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Modeling of Avian Influenza Mitigation Policies Within the Backyard Segment of the Poultry Sector

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This study presents a conceptual model for the analysis of avian influenza mitigation options within the small poultry farm sector (backyard flocks). The proposed model incorporates epidemiologic susceptible-infected-recovered (SIR) methodology into an economic cost-minimization framework. The model is used to investigate the implications and interdependencies of mitigation options that influence inter-flock contact rates of asymptomatic and symptomatic flocks, and reduce the duration of symptomatic and asymptomatic periods. The results indicate that for shorter asymptomatic periods the efforts to control inter-flock contact rates should concentrate on symptomatic flocks, while for longer asymptomatic periods the control of inter-flock contacts should be focused on asymptomatic flocks. Efforts to reduce the length of asymptomatic and symptomatic periods and efforts to reduce inter-flock contact rates function as substitute strategies.

Key words: asymptomatic and symptomatic periods, avian influenza, contact rates, cost minimization

Introduction

The spread of the highly pathogenic avian influenza (AI) in many Asian and European countries, and its associated economic consequences (Taha, 2007), has attracted the attention of policy makers as well as academicians. Unlike other animal diseases, such as bovine spongiform encephalopathy and foot-and-mouth disease (FMD), avian influenza could be highly contagious and zoonotic—meaning the disease could spread rapidly within and between animal and human populations. Clearly, avian influenza could present a serious threat to the U.S. agricultural industry. Therefore, this threat demands a well-planned and well-thought-out prevention, preparedness, and response policy.

Avian influenza types include various combinations of H (16) and N (9) subtypes (Pelzel, McClusky, and Scott, 2006), which could be classified into high pathogenic and low pathogenic groups based on the ability to cause serious illness. High pathogenic strains include subtypes H5 and H7, while low pathogenic strains include all other subtypes, which, under favorable circumstances, could mutate into more serious threats (Alexander, 2000). Of particular significance are H5N1 and H5N2 subtypes, which could exhibit mortality rates of 100% in poultry as well as cause serious illness and even death

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in humans. The latent period for infected birds is on average 3–5 days, but could extend up to 21 days (OIE, 2007). The virus spreads through direct bird-to-bird contact, as well as through indirect contact via contaminated feed, equipment, water, personnel, etc.

Effective management and control of AI is important not only in wildlife, but also within domestic and commercial poultry populations. Mitigation strategies essentially focus on early diagnosis and reduction of inter-flock contacts to reduce the spread of the disease. Current localized response plans within the commercial poultry sector generally involve combinations of culling, movement restrictions, and surveillance. For example, guidelines adopted by the Texas Animal Health Commission (TAHC) include depopulation of the infected flocks, movement restrictions on all flocks within five miles from the infected flocks, surveillance testing of all flocks within 10 miles from the infected flocks, movement restrictions on and surveillance testing of all flocks having direct contacts with the infected flock, and cleaning and disinfection of the infected premises (Pelzel, McClusky, and Scott, 2006).

Participation in an ongoing routine serologic surveillance program (involving testing of bird fluids like blood), established by the Texas Poultry Federation (TPF), is voluntary and the costs of this monitoring program are paid by participating companies. Although participation in the TPF's ongoing surveillance program is voluntary, a response by the TAHC to a confirmed AI virus outbreak is mandatory.

In general, mitigation strategies can be categorized into four groups: reducing contact rates of asymptomatic flocks, reducing contact rates of symptomatic flocks, reducing the length of symptomatic infectiousness, and early detection of asymptomatic flocks. In this study the interdependencies of actions among these four groups are examined in the context of backyard flocks.

The most recent outbreak of AI in the poultry sector was observed in Texas in February of 2004 (Pelzel, McClusky, and Scott, 2006), where a flock of approximately 6,600 broilers and two live bird markets were diagnosed as infected with subtype H5N2. Epidemiologic investigation revealed that the most likely source of infection for the broiler flock occurred as a result of birds from this farm being exposed to the virus at one of the live bird markets in Houston and later being returned to the broiler farm. All known suppliers of the infected live bird market were isolated and tested, but no presence of AI was confirmed. It was also established that there were several one-time suppliers who delivered birds to the live bird market in the months prior to the outbreak and for which the live bird market operators were unable to provide names or contact information. Similarly, the epidemiologic investigations of AI outbreaks in 1983–84 and 1986 in the northeastern states concluded that the index cases (first traceable cases of infection) originated at the live bird markets. In the 1986 northeastern outbreak, 26 of 44 live bird markets in New York and 12 of 26 in New Jersey had birds testing positive for the H5N2 virus (Garnett, 1987). This signals that perhaps the most likely source of the outbreaks was live bird market suppliers.

Considering that most live bird market suppliers are small operations, it may be important to investigate mitigation options for small-scale poultry operations. Specifically, it is important to investigate small backyard flocks of less than 400 birds because, unlike large commercial poultry operations, backyard farms do not adhere to strict bio-security regulations such as isolating farm birds from wild birds, cleaning and disinfection, etc. Furthermore, data on geographic locations, systematic functionality, and other characteristics of backyard flocks needed for the design of disease control

strategies are not generally available. Therefore, it is important to study the options that could facilitate disease-control efforts across small poultry farms.

Mitigation of infectious diseases at the backyard farm level would essentially involve the same control options as at the large commercial farm level outlined above. However, enforcing movement restrictions and carrying out surveillance programs would be logistically more difficult than for large commercial operations. Hence, exploration of alternatives at the backyard level is warranted. Generally, control of disease spread at the backyard level could be achieved via control of inter-flock contact rates and lengths of asymptomatic and symptomatic periods. These could be implemented through early detection technology and/or through incentive-compatible mechanisms for reporting disease presence at backyard flocks. In this study we investigate how control options which reduce contact rates and lengths of asymptomatic and symptomatic periods could be used to form a mitigation strategy under a cost-minimization context.

