Received Date : 27-Aug-2015

Revised Date : 30-Mar-2016

Accepted Date : 25-Apr-2016

Article type : Original Article

Turnover of village chickens undermines vaccine coverage to control HPAI H5N1

J.P. Villanueva-Cabezas^{1,2}, P.T. Campbell^{1,3}, J.M. McCaw^{1,3,4}, P.A. Durr², J. McVernon^{1,3}

¹ Centre for Epidemiology and Biostatistics, Melbourne School of Population and Global Health, University of Melbourne, Melbourne, Australia

² Australian Animal Health Laboratory, CSIRO, Geelong, Victoria, Australia.

³ Modelling and Simulation Research Group, Murdoch Childrens Research Institute, Royal Children's Hospital, Parkville, Victoria, Australia.

⁴ School of Mathematics and Statistics, The University of Melbourne, Melbourne, Australia

Corresponding author: J.P. Villanueva-Cabezas | juanvc@student.unimelb.edu.au

Summary: Highly pathogenic avian influenza (HPAI) subtype H5N1 remains an enzootic disease of village chickens in Indonesia, posing ongoing risk at the animal-human interface. Previous modelling showed that the fast natural turnover of chicken populations might undermine herd immunity after vaccination, although actual details of how this effect applies to Indonesia's village chicken population have not been determined. We explored the turnover effect in Indonesia's scavenging and mixed populations of village chickens using an extended Leslie Matrix model parameterized with data collected from village chicken flocks in Java region, Indonesia. Population dynamics were simulated for 208 weeks; the turnover effect was

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1111/zph.12282](https://doi.org/10.1111/zph.12282)

This article is protected by copyright. All rights reserved

1 simulated for 16 weeks after vaccination in two ‘best case’ scenarios, where the whole
2 population (scenario 1), or birds over 14 day-old (scenario 2), were vaccinated. We found that
3 the scavenging and mixed populations have different productive traits. When steady-state
4 dynamics are reached, both populations are dominated by females (54.5%), and “growers” and
5 “chicks” represent the most abundant age-stages with 39% and 38% in the scavenging, and 60%
6 and 25% in the mixed population, respectively. Simulations showed that the population turnover
7 might reduce the herd immunity below the critical threshold that prevents the reemergence of
8 HPAI H5N1 4 to 8 weeks (scavenging) and 6 to 9 weeks (mixed population) after vaccination in
9 scenario 1, and 2 to 6 weeks (scavenging) and 4 to 7 weeks (mixed population) after vaccination
10 in scenario 2. In conclusion, we found that Indonesia’s village chicken population does not have
11 a unique underlying population dynamic and therefore, different turnover effects on herd
12 immunity may be expected after vaccination; nonetheless, our simulations carried out in best
13 case scenarios highlight the limitations of current vaccine technologies to control HPAI H5N1.
14 This suggests that improvements and complementary strategies are necessary and must be
15 explored.

16 **Keywords:** Avian influenza, poultry, population dynamics, mathematical modelling

18 **Impact**

- 19 • Village poultry infected with HPAI H5N1 remain a risk at the animal-human interface within
20 Indonesia;
- 21 • We explored two population dynamics coexisting amongst the Indonesian village chickens
22 that could have different impact on the effectiveness of vaccine interventions and duration of
23 adequate herd immunity;
- 24 • Our simulations highlight the importance of developing separated demographic models for
25 the Indonesian sector 4 when planning vaccine strategies to control HPAI H5N1.

27 **Introduction**

28 The emergence and reemergence of zoonotic diseases during the last three decades has prompted
29 a holistic approach to public health, with the aim of attaining the best health possible for humans
30 and animals, the effort being called ‘One Health’ (Zinsstag *et al.*, 2015). In this context, the
31 World Health Organization (WHO), the World Organization of Animal Health (OIE), and the

1 Food and Agriculture Organization of the United Nations (FAO) formed an alliance to consider
2 the challenges posed by highly pathogenic avian influenza (HPAI) subtype H5N1 in countries of
3 Asia and Africa (FAO/OIE/WHO, 2010a). This alliance called for further research including the
4 study of animal and human population dynamics as a priority (FAO/OIE/WHO, 2010b) to
5 further understand their role in spreading zoonotic HPAI at the animal-human interface.

