the remainder of the paper shall proceed under that assumption.

3 The government's problem

3.1 Justifying the government's objective

Presumably, governments care directly about humans and not chickens. There are two ways, however, that sick chickens affect human welfare. First, they may reduce overall consumer plus producer surplus in chicken markets. Although the government does not ordinarily care about the quality of products, in the case of chickens lower quality may be due to an externality. Because of incomplete information, farmers with sick chickens reduce the price that farmers with healthy chickens can obtain in the marketplace. This is true in our model even though all farmers are identical. Second, and more importantly, sick chickens may infect humans. Since this paper is primarily about the threat of bird flu to humans, we shall focus exclusively on the health risk from sick chickens. We believe this is justified because the overriding motivation for existing government programs to cull chickens is to reduce the risk of human infections.

8

To arrive at the government's objective function, we employ another simple S-I model for the ecology of flu among humans:

$$\dot{y}_h = dy_h - \gamma w x_s y_h - \mu y_h \tag{11}$$

$$\dot{y}_s = \gamma x_s y_h - (\mu + \rho) y_s \tag{12}$$

where 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 mortality rate among humans infected with bird flu.

Given that roughly 60 percent of human H5Np1 infections result in mortality within weeks [40], we can presume ρ is very very large. If we suppose 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, we can state the government's narrow objective as to minimize the number of chickens that it fails to cull, $X_s - X_{gs}$, where X_s is the aggregate supply of sick chickens in a market and X_{gs} is number of chickens the government culls.

3.2 Constraints on the government

The problem, as we stated in the introduction, is that many governments cannot simply mandate farmers surrender their chickens for culling. Therefore, the government must pursue narrowly incentive compatible policies to procure chickens for culling. In this section we explore two such policies, either buying chickens outright or combining a ban on chicken sales with purchases of chickens at depressed prices.[8] We can compare these two policies by writing the government's loss function as

$$L = \varphi (X_s - X_{gs}) + k(f) + gX_g \tag{13}$$

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 chickens from farmers, and X_g is the number of chickens that the government purchases from farmers. We assume $k' > 0$ and $k'' < 0$.[9] The government's problem is to minimize loss by its choice of (f, g, X_{gs}).

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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 $-t(X_s - X_{gs}) + k(t)$. This would have the effect of lowering the cost of a

Due to our assumption of incomplete information, the government (like consumers) cannot buy only sick chickens. Rather it must buy any chicken and its yield of sick chickens is

$$X_{gs} = (1 - q) X_g \tag{14}$$

The government is subject to a number of additional constraints. The most important is the farmer's response to the government's offer to buy chickens. If we let δ be the fraction of his flock that a farmer sells to the government, then the farmer's best-response constraint is

$$\max_{\delta, b, z} \left[(1 - \delta) p + \delta g \right] x (b, z) - r (b) - c (z) \tag{15}$$

Since the government can only purchase chickens that the farmer sells, government purchases are constrained by

$$X_g = N \delta x \tag{16}$$

Moreover, the government's offer is indirectly constrained by the market clearing condition

$$Nx = D (q, f, X_g, p) \tag{17}$$

where $D_f < 0$ and $D_{X_g} > 0$. Finally, both the government and the farmer are constrained by the ecological model (1) and (2).

We shall simplify this problem in two steps. First, we derive the optimality conditions for the farmer's response (in the ecological steady state) and substitute them for (15). 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.) Suppose the government complies and offers $g = p$. Then the farmer will be indifferent between selling to the government and to private consumers. Therefore, the government can choose δ for the farmer. Moreover, the optimality conditions for b and z simplify to (6) and (7). Plugging in the incomplete information constraint (14) and the voluntary sales constraint (16) in the government's loss function now allows the government's problem to be restated more concisely as

$$\min_{\delta, f} \varphi (1 - \delta) N \hat{x}_s (b, z) + k (f) + p \delta N \hat{x} (b, z) \tag{18}$$

subject to the farmer's optimality conditions (6) and (7), the market clearing condition $N \hat{x} = D (\hat{q}, f, \delta, p)$, and the ecological conditions (3) - (5).