Numerous studies have addressed avian influenza and efforts to combat the virus. In 2006 alone, several dozen articles were published in the scientific literature (e.g., Hoelscher et al., 2006; Mannelli, Ferre, and Marangon, 2006; Cinti, 2005; Wang et al., 2006; Swayne, 2006; Jong and Hien, 2006; Pelzel, McCluskey, and Scott, 2006). Most studies concentrate on the biological aspects of AI eradication or on the spread of AI among humans (Germann et al., 2006). Studies in the economic literature have focused on evaluating monetary damages or trade implications due to an AI outbreak (Brown et al., 2007; Paarlberg, Seitzinger, and Lee, 2007; Djunaidi and Djunaidi, 2007; Taha, 2007).

Limited attention has been devoted to systematic operational effectiveness of mitigation strategies and control mechanisms at the small-scale poultry farm level. To the best of my knowledge, there have been no published studies addressing the economic effectiveness of various strategies to combat AI within the poultry industry, nor have there been studies investigating methodologies for such analysis. This paper proposes a framework where an economic model is integrated with an epidemiologic simulation method to study the effectiveness of AI mitigation strategies. The study's primary purpose is to illustrate a framework that can be used for comprehensive modeling of AI spread and mitigation options given the availability of necessary data, which are limited at this time. Here this framework is used to numerically examine the effectiveness of controlling the contact rates during asymptomatic and symptomatic periods for backyard flocks.

A similar body of work has been documented in the context of infectious livestock disease introductions in the United States (Schoenbaum and Disney, 2003; Bates, Thurmond, and Carpenter, 2003; Elbakidze and McCarl, 2006; Elbakidze, 2007). Most studies of livestock disease mitigation have concentrated on post-event response effectiveness, while limited attention has been devoted to pre-event prevention and preparedness activities. Elbakidze and McCarl (2006) conducted analyses of pre-event surveillance and post-event slaughter of infected and contact livestock herds as ex ante and ex post measures, respectively, to reduce the vulnerability of the U.S. livestock sector to infectious diseases such as FMD. Their results indicate that the probability of disease introduction, event characteristics, costs, and effectiveness of response actions all have significant influence on allocation of resources among ex ante and ex post mitigation measures. A similar framework was used to compare the economic effectiveness of investing in an animal traceability (identification) system to economic effectiveness of relying on post-event response actions (Elbakidze, 2007).

The simplified analysis presented in this paper is applied to a homogeneous population of flocks under the conditions of limited data availability on contact rates, potential losses, and costs of mitigation actions. Specifically, mitigation actions are studied within the context of the spread of AI across small backyard flocks. While this in itself is a valuable exercise, the ultimate goal is to apply this framework to a heterogeneous population of poultry farms to arrive at a more realistic representation of AI spread and its mitigation across the overall poultry sector. The framework presented here could easily be modified and used in a heterogeneous poultry farm setting. However, before such analysis can be carried out, appropriate data for each of the poultry farm categories, such as turkey and various size categories of broiler and layer flocks, will need to be obtained. This includes, but is not limited to, direct and indirect contact rates across poultry farms of various categories, and costs as well as effectiveness of mitigation actions specific to each poultry farm category.

Methodology and Theoretical Background

The spread of infectious animal diseases has been studied using state transition frameworks (Berentsen, Dijkuizen, and Oskam, 1992; Schoenbaum and Disney, 2003; Carpenter, 1988) based on Markov chain processes, in which the number of individuals in each state at a given time period depends on the number of individuals in each state in the previous time period and on transition probabilities between states. Spatial modeling techniques have also been employed to study disease spread (Bates, Thurmond, and Carpenter, 2003; Jalvingh et al., 1999), which take into account the geographic distribution of susceptible units. Such models allow for examination of geographically imposed control strategies, but are expensive, data intensive, and time consuming to build. In addition, various mathematical functional forms have been used, such as logistic or Reed-Frost formulations (Carpenter, Thurmond, and Bates, 2004; Elbakidze, 2007). These approaches allow for quick analysis of disease-spread mechanics by estimating and fitting functions that depict the progression of disease spread. In the current study, the method used is less data intensive and less time consuming but still allows for explicit modeling of asymptomatic and symptomatic periods of infectiousness with corresponding duration and contact rates.

This study relies on the susceptible-infected-recovered (SIR) framework for modeling the spread of avian influenza within a finite population of backyard flocks. Hufnagel, Brockmann, and Geisel (2004) employ the SIR framework to study spread and control of acute respiratory syndrome throughout the world. Using a reduced form of SIR which incorporates susceptible and infectious categories, Bicknell, Wilen, and Howitt (1999) study individual incentives of profit-maximizing producers to control bovine tuberculosis in New Zealand. Garner and Lack (1995) adopt a state transition Markov chain model based on SIR to arrive at direct and indirect economic impacts of FMD control options in Australia. Schoenbaum and Disney (2003), evaluating economic consequences of a hypothetical outbreak of FMD in the United States, and Berentsen, Dijkuizen, and Oskam (1992), investigating economic effectiveness of various FMD control policies in the Netherlands, use SIR state transition frameworks. Rich and Winter-Nelson (2007) also rely on the state transition framework to model spread of FMD in the southern cone of South America and assess economic effectiveness of spatially sensitive control options.