6 As of 2016, 63 countries have reported circulation of HPAI H5N1 among poultry
7 (EMPRES/FAO-GLEWS, 2012) and 16 have reported human cases (World Health Organization,
8 2015a). Among them, Indonesia is one of the most severely affected, reporting enzootic
9 circulation of the virus at the poultry level (World Health Organization, 2013) and the world's
10 second largest number of human reported cases, after Egypt (World Health Organization,
11 2015a). Undoubtedly, the control of HPAI H5N1 in Indonesia is a complex public health
12 challenge since over 60% of the households keep *village chickens* (Farnsworth *et al.*, 2011), a
13 backyard production with subsistence or side business purposes. These productions, denominated
14 “sector 4”, generally lack biosecurity measures (FAO, 2008a) and, therefore, are presumed to
15 have an important role in the circulation of HPAI H5N1 (Sims *et al.*, 2005). In 2004, the
16 Indonesian government implemented a vaccination plan designed to generate herd immunity in
17 these flocks and reduce the circulation of this virus (Siregar *et al.*, 2007).

18 Since 2009, Indonesia has successfully been able to keep HPAI H5N1 under control which has
19 reduced the number of new human cases (World Health Organization, 2015a) and the number of
20 poultry outbreaks (EMPRES/FAO, 2012) although these continue to be reported (EMPRES-i
21 FAO, 2015). It is not completely clear how poultry in sector 4 contribute to sustain HPAI H5N1
22 in Indonesia; however, the low biosecurity, the discontinuous mass vaccination programs, and
23 the fast turnover that increases the number of influenza-susceptible individuals undermining the
24 herd immunity, might imply that the village chicken population is a reservoir that sporadically
25 infects the commercial sector and the human population.

26 To date, there are no studies specifically investigating Indonesia's village chicken population
27 dynamics and their effect on vaccine interventions to control HPAI H5N1. With the objective of
28 overcoming this limitation, we model the Indonesian village chicken population whereby we
29 simulate population dynamics with the specific aim to assess the effect of the turnover on the
30 achievable herd immunity after vaccination.

Material and Methods

Village Chickens parameters

We undertook a detailed review of the formal and informal literature on the population dynamics of village chicken populations in Indonesia and the region. This showed a general tendency to treat the village chicken population as homogeneous, comprising free-range scavenging birds (Siregar *et al.*, 2007, FAO, 2009b, ILRI, 2011, Unger *et al.*, 2012). However, a more careful revision indicates the existence of subpopulations of village chickens according to the rearing system: the “traditional”, where birds are left to scavenge freely in the village without farmer’s management or care; the “semi-improved”, where birds receive feed and some health care; and the “improved” where birds are fed, cared for, separated by age-stage, and is fully business-oriented in contrast with the traditional and semi-improved (FAO, 2008b). The scavenging (or traditional) system remains the most popular in Indonesia because most villagers are unable or unwilling to initiate commercialized production (FAO, 2008b).

There is limited literature on the demographic and production traits of the current scavenging village populations; however, as this system is resistant to change (Alders & Pym, 2009), we considered that a detailed investigation undertaken in the 1970s (Kingston, 1980), is likely to remain relevant. We did not find specific literature describing the semi-improved or improved village production populations; however, a detailed survey of village production was undertaken in West and Central Java in 2008 (FAO, 2009b) in which average parameters for the three subpopulations were provided. The traits described in this survey resemble a “mixed” farming system as described by Handaka (2009) where birds are obtained on-farm or with some purchase, production is partly consumed and partly sold in markets, and rearing poultry is deemed a diversification for family income. Therefore, we parameterized a scavenging and a mixed population of Indonesian village chickens, with data collected in the Java region.