_____

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.

Second, we reformulate all key parameters except the control variables as functions of price. We derived the relationship between price and farmers' optimal choice of (b, z) and thus $(\hat{x}_s, \hat{x})$ in (8) - (9) from Part 2. Moreover, we can totally differentiate the market clearing constraint $N\hat{x}(p) = D(\hat{q}(p), f, \delta, p)$ with respect to price to obtain

$$\frac{\partial p}{\partial \delta} = \frac{D_\delta}{N\hat{x}_p - D_q\hat{q}_p - D_p} > 0, \quad \frac{\partial p}{\partial f} = \frac{D_f}{N\hat{x}_p - D_q\hat{q}_p - D_p} < 0 \tag{19}$$

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

$$\min_{\delta, f} \varphi(1 - \delta) N\hat{x}_s(p) + k(f) + p\delta N\hat{x}(p) \tag{20}$$

subject to (8) - (9) and (19).

3.3 Optimality conditions

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

$$\frac{\partial L}{\partial p} = \delta N\hat{x} + p\delta N \frac{\partial \hat{x}}{\partial p} + \varphi(1 - \delta) N \frac{\partial \hat{x}_s}{\partial p} > 0 \tag{21}$$

First, it raises the amount the government pays for the fraction of chickens it buys. Second, it has the dynamic effect of raising the number of sick chickens farmers produce and thus the number of sick chickens in the fraction that the government does not purchase. Third, the dynamic effect also increases the total number of chickens farmers produce and, given that the government cannot distinguish sick and healthy chickens, the total number the government purchases.

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:

$$\varphi N\hat{x}_s = pN\hat{x} + \frac{\partial L}{\partial p}\frac{\partial p}{\partial \delta} \tag{22}$$

The 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 of government purchases is simply the payment for chickens. The indirect cost is that government demand raises the market price. Likewise, the government should choose its sanction so that

$$\frac{\partial L}{\partial p}\left(\frac{-\partial p}{\partial f}\right) = k'(f) \tag{23}$$

11

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

There are two 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. In the next section, however, we consider extensions to the model that challenge these conclusions.

4 Extensions

4.1 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, we shall model export markets and 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

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

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 condition for the domestic and foreign markets

$$N (1 - \alpha) \hat{x} = D (\hat{q}, f, \delta, p) \tag{24}$$
$$N \alpha \hat{x} + N^F \hat{x}^F = D^F \left(\hat{q}^F, p^F \right) \tag{25}$$

will ensure that $p \geq p^F - \tau$ in equilibrium, though possibly after some chickens have been exported. For simplicity we have ignored imports in the market clearing conditions.

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[10]To be clear, we are do not 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 (11) and (12) does not permit herd immunity as the infection is from chickens, not infected humans.

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 (17) with dual conditions (24) and (25) or by adding the no-exports constraint

$$p > p^F - \tau \tag{26}$$

Let $\lambda \geq 0$ be the multiplier on this last constraint. Then the optimality condition (23) 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 (26). 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 (22) for δ, which becomes

$$\varphi \hat{x}_s + \lambda = p\hat{x} + \frac{\partial L}{\partial p}\frac{\partial p}{\partial \delta}$$

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

Finally, our analysis of exports can be extended to storage. From a static perspective, storage is similar to 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 storage. A better approach to modeling storage is to treat stored chickens as another state variable [21]. The advantage

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of that approach is that it accounts for the effect of storage on future domestic prices. Accounting for that effect, however, is unnecessary to obtain the central insight that storage is another method of evading current domestic sanctions. The social cost of storage is that sick chickens contaminate future flocks. The immediate implication for the government's problem is that current domestic price is constrained to be less that the discounted future price minus the cost of storage, i.e., $p(t) < e^{-rj}p(t + j) - \tau$. 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.

