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Modeling the burden of poultry disease on the rural poor in Madagascar

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ABSTRACT

Livestock represent a fundamental economic and nutritional resource for many households in the developing world; however, a high burden of infectious disease limits their production potential. Here we present an ecological framework for estimating the burden of poultry disease based on coupled models of infectious disease and economics. The framework is novel, as it values humans and livestock as co-contributors to household wellbeing, incorporating feedbacks between poultry production and human capital in disease burden estimates. We parameterize this coupled ecological–economic model with household-level data to provide an estimate of the overall burden of poultry disease for the Ifanadiana District in Madagascar, where over 72% of households rely on poultry for economic and food security. Our models indicate that households may lose 10–25% of their monthly income under current disease conditions. Results suggest that advancements in poultry health may serve to support income generation through improvements in both human and animal health.

Introduction

Globally, there are 2.2 billion people who live on less than 2 USD a day [1], and approximately half rely on livestock for their livelihoods [2]. For the rural poor who rely on agricultural production for subsistence [3], production outputs are often generated from physical labor, and may be sold, consumed, or traded for goods and services. Livestock have been shown to contribute to the production process through multiple pathways. They provide financial capital, as a liquid asset; physical capital, when used for transportation or traction; natural capital, when manure is used to improve soil fertility; and human capital, through the effects of improved nutrition on physiological growth, cognitive development, and education attainment [4].

The majority of poor livestock keepers live in South Asia (600 million) and Sub-Saharan Africa (300 million) [2], regions of the world where infectious and parasitic diseases continue to undermine the health and productivity of both humans and livestock [5,6]. Good health is essential for the development of human capital, as it influences an individual's capacity to grow, learn, and actively engage in productive labor [7]. Like their human counterparts, livestock are complex biological organisms whose reproduction, growth, and economic value are necessarily influenced by their health status [8]. Therefore, diseases that afflict livestock threaten the subsistence of poor households in ways that are directly comparable to the effects of human disease; not only through direct loss of income, but also by undermining immediate and long term human capital accumulation through poor nutrition and health. Although there is a growing body of literature that supports the role of improving livestock health in poverty reduction [9–11], we lack frameworks for measuring disease burden that capture the cumulative impacts of livestock disease on the livelihoods and health of the rural poor.

Madagascar, a country with high levels of material deprivation, malnutrition, and reliance on agriculture, provides an exemplar setting for exploring these relationships. As one of the poorest countries in the world, Madagascar consistently ranks within the bottom 20% of all

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countries for indicators of development [12] and food security [13]. Eighty-seven percent of Malagasy survive on less than 1.25 USD per day [1], and approximately 15 million people, or two-thirds of the total population, live in rural areas where agriculture and livestock production are the primary forms of employment [14]. Madagascar has over 27 million chickens and 9.2 million other varied poultry species [14]; and as in many other low income countries, poultry are important livestock species for the poor. They produce meat and eggs for household consumption, and are easily transported to local markets for sale [15,16].

Many of the major pathogens with the potential to impact poultry production have been reported in the country, including: avian influenza virus, Newcastle Disease virus, infectious bursal disease virus, fowl cholera (*Pasteurella multocida*), and intestinal parasites [17–19]. These pathogens decrease production as a result of high morbidity and mortality, with sequela including transient immune suppression, poor weight gain, and reduced egg production [20]. In order to quantify the effects of poultry disease on economic productivity, we present an ecological model framework that accounts for long-term interactions between poverty and infectious disease. The model is based on the premise that human and poultry capital are complementary inputs for generating household income, and that human capital (in the form of nutrition) is also supported by poultry production. The dynamic relationship between poultry disease and economic outcomes is modeled by coupling well-established susceptible–infectious–susceptible (SIS) disease-type models [21–23] with a simple economic growth model [24].

The framework builds on a theory of infectious diseases as ecological drivers of poverty [25–27], and allows one to measure the impact of poultry disease dynamics on household income directly, and on household capital accumulation. In this study, we estimate the burden of poultry disease in the Ifanadiana District of Madagascar recognizing that feedbacks between loss of production and human capital can exacerbate the economic impact that infectious diseases of poultry can have on poor households. We calibrate our model using data from a 1520-household human health and demographic survey and an 80-household pilot study of livestock health.

