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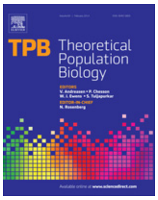

Economic epidemiology of avian influenza on smallholder poultry farms[☆]

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ABSTRACT

Highly pathogenic avian influenza (HPAI) is often controlled through culling of poultry. Compensating farmers for culled chickens or ducks facilitates effective culling and control of HPAI. However, ensuing price shifts can create incentives that alter the disease dynamics of HPAI. Farmers control certain aspects of the dynamics by setting a farm size, implementing infection control measures, and determining the age at which poultry are sent to market. Their decisions can be influenced by the market price of poultry which can, in turn, be set by policy makers during an HPAI outbreak. Here, we integrate these economic considerations into an epidemiological model in which epidemiological parameters are determined by an outside agent (the farmer) to maximize profit from poultry sales. Our model exhibits a diversity of behaviors which are sensitive to (i) the ability to identify infected poultry, (ii) the average price of infected poultry, (iii) the basic reproductive number of avian influenza, (iv) the effect of culling on the market price of poultry, (v) the effect of market price on farm size, and (vi) the effect of poultry density on disease transmission. We find that under certain market and epidemiological conditions, culling can increase farm size and the total number of HPAI infections. Our model helps to inform the optimization of public health outcomes that best weigh the balance between public health risk and beneficial economic outcomes for farmers.

1. Introduction

Animal surveillance and management are critical for preventing future influenza pandemics, as evidenced by over a decade of intermittent outbreaks of highly pathogenic avian influenza (HPAI), especially H5N1 and H7N9, and by the animal origin of the 2009 H1N1 pandemic. Although the case fatality rate for the 2009 pandemic was within the moderate range for seasonal influenza (Khandaker et al., 2011), case fatality rates based on reported cases for human H5N1 infections have stayed above 50% (Abdel-Ghafar et al., 2008; Wang et al., 2012) and the early estimated case fatality for human H7N9 infections is approximately 25% (WHO, 2013a). Over 60 nations have experienced an outbreak of H5N1 in their poultry populations (Otte et al., 2008a), causing 628 human infections with H5N1 and 374 deaths worldwide (WHO, 2013b). For most governments, preparedness and prevention strategies against avian influenza include stockpiling antiviral agents, culling sick poultry, and vaccinating poultry flocks (Otte et al., 2008a; Hinrichs et al., 2010). Despite the success of some of these control policies, regular HPAI outbreaks and human cases of avian influenza continue to occur. Recent indications of weakening vaccine efficacy (Henning et al., 2011; Long et al., 2011) and the possibility of drug resistance evolution (Le et al., 2005; de Jong et al., 2005) necessitate the optimization of HPAI control policies.

Since 2003, over 400 million birds have been culled worldwide as a direct result of avian influenza outbreaks (FAO, 2012). In most countries, farmers are compensated for culled poultry, but often at far below market price (Otte et al., 2008a; McLeod, 2010; Hall et al., 2006). From 2003 to 2006, the peak outbreak years in Southeast Asia, government culling policies arose in an environment of public panic, and led to reduced poultry demand and lower

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poultry prices (Otte et al., 2008a); in some cases, poultry prices rebounded to above pre-outbreak levels (Otte et al., 2008a; Hall et al., 2006). Such price dynamics may be fundamental to policy optimization – in particular, the level at which the government should compensate farmers for culled poultry and/or the effort to expend on detection of disease emergence. If future public health responses to HPAI outbreaks lower poultry prices, HPAI prevalence should decrease as poultry farming will temporarily become less profitable. Conversely, if the public health response causes poultry prices to rise, a variety of outcomes are possible, which are considered here.

The effect of market price on farm size – defined here as the number of poultry on each farm – can undermine the intended benefits of culling. Thus far, the elasticity of farm size to market price (the percentage change in farm size resulting from a 1% increase in market price) has only described smaller farms in the context of falling prices (Hall et al., 2006; Basuno et al., 2010; Yalcin et al., 2010). In theory, higher prices should lead to larger farms. Empirically, however, it is not known how short-term or sustained price changes would affect farm sizes, or how strongly higher prices could incentivize the intensification of poultry farming activities. Nevertheless, given the dynamic (McLeod, 2010) and heterogeneous (Rushton et al., 2005) nature of poultry production systems in Asia, this is an important effect to explore. Changes in farm size are crucial aspects of general animal/agricultural disease systems, as larger farms are more susceptible to disease outbreaks than smaller farms (Keeling et al., 2001; Ferguson et al., 2001; Otte et al., 2008b).

Here, we evaluate how certain farm characteristics – size, turnover, and infection control effort – can be shaped by epidemiological and economic incentives, as well as how culling and its effects on market price can influence the prevalence of avian influenza in poultry and the risk of HPAI outbreaks. We combine an epidemiological model of avian influenza transmission with profit maximization for the farmer to determine the farmer's optimal behavior, and subsequently, the effect of the government's poultry procurement policy on poultry production and HPAI risks to humans.