This study expands the SIR framework (Bicknell, Wilen, and Howitt, 1999; Hufnagel, Brockmann, and Geisel, 2004; Garner and Lack, 1995) for modeling the spread of avian influenza within a finite population of individuals to explicitly include asymptomatic category (A). This approach allows for explicit modeling of the lengths of asymptomatic and symptomatic periods as well as corresponding inter-flock contact rates. Differential equations (1)–(4) are used to formulate the resultant SAIR framework. The individuals in the SAIR framework are categorized according to their infection statuses: susceptible (S), asymptomatic state of infection (A), symptomatic state of infection (I), and recovered and/or removed (R). Thus, we differentiate between infected flocks that are symptomatic (I) and infected flocks that are in an asymptomatic state (A).

In the resulting SAIR framework, each individual at any given time is in any of the following four states: susceptible (S), infected-symptomatic (I), infected-asymptomatic (A), or removed (R). Individuals in the "removed" category include those who are dead from the disease or those who are culled as part of a response strategy. The units in this representation move through the chain of categories as follows: $S \rightarrow A \rightarrow I \rightarrow R$. This representation allows us to reflect the impact of policies and technologies which would aid in early identification of infected flocks or in reduction of inter-flock contact rates.

Differential equations (1)–(4), consistent with the SAIR framework, show the process over time:

$$\dot{S} = -b * I(t) * \frac{S(t)}{N} - d * A(t) * \frac{S(t)}{N}, \tag{1}$$

$$\begin{aligned}\dot{A} = {} & b * I(t) * \frac{S(t)}{N} + d * A(t) * \frac{S(t)}{N} - b * I(t-ap) * \frac{S(t-ap)}{N} \\ & - d * A(t-ap) * \frac{S(t-ap)}{N},\end{aligned} \tag{2}$$

$$\begin{aligned}\dot{I} = {} & b * I(t-ap) * \frac{S(t-ap)}{N} + d * A(t-ap) * \frac{S(t-ap)}{N} \\ & - b * I(t-ap-sp) * \frac{S(t-sp-ap)}{N} - d * A(t-sp-ap) * \frac{S(t-sp-ap)}{N},\end{aligned} \tag{3}$$

$$\dot{R} = b * I(t-sp-ap) * \frac{S(t-sp-ap)}{N} + d * A(t-sp-ap) * \frac{S(t-sp-ap)}{N}, \tag{4}$$

where N is the total number of flocks, $S(t)$ is the population of susceptible flocks at time t, I is the number of infected symptomatic flocks at time t, A is the number of infected asymptomatic flocks at time t, and R is the number of removed flocks at time t. The average number of daily inter-flock contacts adequate for the spread of disease from the symptomatic infected to the susceptible flock is denoted by b; similarly, d is the average number of inter-flock contacts adequate for the spread of disease from an asymptomatic to a susceptible flock. The length of the period in which an infected flock remains in an asymptomatic state is represented by ap, and sp is the length of the symptomatic period. The spread of infectious disease in this representation depends on inter-flock contact rates (b) and (d), which are assumed to include both direct and indirect contacts, and on the length of the asymptomatic (ap) and symptomatic (sp) periods.

Assuming a fixed number of total individuals (N), $\dot{S}$ shows the change in the number of susceptible flocks—i.e., how many flocks went from the susceptible to the asymptomatic infected category. The right-hand side of equation (1) states that the number of new infections equals the number of new infections generated by asymptomatic infected flocks, plus the number of new infections generated by symptomatic flocks. The number of new infections generated by asymptomatic flocks is equal to the rate of inter-flock contact for asymptomatic flocks, times the number of asymptomatic flocks at time t, times the proportion of total flocks that are susceptible. The number of new infections generated by symptomatic flocks is represented in a corresponding fashion.

Equation (2) shows that the change in the number of asymptomatic individuals is equal to the number of new infections generated by asymptomatic and symptomatic individuals, minus the number of infections generated $t = ap$ periods ago. The length of asymptomatic period equal to ap implies that flocks infected ap periods ago are starting to show signs of infection and are therefore becoming symptomatic. Notice that decreasing the asymptomatic period (ap) to zero simply transfers newly infected flocks directly into the symptomatic infectious flock category instead of letting them remain in an asymptomatic state for some period. In other words, with $ap = 0$, newly infected flocks are known to be infected in the next period. For ap not equal to zero, newly infected flocks stay in an asymptomatic state for ap number of periods, after which they become "symptomatic," either because of signs of disease or because of enhanced detection efforts.

Equation (3) shows the change in the number of symptomatic flocks, which is equal to the number of flocks that became infected-asymptomatic ap periods ago and are now becoming symptomatic, minus the number of flocks that became infected-asymptomatic ($ap + sp$) periods ago and are now leaving the "symptomatic" category, either because of death from the disease or because of culling as part of a response strategy. From the symptomatic infectious state (I), infected flocks are transferred to the "removed and recovered" state, in which the flocks are no longer infectious or susceptible.

The number of newly removed flocks $\dot{R}$ is given in equation (4) and is equal to the number of infections generated ($ap + sp$) periods ago, which have gone through the asymptomatic and symptomatic periods. This category normally consists of units that are dead due to the disease or units culled due to the policy of depopulating infected farms and premises. This representation, via parameters b, d, ap, and sp, reflects the effects of such disease mitigation options as depopulation of symptomatic flocks in response to the disease outbreak, early detection of infected flocks, and quarantining infected flocks—thereby decreasing contacts between infected and susceptible flocks. Note, this formulation assumes the flocks that are first to become infected are first to become symptomatic. Similarly, flocks that are first to become symptomatic or diagnosed are first to be depopulated.