4.2 Chicken imports and exchanges

In a seminal paper on the management of elephant populations when poachers can store tusks, Kremer and Morcom [21] suggest that governments also 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. If dumping drove down chicken prices, it would lower the cost of purchasing chickens. There is an important complication, however, in the incomplete information case. Price depends not only on the quantity of chickens, but also 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]

We can capture this dynamic in the formal model by modifying the government's objective in (20) to be

$$\max_{\delta, f, g} \varphi (1 - \delta) N \hat{x}_s (p) + k (f) + p\delta N \hat{x} (p) + p^F X_g^F$$

where p^F is the market price in the foreign market in which the government buys chickens, X_g^F is the number of healthy chickens the government buys in that market. With no loss in insight, we assume the government does not sell the healthy chickens but simply gives them away and we ignore exports. The new domestic market clearing condition is $N\hat{x} + X^F = D(\hat{q}, f, \delta, p)$, where quality is now

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

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[11] A similar idea is found in [5, pp. 173-175] and [9, pp. 34-35].

[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."

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Totally differentiating the market clearing condition with respect to price yields

$$\frac{\partial p}{\partial X^F} = \frac{D_q \left(\partial \hat{q}/\partial X_g^F\right) - 1}{N\hat{x}_p - D_q\hat{q}_p - D_p}$$

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 or the negative effect from additional supply. 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

$$-\frac{\partial L}{\partial p}\frac{\partial p}{\partial X^F} = X^F \frac{\partial p^F}{\partial X^F} + p^F$$

where the left-hand side are the possible marginal benefits (driving down domestic price) and the right-hand side are the clear marginal costs (the direct costs of purchasing chickens in foreign markets).

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, dumping chickens from a competing foreign market into an export market can reduce the price that domestic farmers get from exports. Like a quarantine, this policy may be useful as a complement to domestic sanctions. The price of foreign healthy chickens is likely to be greater, however, 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 is surely less expensive to simply purchase more domestic chickens and reduce domestic sanctions.

Third, 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. Moreover, whether farmers anticipate this policy or not, this policy is surely

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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.

more expensive than simply purchasing all domestic chickens unless the price elasticity of the foreign market supply is much less the price elasticity of the domestic market supply.

4.3   Evolution of virulence

An important challenge for the control of bird flu is that the influenza virus is capable of rapid evolution. Because of the large amount of variation in influenza virus populations, strong selection pressures can alter average traits of the viral population on a time scale of just a few years [22] and probably months [REF]. Since infection control is an important source of selection pressure, and procurement policies, by altering the price of chickens, alter incentives for infection control, evolution may affect the determination of optimal procurement policy.

The difficulty with incorporating evolution into our analysis of procurement is that the effect of infection control on the evolution of flu varies dramatically depending on the specific ecology of flu on chicken farms. The literature on the evolution of virulence indicates that influenza virulence could evolve to be greater, lower, or be unaffected depending on (i) the extent of coinfection and superinfection, (ii) the type of infection control, (iii) the ability of a farmer to identify a sick chicken, and (iv) whether the analysis is carried with equilibrium methods or non-equilibrium methods. Coinfection is defined as one strain of a pathogen infecting an already infected host without displacing the resident strain. Superinfection occurs when one strain of a pathogen infects an already infected host and completely replaces the resident strain.

The most basic equilibrium method suggests that infection control should not have any effect on the pathogen's optimal virulence (equation (5) in Day [12]) while the most basic non-equilibrium method seems to indicate that infection control will lower virulence (equation (3.7) in Day and Gandon [13]). Day [12] also shows that virulence can increase if infected hosts are quarantined (equation (14) and Figure 3) and Knolle [20] shows that infection control can increase virulence by making the virus more of a generalist in terms of tissue tropism (although this mechanism may operate on a slightly slower time scale).