The scavenging and mixed populations were divided into four gender-specific age-stages including eggs, chicks (< 1 month), growers (1-6 months), and adults (> 6 months). For model purposes, duration of age-stages was counted in weeks. Female reproductive output was calculated using the number of eggs described in Kingston (1980) and the clutches/hen/year in FAO (2009b). Eggs and chicks were anticipated to be of ratio 1:1 female: male, based on scientific observations (Parker & Winker, 2005). Survivorship for eggs and chicks were

1 calculated using the reported abundance of individuals at different times of each particular age-
2 stage (Kingston, 1980, FAO, 2009b). Given the lack of information on overall survivorship for
3 growers and adult village chickens in the Indonesian context, these were estimated to be 30%
4 and 20% for female and male growers, and 20% and 10% for hens and cocks based on the
5 average flock structure of village chickens in Java (FAO, 2009b). The maximum age for adults
6 for the scavenging chicken population was set to two years for hens and one and a half years for
7 cocks (Diwyanto & Iskandar, 1999). We assumed a maximum age of one year for hens and
8 cocks in the mixed population.

9 **Demographic Model**

10 We broadly used the demographic matrix modelling approach published by Lesnoff *et al.* (2009),
11 wherein the turnover of a free-range chicken population characteristic of the African context and
12 its effect on the herd immunity after vaccination were simulated. Lesnoff *et al* model extends
13 upon the classic Leslie Matrix Model based on methods published elsewhere (Crouse *et al.*,
14 1987, Caswell, 2001, Skalski *et al.*, 2010). Given the limited husbandry that village chickens
15 receive in the Indonesian context (Kingston, 1980, Aini, 1990, FAO, 2008a, FAO, 2009b) which
16 compromises the ascertainment of detailed age-specific parameters and population counts for
17 these birds, we used an aggregated modelling approach reflecting age-stages.

18 Lesnoff *et al* model respects most of the classic Leslie Matrix Model characteristics but
19 acknowledges that age-stages may differ in duration. Additionally, their model allows the
20 inclusion of both female and male parameters (Skalski *et al.*, 2010, Lefkovitch, 1965). Thus, in
21 our aggregated version of Lesnoff *et al* model the projection matrix (A) includes the female
22 reproductive output, and the survivorship *within* and *between* age-stages for both genders; the
23 population vector (N) includes the female and male abundance in every age-stage. The general
24 model is denoted:

$$A * N_t = N_{t+\Delta t} \text{ or } \begin{bmatrix} P_{1f} & F_{2f} & F_{3f} & F_{4f} & 0 & 0 & 0 & 0 \\ S_{1f} & P_{2f} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & S_{2f} & P_{3f} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & S_{3f} & P_{4f} & 0 & 0 & 0 & 0 \\ \hline F_{1m} & F_{2m} & F_{3m} & F_{4m} & P_{1m} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{1m} & P_{2m} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{2m} & P_{3m} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & S_{3m} & P_{4m} \end{bmatrix} * \begin{bmatrix} n_{1f} \\ n_{2f} \\ n_{3f} \\ n_{4f} \\ n_{1m} \\ n_{2m} \\ n_{3m} \\ n_{4m} \end{bmatrix}_t = \begin{bmatrix} n_{1f} \\ n_{2f} \\ n_{3f} \\ n_{4f} \\ n_{1m} \\ n_{2m} \\ n_{3m} \\ n_{4m} \end{bmatrix}_{t+\Delta t},$$

where the upper-left matrix is the original Leslie Matrix (Leslie, 1945, Leslie, 1948) including the number of females born from a female in each age-stage (F_{xf}), the female probability of surviving and remaining within the same age-stage (P_{xf}), and the probability of surviving an age-stage and passing to the next (S_{xf}); the lower left matrix is the number of males born from a female in each age-stage (F_{xm}); the lower-right matrix is the male probability of surviving and remaining within the same age-stage (P_{xm}), and the probability of surviving an age-stage and passing to the next (S_{xm}). The upper-right matrix is completed with zero (males do not have offspring). The n_{xf} , n_{xm} values in population vectors N_t and $N_{t+\Delta t}$, represent the female and male abundance in each age-stage at time t and $t+\Delta t$, respectively. This model allows for calculation of the *multiplicative factor of change in population size from one time period to the next*, λ ; and the *relative gender-age-stage abundance in a stable population* (Skalski et al., 2010). Demographic traits are in Table 1; detailed calculations of the model's parameters are in Supplement 1.