The above formulation provides input in the form of the total number of infected flocks for the objective function, thus minimizing total costs associated with infectious animal disease introduction. Assuming all infected flocks will eventually be removed, the objective function can be formulated as follows:

$$TC = \int_0^T \left[D(\dot{R}) \right] dt + C(b, d, ap, sp), \tag{5}$$

where total costs TC is equal to damages (D) as a function of the total number of removed flocks over time, and costs (C) as a decreasing function of contact rates and lengths of

asymptomatic and symptomatic periods. In some ways this formulation appears to be similar to the typical optimal control problem (Leonard and Van Long, 1992; Clark, 1976; Horan and Wolf, 2005; Rondeau, 2001). Yet, two significant features of the formulation used here make optimal control theoretic analysis not as appropriate as it may seem.

First, control variables in this study—control of contact rates and reduction of lengths of symptomatic and asymptomatic periods—are not dynamic. In other words, decisions on early detection of asymptomatic flocks, reduction of the length of symptomatic period, and control of contact rates of asymptomatic as well as symptomatic flocks are made ex ante (prior to disease outbreak) and do not change over time. The purpose of this investigation is not to determine how efforts to reduce contact rates and efforts to reduce lengths of symptomatic and asymptomatic periods change over time, but rather to identify how these efforts are used in relation to one another. Although investigation of a temporal aspect of control of contact rates and duration of asymptomatic and symptomatic periods would be a worthy effort, this topic is left to another study. Since the control variables here are not formulated as dynamic, the phase diagram analysis of optimal control would be of very limited use.

Second, even if optimal control techniques of maximum principle conditions (Leonard and Van Long, 1992; Clark, 1976) were to be used, there would be four state equations, with four corresponding co-state variables and four control variables. The dimensionality of this problem, together with SAIR functional formulation, makes the analytical derivation of results intractable. Accordingly, we turn to empirical representation and analysis.

The Numerical Model

Small-scale poultry operations, such as family-owned backyard flocks, comprise a significant proportion of the number of U.S. poultry farms. For example, in 2002, of the total of 98,000 poultry farms with layers of 20 weeks or older, 93,000 were farms with less than 100 birds (USDA, *Census of Agriculture*, 2002). Therefore, while large commercial operations are important to investigate in terms of infectious poultry disease control and prevention, it may also be appropriate to concentrate the analysis on small-scale operations, which frequently do not adhere to the strict sanitary and bio-security procedures followed by large operations. Unfortunately, data on such operations are practically nonexistent. Particularly, there is a lack of data on direct and indirect inter-flock contact rates, as well as the costs and options for implementing bio-security and disease-control strategies. To our knowledge, the only documented source of data on the distribution of backyard flocks and some contact rates is a study conducted by Garber et al. (2007), where some information is provided on the distribution of backyard flocks in the proximity of commercial poultry operations. Unfortunately, even the data in the aforementioned document is not adequate for the type of model adopted in this study. Specifically, not enough information is provided to estimate direct and indirect contact rates or to calculate costs of particular mitigation strategies.

Given limited availability of appropriate data, the analysis must be constrained to scaled examination with assumed parameter values and sensitivity analysis. Consequently, the empirical framework in this study is based on a cost-minimization approach where total costs are represented by a normalized total damage function, and proportional

Table 1. Definitions of Mathematical Notations Used in the Model

Notation	Definition	Base Value
TCI	Total cost index	
TI	Total number of infected flocks	
N	Total number of flocks in the area	1,000
x_t	Number of newly infected flocks on day t	
S_t	Number of susceptible flocks on day t	
β_1	Parameter for logistic damage function	1,000
β_2	Parameter for logistic damage function	−10
c	Cost coefficient for mitigation efforts	0.5
ape	Choice variable for efforts to reduce length of asymptomatic period	[0:1]
ipe	Choice variable for efforts to reduce length of symptomatic period	[0:1]
be	Choice variable for efforts to reduce contact rates of asymptomatic flocks	[0:1]
de	Choice variable for efforts to reduce contact rates of symptomatic flocks	[0:1]
$brate$	Contact rate of asymptomatic flocks	0.3 contacts/day
$drate$	Contact rate of symptomatic flocks	0.15 contacts/day
$aperiod$	Asymptomatic period	5 days
$speriod$	Symptomatic period	10 days
b	Contact rate of asymptomatic flocks as a function of efforts to control asymptomatic contacts	
d	Control rate of symptomatic flocks as a function of efforts to control symptomatic contacts	
ap	Length of asymptomatic period as a function of efforts to reduce length of asymptomatic infectiousness	
sp	Length of symptomatic period as a function of efforts to reduce length of symptomatic infectiousness	

mitigation costs associated with total optimal efforts to reduce inter-flock contact rates and to shorten periods of asymptomatic and symptomatic infectiousness. In addition, the empirical examination is carried out for a hypothetical region of 1,000 backyard flocks. Such a formulation will yield insight on the characteristics of the optimality of efforts to control inter-flock contact rates relative to early detection of asymptomatic flocks and efforts to decrease the length of asymptomatic and symptomatic infectious periods at small-scale poultry operations. The mathematical notations used in the model are presented and defined in table 1.