Gandon et al. [17] and equation (21) of Nowak and May [29] suggest that infection control would decrease virulence in a viral population with superinfection dynamics. Also, as noted by Gandon et al. [16], superinfecting parasites tend to be subject to selection for the fastest within-host reproducers; thus, infection control can decrease the prevalence of within-host competition, which would in turn decrease the selective pressure for the more rapid reproducers (which are more virulent). When viewing influenza infections in chickens as coinfections (rather than superinfections), equation (5) of May and Nowak [24] suggests that mean virulence may increase if infection control is practiced. In reality, avian influenza infections in chickens probably exhibit both coinfection and superinfection dynamics. A specific evolutionary-epidemiological model would need to be built to analyze virulence evolution when infection control is practiced on chicken farms.

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To explore the policy implications of the alternative evolutionary scenarios in a simple manner, we shall make the following assumptions concerning the evolution of flu. First, although it incorporates neither coinfection or superinfection, we shall retain the two-compartment model of flu in chickens in (1) and (2). A proper model of superinfection would require a third compartment for the second strain of flu and a proper model of coinfection would require yet a fourth compartment for chickens infected with both strains of chickens. The endemic equilibrium in either more complicated model, however, would have the structure: $\hat{x}_h \approx z\bar{\beta}/\bar{v}$ and $\hat{x}_{s1} + \hat{x}_{s2} + \hat{x}_{s1,s2} \approx b/\bar{v}$, where $\bar{\beta}$ and $\bar{v}$ are weighted averages of transmissibility and virulence, respectively, across strains $s1$ and $s2$. Because these equations are similar to the endemic equilibrium (3) of the simpler ecological model, there is little loss in ecological dynamics from using endemic equilibrium values from the simpler model.

Second, we will model the effect of infection control on evolution of average transmissibility and virulence in a flock simply by letting the previously exogenous parameters β and v be functions of z, where $\beta'(z) < 0$ and $v'(z) < 0$ in the case where flu is capable of coinfection and $\beta'(z) > 0$ and $v'(z) > 0$ in the case where flu is capable of superinfectionin chickens. (Note that these functions describe long term values of β and v in the evolutionary time scale, that is, values of β and v after a few months or years.) Third, we shall assume that farmers do not account for the evolution of flu when they choose birth rates and infection control on their farms. We believe this is realistic because it is unlikely that farmers in developing countries have either derived the equations of population genetics or read papers that have derived the effect of infection control on the evolution of flu in chickens.

The effect of evolution on optimal procurement will depend on two factors. One is the immediate health risk to humans from heightened virulence of flu in chickens. We shall capture this by letting φ be a function of virulence and supposing that virulence in chickens is positively correlated to virulence in humans [19], so that $\varphi'(v) > 0$. Because evolution of virulence is driven by infection control and incentives for infection control are a function of price, the effect of viral evolution on health risks to humans is a function of the effect of government policy on price.

The other factor that mediates the effect of evolution on optimal procurement is the effect of evolution on the elasticity of chicken supply with respect to price. Comparative

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statics on the farmer's problem reveals

$$\frac{\partial \hat{x}_s}{\partial p} = \frac{\partial \hat{x}_s}{\partial p}\bigg|_{v(z),\beta(z)} + \left[\hat{x}_s \frac{v'(z)}{v}\right]\left(\frac{-\partial z}{\partial p}\right)$$

$$\frac{\partial \hat{x}}{\partial p} = \frac{\partial \hat{x}}{\partial p}\bigg|_{v(z),\beta(z)} + \left[\hat{x}_h \frac{\beta'(z)}{\beta} - (\hat{x}_h - \hat{x}_s)\frac{v'(z)}{v}\right]\left(\frac{-\partial z}{\partial p}\right)$$

$$\frac{\partial \hat{q}}{\partial p} = \frac{\partial \hat{q}}{\partial p}\bigg|_{v(z),\beta(z)} + \left(\frac{vz}{b\beta z + v^2}\right)\left[\frac{\beta}{\hat{x}}\frac{\beta'(z)}{\beta} - 2z^2\frac{v'(z)}{z}\right]\left(\frac{-\partial z}{\partial p}\right)$$

The first term on the right hand side of each line is the effect of price on quantity or quality
holding evolution constant. This is the same as the effect of price on farmer supply in earlier
sections of the paper. The second term on the right hand side of each line is the effect of
evolution. Because the evolutionary effect is driven by infection control, it is mediated by
the effect of price on infection control. Given our assumption that farmers do not account
for evolutionary dynamics in their choice of birth rates and infection control, the effects of
price on these variables are the same as before.