2. Model

The epidemiological component of our analysis is based on a Susceptible–Infected model of avian influenza transmission among poultry on an individual farm:

$$\begin{aligned} \dot{x}_h &= b - (1-y)\beta\frac{x_h x_s}{N} - \sigma x_h \\ \dot{x}_s &= (1-y)\,\beta\frac{x_h x_s}{N} - \upsilon x_s - \sigma x_s, \end{aligned} \tag{1}$$

where x_h is the number of uninfected (healthy) poultry and x_s is the number of infected (sick) poultry. The parameter b is the rate at which farmers procure chicks/eggs to re-stock their farms or the rate at which non-infected poultry are born; b determines the overall farm size, i.e. number of poultry on the farm. Farmers can maintain a level of infection control y, with $0 < y < y_0$, where y_0 is the level of infection control needed to drive the pathogen's basic reproduction number (R_0) below one. The parameter σ is the rate at which farmers send poultry to market; σ^{-1} determines the age of a chicken at sale. The parameter β is the transmissibility of influenza among poultry and υ is the disease-induced death rate, or virulence, among infected poultry. N is the population size of poultry. For a density-dependent (DD) contact or infection process, we set $N = 1$, and for a frequency-dependent (FD) contact process, we set $N = x_h + x_s$ (Keeling and Rohani, 2008). The density-dependent model is best for describing poultry kept in an enclosure (usually chickens), while the frequency-dependent transmission is suitable for a population of free-range scavenging poultry (usually ducks, sometimes chickens); under the FD-model we sometimes refer to farms as "flocks". In both situations, the system has a disease-free equilibrium and a unique endemic equilibrium. Our use of the endemic equilibrium in this analysis assumes that farms are populated with poultry at all times so that a continuous chain of transmission can be maintained on a single farm. This is frequently the case for smallholder poultry farming in Asia (Burgos et al., 2007; Fasina et al., 2012). In cases where discrete cohorts of birds are raised, farmers will still maintain multiple cohorts (Henning et al., 2012) and/or multiple species of poultry on a single farm ensuring the presence of poultry on the farm at all times (Henning et al., 2012; Burgos et al., 2007; Edan et al., 2006).

We assume that farmers, consumers, and the government have access to the same method of diagnosing infected poultry, such as a molecular diagnostic (Fouchier et al., 2000; Zou et al., 2007) or a visual inspection (Suarez et al., 1998; Peiris et al., 2007). We assume this test has perfect specificity but imperfect sensitivity $\theta \leqslant 1$. The specificity of visual inspections may not always be perfect in the case that other non-influenza avian diseases are circulating, but we make the simplifying assumption here that only influenza viruses are circulating. The equilibrium number of poultry that are ostensibly healthy and the number diagnosed with infection are, respectively,

$$\begin{aligned} \hat{w}_h &= \hat{x}_h + (1-\theta)\,\hat{x}_s \\ \hat{w}_s &= \theta\hat{x}_s, \end{aligned} \tag{2}$$

and these poultry are sent to market for sale. Farmers are price takers, i.e., their actions do not alter the market price of poultry (if all farmers were to change their behavior in the same way, this would have an effect on the market price of poultry, but we do not consider this case here). An individual farmer's instantaneous income is

$$\pi = \left(\hat{w}_h + \kappa\,\hat{w}_s\right)\sigma P\left(\sigma^{-1}\right) - r\,(b) - c\,(b, y)\,. \tag{3}$$

Total revenue is the rate σ at which a farmer sends chickens/ducks to market multiplied by the price P obtained for each healthy bird; infected poultry are purchased by consumers or the government at a reduced price κP. A bird's price depends on its weight, which depends on its age (σ^{-1}). For analytical tractability, we assume that the relationship between age and weight is a piecewise linear function where poultry cannot be sold before age d days and gain weight linearly for g days afterward; Section 3 (see Appendix A) shows that the results are not sensitive to this assumption. Substituting Eq. (2) into Eq. (3), we see that the diagnostic-test sensitivity parameter θ and the compensation parameter κ always appear together as $(1-\kappa)\theta$; hence, we assume without loss of generality that $\kappa = 0$.

In Eq. (3) we assume there are two major costs of raising poultry. The first is $r(b)$, the cost of maintaining a farm of a particular size; this includes fixed costs as well as the costs of acquiring fertilized eggs or young chicks and caring for them. We assume that this cost is convex: $r'(b) > 0$ and $r''(b) > 0$. With sufficient demand relative to the number of farmers, however, competition ensures that farmers are operating on the upward sloping portion of their average cost curves. The second cost is $c(b, y)$, the cost of controlling infections by cleaning the farm, separating chickens/ducks from one another, or lowering infection rates by some other method. We assume that the cost of infection control increases linearly with the size of a farm and the level of infection control: $c\,(b, y) = aby$, where $a > 0$ is the unit cost of infection control.

Farmers manage their flocks through the birth rate b (or purchase rate) of non-infected poultry, the level of infection control y, and the age at which poultry are sent to market σ^{-1}. The farmer sets these parameters (b, y, σ) to maximize Eq. (3) subject