Suppose the maximum value of losses, which is associated with all flocks in the area being infected, is scaled down to equal one. It could also be assumed that there is a nonlinear relationship between the number of infected small-scale poultry flocks and associated losses on a 0-to-1 (maximum losses) scale. Particularly, the first few infected backyard flocks may cause relatively small total losses. However, as the number of infected flocks increases, the total losses also continue to increase, at an increasing rate, up to a certain level. At some point, total losses will increase at a decreasing rate because

an uncontrolled epidemic has claimed a substantial proportion of the poultry industry including infections of large commercial operations. Further, as the outbreak gets larger, total losses will reflect demand implications and trade restrictions. Therefore, the damage function is assumed to have a logistic form to approximate the mechanics of increasing (decreasing) marginal costs at a low (high) number of infected flocks. In addition to damages brought by the outbreak, the objective function also includes costs associated with outbreak mitigation efforts such as costs of imposing quarantine zones, depopulation, etc. Thus, total costs associated with AI spread and associated preparedness, prevention, and control options are represented as:

$$TC = \frac{1}{1 + \beta_1 e^{\beta_2 (TI/N)}} + c(be + de + ipe + ape), \tag{6}$$

where TI is the total number of infected flocks, N is the total number of flocks, and β_1 and β_2 are coefficients to control the severity of damages as a function of the number of infected flocks. The cost index coefficient corresponding to mitigation efforts, c, shows how TC changes as a response to an increase in the level of overall mitigation efforts. For example, c of 0.1 would suggest that TC would increase by 0.1 as a result of a unitary increase in mitigation efforts up to the maximum amount of mitigation efforts corresponding to zero length of asymptomatic and symptomatic periods and zero contacts for asymptomatic and symptomatic flocks. Note, this representation implies the costs associated with control of contact rates and with decrease of the lengths of asymptomatic and symptomatic periods are proportionally equal. While this representation is restrictive, given the scarcity of data on actual costs, it still allows some analysis of relative effectiveness and interdependencies of mitigation efforts. This assumption could be relaxed upon availability of relevant cost data. Finally, ape, ipe, be, and de are [0:1] choice variables indicating the extent to which mitigation efforts are adopted to reduce the lengths of asymptomatic and symptomatic periods and to control inter-flock contact rates during asymptomatic and symptomatic periods, respectively.

Contact rates and lengths of time corresponding to asymptomatic and symptomatic statuses, as functions of mitigation efforts, are formulated as follows:

$$b = brate - brate * be, \tag{7a}$$

$$d = drate - drate * de, \tag{7b}$$

$$ap = aperiod - aperiod * ape, \tag{7c}$$

$$sp = speriod - speriod * ipe, \tag{7d}$$

where $brate$, $drate$, $aperiod$, and $speriod$ are coefficients, assumed to be 0.3, 0.15, 5, and 10, respectively (OIE, 2007). So, $be = 0$, corresponding to no efforts to control inter-flock contact rates for asymptomatic flocks, would suggest that $b = 0.3$, which would mean each flock, on average, contacts 0.3 flocks per day. In other words, on average, each flock has contact with another flock every three to four days. Similarly, $de = 0$, corresponding to no efforts to control inter-flock contact rates for symptomatic flocks, implies $d = 0.15$, which, by assumption, means contact rates of symptomatic flocks are cut in half, relative to asymptomatic flocks, as a result of showing infection signs or otherwise being diagnosed as infected. The value of $be = 1$ would suggest that maximum inter-flock contact

control efforts lead to zero contacts among flocks during the asymptomatic state, while $de = 1$ leads to no contacts during the symptomatic state. A value of $ape = 0$ would indicate no efforts to decrease the average asymptomatic period, which would equal five days. On the other hand, $ape = 1$ would suggest a maximum effort to decrease the asymptomatic period, resulting in zero asymptomatic days, which means infected flocks are known to be infected the next day. Similarly, $ipe = 0$ would imply a symptomatic period of 10 days, while $ipe = 1$ would indicate a symptomatic period of zero days, which means infected flocks are depopulated by the next day.

Numerically, the spread process of AI is represented by equations (8) and (9):

$$x_t = b * \frac{S_t}{N} * \left[\sum_{\tau=0}^{t-1} x_\tau - \sum_{\tau=0}^{t-ap} x_\tau \right] + d * \frac{S_t}{N} * \left[\sum_{\tau=0}^{t-ap} x_\tau - \sum_{\tau=0}^{t-ap-sp} x_\tau \right], \tag{8}$$

$$S_t = N - \sum_{\tau=0}^{t} x_\tau, \tag{9}$$

$$TI = \sum x_t, \tag{10}$$

where x_t is the number of newly infected flocks on day t; τ is used for notational convenience to denote new infections generated in the periods prior to day t. The remainder of the notation is consistent with previous discussion. New infections on day t are generated by contacts made by susceptible flocks with infected flocks that may be in either asymptomatic or symptomatic states. Asymptomatic flocks are those which were infected up to ap periods preceding t. Symptomatic infected flocks are those infected during the period between $(t - ap)$ and $(t - sp - ap)$. Equation (9) calculates the number of susceptible flocks in each period, and equation (10) calculates total number of infected flocks.

Results and Discussion

The results of this analysis provide insight into the interrelationships between actions influencing some of the factors essential in avian influenza spread within the backyard poultry sector. Specifically, this study investigates the implications and interdependencies of controlling inter-flock contact rates and the duration of symptomatic and asymptomatic states of infected flocks.

Figure 1 shows the spread of the disease under the scenario where outbreak damages accumulate less severely ($\beta_1 = 0.1$). Each solid line shows the number of daily infections over time, corresponding to cost-minimizing mitigation efforts under three scenarios with low, medium, and high mitigation costs ($c = 0.25$, $c = 0.5$, and $c = 0.75$, respectively). The dashed line shows daily infections under the scenario where no mitigation strategy was used—i.e., no efforts were made to either reduce inter-flock contact rates or to reduce the lengths of asymptomatic or symptomatic periods.