While it is evident that price now has a smaller, perhaps negative (larger positive) effect
on the population of sick chickens in the case of coinfection (superinfection), its effects on
total chickens and quality are ambiguous. It is theoretically possible that evolution with
either coinfection or superinfection can generate backward-bending regions in the supply
curve for total chickens. Assuming the market is at a stable equilibrium before government
intervention, this raises the possibility that the government can have its cake and eat it
too. That is, the government can offer a higher price without increasing the supply of sick
chickens. (And unlike sanctions, this does not encourage exports.)

However, if we employ equilibrium methods as in Day [12] or Gandon et al. [17],
we can see this is very unlikely. In this approach selection operates to maximize the
virus's reproductive rate $R_0 = z\beta(v)/v$ with respect to virulence, where $\beta(v)$ is a function
that expresses the statistical correlation between transmissibility and virulence in a viral
population and $\beta'(v) > 0$. It is easily shown that R_0 maximization implies that $\varepsilon_{\beta v} = 1$
where $\varepsilon_{\beta v} = \beta'(v) \cdot (v/\beta)$ is the elasticity of transmissibility with respect to virulence.
Since models in the virulence evolution literature assume the evolution of transmissibility
is mediated by the evolution of virulence, it is the case that $\beta'(z) = \beta'(v)v'(z)$ and thus
$\beta'(z)/\beta = v'(z)/v$. This in turn yields

$$\frac{\partial x}{\partial p} = \frac{\partial x}{\partial p}\bigg|_{v(z),\beta(z)} + \left[x_s \frac{v'(z)}{v}\right]\left(\frac{-\partial z}{\partial p}\right) = x_s \frac{\partial b/\partial p}{b} + [x_h + x_s \varepsilon_{vz}]\frac{-\partial z/\partial p}{z}$$

where $\varepsilon_{vz} = v'(z) \cdot (z/v)$ is the elasticity of virulence with respect to contact rates. This
is negative only if $\varepsilon_{vz} < -x_h/x_s$. Note that this is not possible with superinfection, which
generates a positive elasticity between virulence and contact rates. It is also very unlikely

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even with coinfection. In an endemic equilibrium, the ratio of health chickens is likely to be on the order of, say, 10 to 1. It is seems implausible that the elasticity of virulence with respect to contact rates exceeds this value, that is, that a 10 percent decrease in contact rates would increase evolved virulence by 100 percent. More plausible is an elasticity in the neighborhood of, if not less than, one. Therefore, it is very unlikely that virulence evolution will generate backward bending supply and we proceed assuming otherwise. That is, price probably has a smaller (larger) positive effect on both the supply of sick chickens and of total chickens in the case of coinfection (superinfection).

The two factors that mediate the effect of evolution on policy – the risk from virulence in chickens to humans and the effect on the supply elasticity of chickens – in turn have three discrete effects on the government's optimality conditions. The first two effects can be seen in the direct effect of price on the government's loss:

$$\frac{\partial L}{\partial p} = (1 - \delta) N \hat{x}_s \varphi'(v) \frac{\partial v}{\partial z} \frac{\partial z}{\partial p} + \delta N \hat{x} + p \delta N \frac{\partial \hat{x}}{\partial p} + \varphi (1 - \delta) N \frac{\partial \hat{x}_s}{\partial p} \tag{27}$$

The health risk to humans from virulence in chickens is captured in the first term. Given the higher prices encourage lower contact rates, this term is positive in the case of coinfection and negative in the case of superinfection. The effect of evolution on supply elasticity alters the last two terms. Both terms fall in the case of coinfection and rise in the case of superinfection. Because the effects of the two factors run in opposite directions, viral evolution may either increase or decrease the government's loss in both the case of coinfection and of superinfection.