For each of the scavenging and mixed populations, population dynamics were simulated as follows: matrix A was filled with the fixed parameter values in Supplement 1 derived from population traits in Table 1. A starting population based on the number of households and average number of chickens per flock in Central Java was estimated; then, the relative abundance of age-stages in these flocks (FAO, 2009b) was directly extrapolated to the starting population to produce the distribution included in vector N for week 0. This extrapolation is possible since Leslie Matrix models produce a unique relative age-stage abundance when steady-state dynamics are reached, regardless of the initial distribution included in vector N ; therefore, the relative age-stage abundance is characterized by the parameter values included in matrix A (Caswell, 2001, Skalski et al., 2010). Population dynamics were simulated in R software (R Development Core

Team, 2014) for 208 weeks, until the populations reached steady-state dynamics. Given that the average Indonesian village chicken population is fairly stable (Unger et al., 2012), in a final step we compared our projection of *steady-state* relative age-stage distribution for the scavenging and mixed populations against validation data of the Javanese village chicken population (ILRI, 2011).

Simulation of a vaccine intervention for H5N1

Two “best vaccine intervention scenarios” were simulated in which all birds are immunocompetent, one dose is enough to provide effective immunization, birds become immediately immune after vaccination (100% immune response), and 100% of target birds are vaccinated. Simulations allowed estimation of the population turnover effect alone on the achievable herd immunity level, and the number of weeks after vaccination the herd immunity lasts before reaching the herd immunity critical threshold that prevents viral reemergence. This critical herd immunity threshold was estimated to lie between 50% to 67% , calculated as in Fine et al. (2011), using the R_0 reported in Ward et al. (2009) and Tiensin et al.(2007).

Once the population achieved *steady-state dynamics*, vaccination was implemented at a single time. Village flocks in Indonesia have been recommended to be vaccinated twice, with an interval period of approximately 14 weeks (Bouma et al., 2008); we assumed that a second vaccination could be completed up to 16 weeks after the first intervention since logistic difficulties are often reported (Siregar et al., 2007, Bouma et al., 2008). Thus, simulation of herd immunity after vaccination was conducted in two scenarios: the whole population is vaccinated (scenario 1) or only those >14 day-old received the vaccine (scenario 2).

Population turnover was assumed to be driven by birth and removal (death, consumption or sale) of birds from the population; however, purchase of chicks also occurs in the “mixed” population (FAO, 2009b, Handaka, 2009). Chicks born were calculated based on hen and egg parameters of fertility and survival included in Table 1. The population removed was estimated for every week to avoid overestimating the number of individuals susceptible to H5N1. Detailed calculation of herd immunity after vaccination is in Supplement 2.

We conducted an uncertainty analysis to determine the robustness of herd immunity estimates to variations in model parameters. Data from Indonesia and Asia (Kingston et al., 1982, Cumming,

1992, Gunaratne *et al.*, 1993, FAO, 2009b) were collated to estimate triangular densities (minimum, maximum, and most likely values) for each parameter. Population dynamics were simulated for sets of parameters randomly selected from triangular densities (Supplement 2) using Latin Hypercube Sampling (McKay *et al.*, 1979); those sets producing variations of population abundance larger than 2% per week were excluded from our analysis to reflect the stability of the village chicken population over time (Unger *et al.*, 2012). Finally, we conducted a sensitivity analysis based on partial rank correlation coefficients (PRCC) (Marino *et al.*, 2008) to measure the strength of association between each model parameter and the herd immunity in scenario 1 and 2. Coefficients were calculated for the herd immunity in week 7 post-vaccination, because this time point represents an intermediate time in our simulations.