Two points need to be highlighted regarding figure 1. First, the total number of infected flocks, calculated as area under daily infection curves, is lowest with the least expensive mitigation scenario and highest with the most expensive mitigation scenario. This result is logical since less expensive mitigation strategies increase net marginal benefits of additional units of mitigation efforts, and consequently reduce the total number of infections. However, although true for the scenarios presented in figure 1,

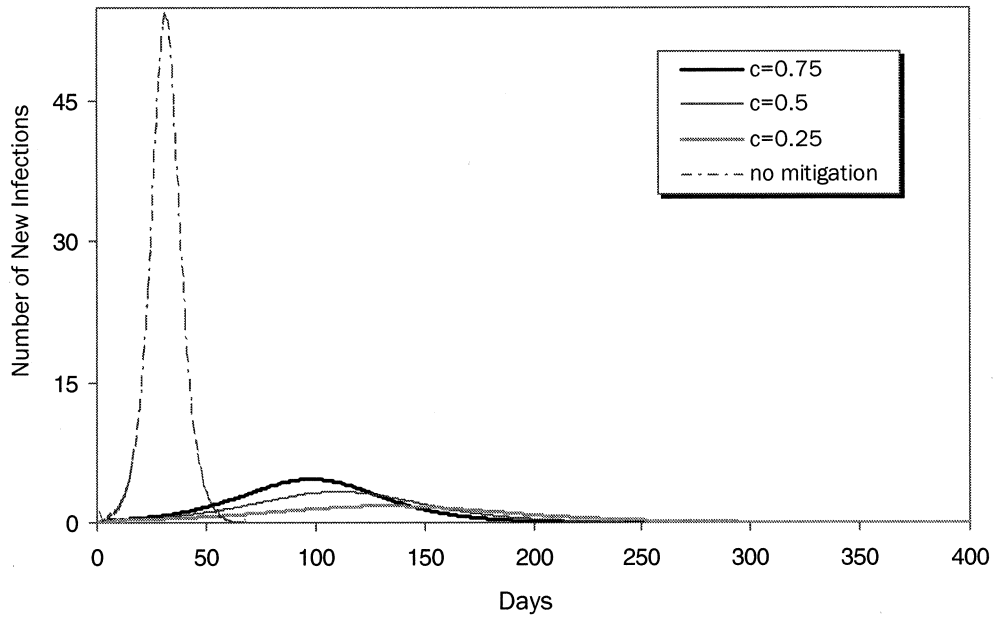

Figure 1. Daily infections under various levels of mitigation costs

minimizing the number of infected flocks does not necessarily imply total cost minimization after taking into account associated mitigation costs.

Second, while the least expensive mitigation scenario in figure 1 corresponds to the least costly outbreak with the fewest infected flocks, the duration of the disease is the longest. It is important to emphasize that the formulation, as presented in the previous section, minimizes total costs as a function of the number of infected flocks and does not include a penalty for lengthy but sparse presence of the disease. Prolonged, even small, presence of diseases like AI may have considerable implications in other industries such as tourism and food service. Hence, future modeling research efforts should include the length of disease presence as a significant component of costs associated with infectious livestock disease outbreaks.

To examine the relationships between the efforts to decrease the lengths of asymptomatic and symptomatic periods and efforts to decrease inter-flock contact rates for asymptomatic and symptomatic flocks, the efforts to control contact rates were optimized while fixing the efforts to decrease the lengths of symptomatic and asymptomatic periods at various levels ranging from zero to one.

Figure 2 presents cost-minimizing conditions under various combinations of efforts to decrease the lengths of asymptomatic and symptomatic periods when costs of mitigation efforts are intermediate ($c = 0.5$). The costs are minimized with respect to efforts to decrease inter-flock contact rates of infected asymptomatic and symptomatic flocks. In other words, each point on the surface corresponds to a cost-minimizing solution with respect to the efforts to control inter-flock contact rates during infected asymptomatic and symptomatic periods under a given combination of efforts to reduce the lengths of asymptomatic and symptomatic states. The respective cost-minimizing combination of efforts to decrease the length of asymptomatic and symptomatic periods is 0.9 and 0, and when using equations (7c) and (7d), corresponds to reducing the asymptomatic

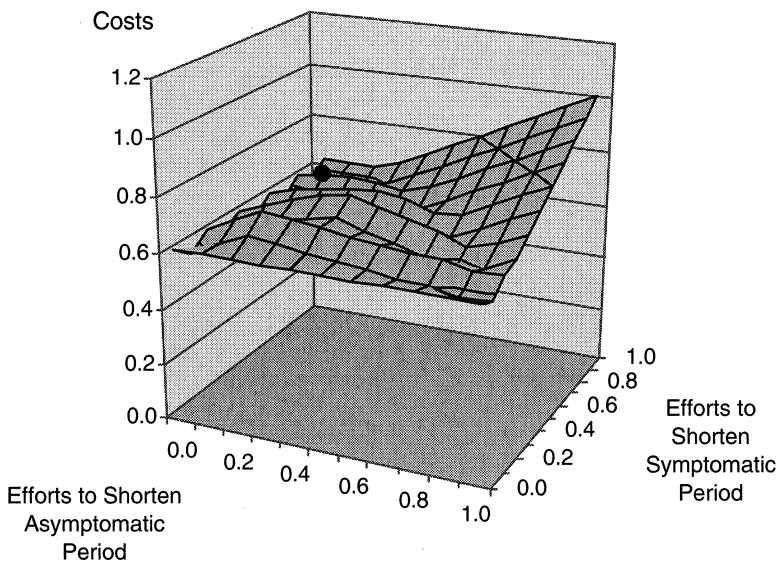

Figure 2. Cost minimization under intermediate mitigation costs (c = 0.5)