The third effect of viral evolution on the government's optimality conditions only complicates things further. The change in the price elasticity of quantity and quality supply alters the denominator of (19) and thus the magnitude of the marginal effect of government purchases or sanctions on price. Even if we ignore the effect on quality supply elasticity, which is ambiguous, we see that an increase in quantity supply elasticity lowers the effect of government interventions on price. This offsets the effects these interventions have on the direct effect of price on government loss in (27).

The proper conclusion to draw from these muddled effects is not that they can be ignored. There is nothing to suggest that they nearly offset each other. Rather, these effects may be important though their direction is unclear. To resolve this ambiguity one must first pin down the ecological dynamics among strains of flu in chicken. Then it is necessary to model the evolution of virulence in response to infection control. (Existing studies tend to focus on evolution in the context of vaccination.) We plan to do this in a future version of the present paper. Finally, it is necessary to estimate the basic elasticities that will dictate optimal policy, especially those between price and infection control and between virulence in chickens and virulence in humans.

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4.4 Partially incomplete information

Thus far we have assumed that neither farmers, consumers, nor the government can identify sick chickens. In this section we relax this assumption and demonstrate three things. First, diagnostic tests create two markets, one for ostensibly sick chickens and another for ostensibly healthy chickens. If diagnostic tests generate false negatives, the government may want to purchase not just ostensibly sick chickens but also ostensibly healthy ones. Second, diagnostic tests complicate the government's problem, and not just because it must now choose the fraction of chickens to buy and how much to sanction chicken production or sales in two markets rather than one. Consumer substitution across the markets for ostensibly healthy and ostensibly sick chickens means that the government's behavior in the two markets is not separable. Purchases or sanctions in the market for ostensibly sick chickens, for example, will affect demand and thus prices in the market for ostensibly healthy chickens; those changes in turn will alter the government's optimal procurement policy in the ostensibly healthy chicken market. Third, despite these changes, the essential trade-offs that guide the government's choice between a higher offer price and sanctions in the partially incomplete information case are similar to those that guide the government's choice in fully incomplete information case.

We shall introduce information on chickens via a diagnostic technology that identifies sick chickens. As before we shall assume symmetric information across all actors, that is, farmers, consumers and the government all have costless access to this technology. This technology has sensitivity θ_s and specificity θ_h. This implies that the probability of a false negative, that is, a sick chicken being mistaken for a healthy chicken, is $1 - \theta_s$, and the probability of a false positive, that is, a healthy chicken being mistaken for a sick chicken, is $1 - \theta_h$. This implies that the number of ostensibly healthy and ostensibly sick chickens in a flock are

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

where (x_h, x_s) are actually healthy and sick chickens, respectively.

The farmer's problem becomes

$$
\max_{b,z} p_h w_h + p_s w_s - r(b) - c(z) \tag{28}
$$

or, equivalently,

$$
\max_{b,z} \pi_h x_h + \pi_s x_s - r(b) - c(z)
$$

where (p_h, p_s) are now the market prices of ostensibly healthy and ostensibly sick chickens and

$$
\pi_h = \theta_h p_h + (1 - \theta_h) p_s \quad and \quad \pi_s = (1 - \theta_s) p_h + \theta_s p_s
$$

are the implicit prices of truly healthy and sick chickens. Because diagnostic technology does not directly affect the basic ecology of flu in chickens, that is, equations (1) and (2), the farmer's decision remains subject to the constraints of that ecology, which in steady state are given by (3).