Results

Village chicken parameters

The demographics of the scavenging and mixed village chicken populations (Table 1) show that the average number of eggs per hen in the scavenging population is – perhaps surprisingly - higher than in the mixed; however, when chicks hatch, the weekly survival of scavenging chicks is about 23% less than the survival of chicks in the mixed population. This means the number of growers surviving weekly in the scavenging population is lower compared to the mixed, despite the same probability of weekly survivorship in this age-stage. However, the few adults in the scavenging population have a better probability of weekly survival given their longer life expectancy.

Direct comparison of the modelled Indonesian village populations with the generalized African free-range chicken population results given by Lesnoff *et al* (2009) is not straight forward since the duration of age-stages has been estimated differently. However, comparing the model inputs shows that the number of eggs in the African system is lower than that expected in the Indonesian populations, the overall survival of African chicks in 10 weeks is equal to that of the Indonesian scavenging chicks at 4 weeks, and adults in African flocks have higher probability of weekly survival than those in any Indonesian village chicken population.

Demographic model and projections

Both the scavenging and mixed populations achieved *steady-state dynamics* producing populations with stable relative age-stage distribution characterized by the best parameter value estimates included in matrix A. When such steady-state dynamics are reached, the scavenging population is dominated by growers and chicks (39% and 38% respectively, females and males combined); hens make up 16% of the population and cocks 7%. The mixed village chicken population is also dominated by growers, although here they represent over half of the population (60% females and males combined); chicks are 25% of the individuals while hens and cocks represent 12% and 6%, respectively.

The multiplicative factor of change in population size from one time period to the next was estimated to be $\lambda_{\text{scavenging}} = 1.002$ and $\lambda_{\text{mixed}} = 0.998$. Where $\lambda=1$ represents no change in population size, the estimated values of λ reflect marginal variation of population size in the period simulated.

When the model output for the scavenging and mixed populations were compared with the validation data (ILRI, 2011), the *steady-state* relative age-stage distribution of the mixed - but not that of scavenging village chickens - was generally consistent (Table 2).

Simulation of a vaccine intervention for HPAI H5N1

The simulation of ‘best case scenarios’ showed that the natural turnover of the scavenging and mixed village chicken population undermines the achievable herd immunity level conferred by vaccination in a short period of time.

When the intervention includes all birds, the herd immunity decreases to 84.7% and 93.2% one week after vaccination; by week 10, less than half of the population would be immune (40.5% of the scavenging and 48.5% of the mixed population); 16 weeks after vaccination, the herd immunity would be only 29.5% and 31% for the scavenging and mixed population, respectively. Trends are more dramatic when only birds >14 days old are vaccinated. The day of vaccination, only 80.7% of the scavenging and 87.6% of the mixed population would be immune; one week after, the immune population drops to 71.3% and 81.5% respectively. By week 10, 37.8% of the scavenging and 42.2% of the mixed chickens remain immune and only 27.7% and 26.9% keep that condition 16 weeks after the intervention (Figure 1).

1 The uncertainty analysis showed that over a range of realistic parameter estimates, the time to
2 reach the herd immunity critical threshold is only a few weeks despite the simulations being
3 perfect scenarios of vaccination (Figure 2). If all birds are vaccinated, the median time to reach
4 the higher critical threshold (67%) after vaccination would be 4 and 6 weeks (interquartile range
5 [iqr] = 5–6 weeks) for the scavenging and mixed population, respectively, while the median time
6 to reach the lower critical threshold (50%), would be 8 weeks (iqr = 7–8) and 9 weeks (iqr = 8–
7 10) respectively. When only birds >14 days old are vaccinated, the higher threshold would be
8 reached in a median time of 2 weeks (iqr = 2–3) in the scavenging and 4 weeks (iqr = 3–4) in the
9 mixed population; the lower threshold would be reached in 6 weeks (iqr = 6–7) and 7 weeks (iqr
10 = 7–8) respectively. These median times are consistent with those observed in the simulation
11 based on best parameter value estimates in our model (scavenging: 4, 7, 2, and 5 weeks; mixed:
12 6, 10, 4, 8 weeks).