period from 5 to 0.5 days and leaving the symptomatic period at 10 days. This condition demonstrates the importance of reducing the lengths of the asymptomatic period. In other words, establishing mechanisms for early detection of AI in asymptomatic poultry flocks is a critical component of pre-event disease control options. The outcome that the length of the symptomatic period is not reduced and, as discussed below, symptomatic flocks are managed by reducing their inter-flock contact rates, is a result of assumed initial inter-flock contact rates. Specifically, contact rates for asymptomatic flocks are twice the contact rates for symptomatic flocks. Therefore, the optimal strategy is to reduce the length of the asymptomatic period and concentrate contact-reducing efforts on symptomatic flocks. Notice also that generally the costs are smaller for lower levels of efforts to decrease the length of asymptomatic and symptomatic periods and are greater for higher levels of efforts to decrease lengths of both asymptomatic and symptomatic periods. This finding suggests that employing mitigation strategies to the maximum available extent is suboptimal.

Cost-minimizing levels of effort to decrease inter-flock contact rates during the asymptomatic period at various levels of efforts to reduce the lengths of asymptomatic and symptomatic periods are given in figure 3. The optimal efforts to decrease inter-flock contact rates during asymptomatic periods are high when efforts to decrease the lengths of asymptomatic and symptomatic periods are low. This result corresponds to the expectation that under a cost-minimization framework the efforts to decrease inter-flock contact rates for asymptomatic flocks and efforts to decrease the lengths of asymptomatic and symptomatic periods generally function as substitute strategies. The optimal level of effort to decrease inter-flock contact rates for asymptomatic flocks, which corresponds to the cost-minimizing point from figure 2, is zero. Hence, using equation (7a), the inter-flock contact rate during the asymptomatic period remains at 0.3. However, effort to reduce the length of asymptomatic periods is 0.9, implying the

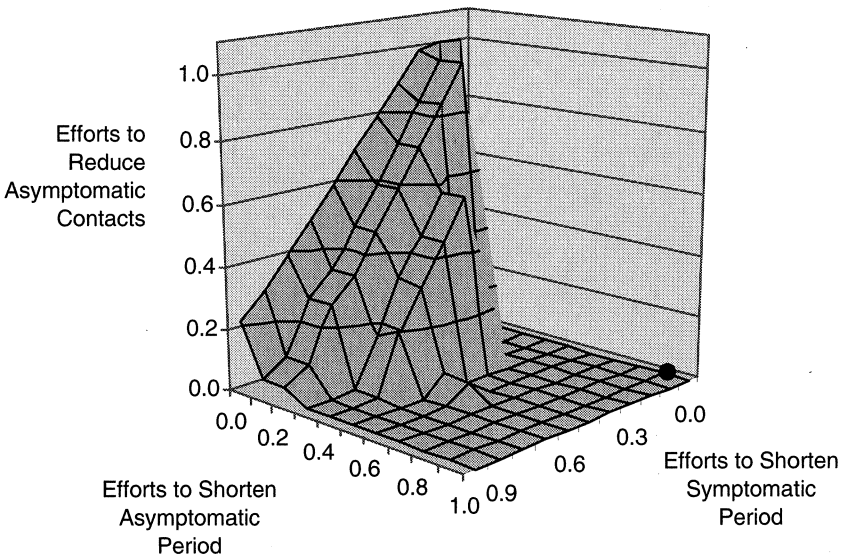

Figure 3. Optimal efforts to control contact of asymptomatic flocks under intermediate mitigation costs (c = 0.5)

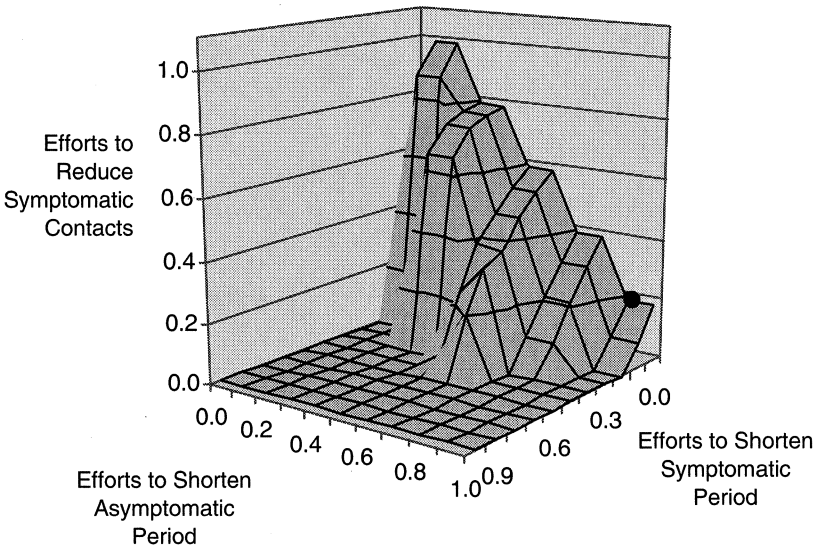

Figure 4. Optimal efforts to control contact of symptomatic flocks under intermediate mitigation costs (c = 0.5)

total number of inter-flock contacts that would otherwise be made by asymptomatic flocks has been significantly reduced because of the shortened length of the asymptomatic period.