Materials and methods

Model framework

The epidemiological model for poultry disease

The poultry disease model is based on standard models in epidemiology and disease ecology [21–23], where the poultry population is apportioned into two compartmental classes, representing disease status. The susceptible or healthy class denoted by S_c consists of uninfected poultry with the potential of being infected, while the infectious or unhealthy class denoted by I_c, consists of infected poultry that can transmit disease. To account for differences in egg production between healthy and unhealthy poultry, we introduce a third class for eggs, denoted by E_c, and use two distinct egg production rates: α_s for egg production by healthy poultry and α_i for egg production by unhealthy poultry. A schematic of the model is presented in Fig. 1.

We present the following system of differential equations for the dynamics of the healthy and unhealthy poultry and egg populations:

$$\dot{S}_c = \Lambda_c + \pi_c + \gamma_c I_c - (\beta_c I_c + \mu_c + \sigma_c) S_c, \quad (1)$$

$$\dot{I}_c = \beta_c I_c S_c - (\gamma_c + \nu_c + \mu_c + \sigma_c) I_c, \quad (2)$$

$$\dot{E}_c = \alpha_c S_c + \alpha_i I_c - (\mu_e + \sigma_e) E_c. \quad (3)$$

We assume new births and purchases occur at respective rates, Λ_c and π_c. The susceptible poultry population also increases when previously sick poultry recover from the infection at rate γ_c, and is reduced as a result of infection occurring at rate β_c, natural mortality or loss at rate μ_c, or through sale or consumption at rate σ_c. The infectious poultry population grows as a result of new infections and is reduced as a result of both natural and disease-induced mortalities occurring at respective rates μ_c and ν_c. The infectious poultry population is also reduced when infected poultry recover to join the susceptible class or when they are sold or consumed at rate σ_c. Eggs, E_c, are laid by susceptible and infectious poultry at respective rates, α_s and α_i, and become consumed or sold at rate σ_e, or lost or hatched at rate μ_e.

Poultry-based income, M, is defined as:

$$M = p_e \sigma_e E_c + \sigma_c (p_s S_c + p_i I_c) - p_p \pi_c, \quad (4)$$

where p_e is the sales price of one unit of egg, p_s is the unit sales price of a healthy bird, p_i is the unit sales price of an unhealthy bird, and p_p is the unit purchase cost of healthy poultry and π_c is the purchase rate.

The economic model

In the economics literature, income generation is typically modeled with production functions [24,28,29], where income (i.e. the monetary value of total production) is generated from inputs, such as physical capital (i.e. infrastructure, equipment, land), human capital (i.e. education, human health, nutrition), and labor. We accordingly model household income with the following production function:

$$y = f(k, h) + M = k^{\alpha_k} h^{\alpha_h} + M, \quad (5)$$

where $f(k, h) = k^{\alpha_k} h^{\alpha_h}$ represents household income from sources other than poultry. The state variables k and h represent household physical and human capital, respectively. The exponents α_k and α_h denote production elasticities. Typically, it is assumed that $\alpha_k + \alpha_h < 1$, so that the system experiences diminishing returns to all capital [24]. Through this production function, capital is transformed into income, a portion of which is reinvested into future capital, while the other proportion is consumed. As in [24] we model the dynamics of physical and human capital through the following system of differential equations:

$$\dot{k} = r_k y - \delta k \quad (6)$$

$$\dot{h} = r_h y - \delta h \quad (7)$$

where r_k and r_h are the rates of physical and human capital accumulation and δ is the rate at which capital depreciates.

The coupled epidemiological–economic model

The coupled model is obtained by combining Eqs. (1)–(7). The coupling occurs through income, M, which is generated from the poultry disease models and fed into the equation for total household income (Eq. (5)), and ultimately into the equations for physical and human capital (Eqs. (6) and (7)). See [25,26] for details on using such integrative approaches for modeling the dynamics of coupled economic-epidemiological systems.

Estimating the economic burden of poultry disease

The framework described by Eqs. (1)–(7) can be used to estimate the economic burden of poultry disease as the difference between household income with current poultry disease prevalence, $y_{I_c = I_c^*}$, and the household income in the absence of any poultry disease, $y_{I_c = 0}$, where I_c^* is the infectious poultry population at equilibrium:

$$\textit{Poultry Disease Burden} = y_{I_c = 0} - y_{I_c = I_c^*} \quad (9)$$

Data

Study site

The Ifanadiana District, centered at 21°18′S 47°38′E, has an average elevation of 466 m, average annual rainfall of 1700 mm, and average