Farmers control birth rates and infection control, which through the ecology of flu most directly affect the supply of actually healthy and actually sick chickens. Because an increase in prices of either ostensibly healthy or ostensibly sick chickens increases the implicit price of both actually healthy and actually sick chickens, an increase in price of chickens of either ostensible quality causes an increase in the supply of chicken of both actual qualities. Through this mechanism, the increase in price of chickens of either ostensible quality also causes an increase in supply of chickens of both ostensible qualities. More succinctly, $\partial \hat{x}_i / \partial p_j > 0$ and $\partial \hat{w}_i / \partial p_j > 0$ for all $i \in \{h, s\}$ and $j \in \{h, s\}$. Further, we can define the actual quality of ostensibly health and ostensibly sick chickens as the probability that such a chicken is actually healthy, that is,

$$\hat{q}_h = \frac{\theta_h \hat{x}_h}{\theta_h \hat{x}_h + (1 - \theta_s) \hat{x}_s} \quad \text{and} \quad \hat{q}_s = \frac{\left(1 - \hat{\theta}_h\right) x_h}{\left(1 - \hat{\theta}_h\right) x_h + \hat{\theta}_s x_s}$$

respectively. As before, an increase in price – now of ostensible quality – has ambiguous effects on actual quality.

Since there are two ostensible qualities of chickens, there are two markets for chickens. Each must clear:

$$N \hat{w}_h = D_h \left(\hat{q}_h, f_h, \delta_h, p_h, p_s\right) \tag{29}$$

$$N \hat{w}_s = D_s \left(\hat{q}_s, f_s, \delta_s, p_s, p_h\right) \tag{30}$$

where δ_i and f_i are the fraction of chickens the government buys and the government's sanction on chickens in market i for $i = \{h, s\}$. Importantly, consumer substitution between ostensibly healthy and sick chickens implies positive cross-price effects on demand, that is, $\partial D_i / \partial p_j > 0$ for $i, j \in \{h, s\}$ and $i \neq j$. This does not disturb the result that an increase in government purchases (sanctions) in one market increases (decreases) prices in that market. But it does raise the possibility that either intervention in one market may increase or decrease prices in the other. (It will remain true, however, that the direction of effect from government purchases will be the opposite of the direction of effect from sanctions.)

Because there are false negatives and imperfect sensitivity, there are actually sick chickens in each market. Therefore, the government's objective is to minimize the health risk from sick chickens being sold in both private markets, keeping in mind the cost of purchasing such chickens and of enforcing sanctions on each private market

$$\min_{\delta_h, \delta_s, f_h, f_s} \varphi N \left[(1 - \delta_h) (1 - q_h) \hat{w}_h + (1 - \delta_s) (1 - q_s) \hat{w}_s\right] + \delta_h p_h N \hat{w}_h + \delta_h p_h N \hat{w}_s + k \left(f_h, f_s\right)$$

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subject to the ecological steady state (3), farmer's problem (28) and the market clearing conditions (29) and (30). Plugging in the definition of quality from above, the government's loss function simplifies to

$$\varphi N \left[(1 - \delta_h)(1 - \theta_s) + (1 - \delta_s)\theta_s\right] \hat{x}_s + \delta_h p_h N \hat{w}_h + \delta_h p_h N \hat{w}_s + k(f_h, f_s)$$

Define the direct effect an increase in ostensibly healthy chicken and ostensibly sick chicken price has on the government's loss as

$$
\begin{aligned}
\frac{\partial L}{\partial p_s} &= \varphi N \left[(1 - \delta_s)\theta_s + (1 - \delta_h)(1 - \theta_s)\right] \frac{\partial \hat{x}_s}{\partial p_s} + \delta_s N \hat{w}_s + \delta_s p_s N \frac{\partial \hat{w}_s}{\partial p_s} > 0 \\
\frac{\partial L}{\partial p_h} &= \varphi N \left[(1 - \delta_s)\theta_s + (1 - \delta_h)(1 - \theta_s)\right] \frac{\partial \hat{x}_s}{\partial p_h} + \delta_s p_s N \frac{\partial \hat{w}_s}{\partial p_h} > 0
\end{aligned}
$$

respectively. Now the government's optimal choice of purchases in the ostensibly healthy and sick markets satisfy

$$
\varphi N (1 - \theta_s) \hat{x}_s = p_h N \hat{w}_h + \frac{\partial L}{\partial p_h}\frac{\partial p_h}{\partial \delta_h} + \frac{\partial L}{\partial p_s}\overbrace{\frac{\partial p_s}{\partial \delta_h}}^{+/-} \tag{31}
$$

$$
\varphi N \theta_s \hat{x}_s = p_s N \hat{w}_s + \frac{\partial L}{\partial p_s}\frac{\partial p_s}{\partial \delta_s} + \frac{\partial L}{\partial p_h}\overbrace{\frac{\partial p_h}{\partial \delta_s}}^{+/-} \tag{32}
$$