Similar information is displayed for the efforts to decrease inter-flock contact rates for symptomatic flocks in figure 4. The optimal level of efforts to reduce symptomatic flock contact rates corresponding to the cost-minimizing point from figure 2 is 0.19. Using equation (7b), this finding reveals that the contact rate of symptomatic flocks is reduced from 0.15 to 0.12 contacts per day. Figure 4 shows that efforts to control contact rates for symptomatic flocks are highest when efforts to decrease lengths of asymptomatic and symptomatic periods are lowest. This suggests that reduction of symptomatic contact rates, to some degree, functions as a substitute for reduction of the lengths of asymptomatic and symptomatic periods. As would be expected, controlling contact rates of symptomatic flocks is more effective than controlling contact rates of asymptomatic flocks at higher levels of efforts to decrease the length of the asymptomatic period. In other words, controlling symptomatic flock contact rates is more desirable when the asymptomatic period is relatively short and the symptomatic period is relatively long. In contrast, as evidenced from figure 3, controlling inter-flock contact rates during the asymptomatic state is more desirable when the asymptomatic period is relatively long.

In addition, as expected, it was confirmed that increasing costs (c) of controlling the spread of AI decreases the optimal level of efforts to control inter-flock contact rates during asymptomatic and symptomatic periods. Increasing mitigation costs also decreases the optimal effort to shorten the length of the asymptomatic periods. Decreasing the severity of damages inflicted by the disease (β_1) slightly decreases the control of inter-flock contact rates during asymptomatic and symptomatic periods. Similarly, the optimal level of reducing the length of the asymptomatic period decreases in response to the decrease in severity of damages.

A word of caution is merited regarding the highly nonlinear nature of the formulation used in this study. The optimal solutions are highly sensitive to starting values of choice variables. Consequently, to check for global versus local minimums, numerous starting points were tried and the resulting optimal solutions are reported.

Conclusions

This paper presents an integrated, economic-epidemiologic framework for analyzing the mitigation strategies against the spread of infectious diseases across backyard poultry farms. Specifically, the framework is used to study the roles of reducing inter-flock contact rates and reducing the lengths of symptomatic and asymptomatic periods under a cost-minimization scheme. Control of inter-flock contact rates is considered for symptomatic as well as asymptomatic flocks.

The results of this work suggest that efforts to reduce the lengths of asymptomatic and symptomatic periods and efforts to control inter-flock contact rates generally function as substitutes. Based on these findings, under limited resource availability for AI control efforts, the mitigation strategy needs to be formed in a manner which takes into account substitutability of efforts to reduce inter-flock contact rates during asymptomatic and symptomatic periods and efforts to reduce lengths of symptomatic and asymptomatic periods. The results also show that as efforts to cut the length of the asymptomatic period increase, the control of inter-flock contact rates is more concentrated on

symptomatic flocks rather than on asymptomatic flocks. In contrast, as efforts to cut the length of the symptomatic period increase, the control of inter-flock contact rates is more concentrated on asymptomatic flocks than on symptomatic flocks. Efforts to control inter-flock contacts are higher for asymptomatic flocks than for symptomatic flocks because, as assumed, symptomatic flocks have lower contact rates than asymptomatic ones even without enforced control policies. Voluntary actions of some of the operators, following recognition of symptoms, are likely to reduce inter-flock contacts made by symptomatic flocks.

The results of this analysis emphasize the importance of careful design of the mitigation strategy to control potential outbreaks of AI within backyard flocks. As documented in earlier publications (Pelzel, McClusky, and Scott, 2006; Garnett, 1987), small backyard operations could play a significant role in the spread of AI within the commercial poultry sector. The more effective is the control of AI at backyard flocks, the less likely that large commercial operations will be infected via indirect contacts. As discussed above, control of contact rates and reduction of the lengths of asymptomatic and symptomatic periods could function as substitute efforts to control the spread of disease. This is an important result given the objective of minimizing the damages inflicted by the infectious disease. Contact rates for infected flocks could be controlled by imposing quarantine zones, depopulation, and disinfection programs, which at the backyard level are more costly and difficult to implement than at larger commercial operations.

Given the substitutability of control of the contact rates and reduction in the lengths of infectious periods, two suggestions can be made. One, aimed at decreasing the length of the symptomatic period, is to design a compensation scheme where the owner of symptomatic flocks would have an incentive to disclose the presence of disease. Such programs would need to be designed with great care to avoid false reporting. The other, intended to decrease the asymptomatic period, is to encourage technological development of inexpensive disease test kits designed to be used by animal caretakers. Availability of such technology, in combination with correctly set up incentive mechanisms for reporting diagnosed disease, would reduce overall infectious periods. This in turn would allow less reliance on controlling inter-flock contact rates which, considering the possibility of direct and indirect contacts, could be a rather expensive and difficult task, especially at the backyard flock level.

Finally, the simplified analysis presented here is applied to a homogeneous population of flocks under the conditions of limited data availability on contact rates, potential losses, and costs of mitigation actions. Specifically, mitigation actions are studied within the context of the spread of AI across small backyard flocks. While this in itself is a valuable exercise, the ultimate goal is to apply this framework to a heterogeneous population of poultry farms to arrive at a more realistic representation of infectious disease spread and its mitigation across the overall poultry sector.

The framework presented in this study could easily be modified and used in a heterogeneous poultry farm setting. However, before such analysis can be carried out, appropriate data for each of the poultry farm categories, such as turkey and various size categories of broiler and layer flocks, will need to be obtained. This includes, but is not limited to, direct and indirect contact rates across poultry farms of various categories, costs, and effectiveness of mitigation actions specific to each poultry farm category. Furthermore, the cost function to be minimized will need to be represented by actual losses, rather than by an assumed representative damage function. The results of this

study suggest this framework could be usefully applied in the context of the spread of AI across heterogeneous poultry farm categories.

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