Likewise, the government's optimal choice of sanctions in the respective markets satisfies

$$
-\frac{\partial L}{\partial p_h}\frac{\partial p_h}{\partial f_h} - \frac{\partial L}{\partial p_s}\overbrace{\frac{\partial p_s}{\partial f_h}}^{-/+} = \frac{\partial k}{\partial f_h} \tag{33}
$$

$$
-\frac{\partial L}{\partial p_s}\frac{\partial p_s}{\partial f_s} - \frac{\partial L}{\partial p_h}\overbrace{\frac{\partial p_h}{\partial f_s}}^{-/+} = \frac{\partial k}{\partial f_h} \tag{34}
$$

Two things are immediately apparent. First, it may be optimal for the government to purchase or ban sales of ostensibly healthy chickens as well as ostensibly sick chickens. This is simply because the risk of false negatives $(1 - \theta_s)$, which yields a positive health benefit (the left-hand side of (31)) to purchasing ostensibly healthy chickens.

Second, conditions (31) and (32) resemble condition (22) for δ while (33) and (34) resemble condition (23) for f in the fully incomplete information model. The primary distinction is the addition of cross-market price effects (marked) of each intervention. It is unclear whether these have the same or opposite sign as same-market price effect of these

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interventions, and therefore whether these effects are marginal benefits or marginal costs of each intervention. If, for example, the cross-market price effect of purchases is positive and that of sanctions is negative, then each intervention will have the same price effects in secondary markets as in primary markets and those effects will additional marginal costs of purchases and benefit of sanctions.

A simple and likely realistic special case that yields an even closer correspondence between the partially incomplete case and the fully incomplete information case is one which makes the following additional assumptions. First, there are no false positive diagnosis of flu in chickens. This implies $\theta_h = 1$ and that ostensibly sick chickens are all actually sick. Second, consumers value actually sick chickens and thus ostensibly sick chickens at price zero. Therefore, third, the government buys all ostensibly sick chickens (at price zero) and does not bother sanctioning the sale of these chickens. In this case the market clearing conditions become

$$
\begin{aligned}
N\hat{w}_h &= D_h\left(\hat{q}_h, f, \delta_h, p_h, 0\right) \\
N\hat{w}_s &= D_s\left(0, 0, 1, 0, 0\right)
\end{aligned}
$$

All cross-market effects of interventions can be ignored because the ostensibly sick chicken market is effectively shut down. The government's only remaining choices are the fraction of ostensibly healthy chickens to buy and the sanctions to impose on the market for those chickens. The optimality conditions for the government's choice are nearly identical to (22) and (23), except that the relevant market is that for ostensibly healthy chickens and

$$
\frac{\partial L}{\partial p_h} = \varphi N\left(1 - \delta_h\right)\left(1 - \theta_s\right)\frac{\partial \hat{x}_s}{\partial p_h} + \delta_h p_h N \hat{w}_h + \delta_h p_h N \frac{\partial \hat{w}_h}{\partial p_h} > 0
$$

which differs from the direct effect of price on the government loss in the full information case most importantly due to its accounting for false negatives $(1 - \theta_s)$ in the ostensibly healthy chicken market.[14]

5 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, the limited policy value of imports, and complications raised by virulence evolution. It also shows that its approach to modeling markets in chickens is largely robust to the introduction of imperfect diagnostic technology for identification of sick chickens.

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[14][Explore the effect of changes to sensitivity θ_s.]

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 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. We shall tackle these and other complications in future drafts.

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