13 The sensitivity analysis revealed monotonic and statistically significant associations ($p < 0.001$)
14 between all the model parameters for the scavenging and mixed population and the herd
15 immunity, in scenarios 1 and 2. Fecundity of hens, the survival of eggs that become chicks, and
16 the survival of female growers becoming hens have the largest impact on the reduction of herd
17 immunity, while better survival of male growers and cocks within the population would help to
18 attenuate the fast decrease of herd immunity observed in both population of village chickens in
19 scenarios 1 and 2 (Figure 3; Supplement 2).

20 Discussion

21 In this study, we modelled a scavenging and a mixed population of Indonesian village chicken
22 populations using an aggregated extension of the classic Leslie Matrix model parameterized with
23 available productive data. The application of this model sought to recreate population dynamics
24 to inform the simulation of vaccine interventions and the achievable level of herd immunity. The
25 model produced meaningful projections that allowed the simulation of vaccine interventions
26 which highlighted the challenges of vaccinating village chickens.

27 The aggregated model approach allowed close representation of the biological processes
28 underpinning the population turnover, despite the assumption of population dynamics
29 independent of density and resources, sufficient males to fertilize every hen and a constant rate
30 of birth and removal of birds. Aggregated models have demonstrated efficiency in simulating

dynamics of poorly characterized populations (Crouse et al., 1987) despite the risk of introducing some bias to transition probabilities between age-stages.

We compared our projections with demographic data from a survey of village chicken populations in Java (ILRI, 2011) for validation purposes. The fitting of the relative age-stage abundance projected for the mixed, but not the scavenging population, demonstrates that Indonesia's village chicken population is not driven by a single population dynamic. When duration of young and adult stages in the validation set were adjusted to match the duration of the grower and adult stage in our model, a maximum difference of 3% was observed with our projection for a mixed population of village chickens (Table 2). Here, growers represent more than 50% of the population, which is possible if chick mortality is not excessive. In contrast, growers in the scavenging population would be only 2/3 of those projected in the mixed population, which reflects the low survival of scavenging chicks. According to the same validation data, 40% of the village chicken population is replaced in 60 days; again, our simulation projected a similar replacement of 44% for the mixed population, but a more intense 55% for the scavenging population after 60 days. These results confirm that the data in ILRI (2011) and FAO (2009b) correspond to averaged traits of the Indonesian village chicken populations, and thus should not be assumed equivalent to those of traditional free-range scavenging village chickens.

Interestingly, the values of $\lambda_{\text{scavenging}}$ and λ_{mixed} were close to 1 suggesting that the scavenging and mixed populations are closed, with dynamics driven by natural processes. While this is likely to be true for the scavenging, it is probably a misleading conclusion for the mixed population because purchasing of poultry is a common practice amongst the improved systems of raising village chickens in Indonesia (). Purchasing of birds, which contributes to the process of immigration on top of the chicks born in-farm, cannot be captured using this model approach. This limitation could be overcome in future works using an age-structured model with the inclusion of immigration and emigration at different life stages, allowing more realistic assessment of health interventions.

We assumed that new individuals coming into the population were influenza-susceptible, which is reasonable given that vaccinated-hens' chicks survive only a few days longer than the chicks of non-vaccinated hens when challenged with HPAI H5N1 at 14 days of age (Maas *et al.* (2011),

1 and that maternal antibodies cannot prevent death due to HPAI H5N1 infection (De Vriese *et al.*,
2 2010). In this context, we simulated vaccine interventions to estimate the herd immunity after
3 vaccination. A field observation in Java suggested that 51.7% of the household flocks in a
4 neighborhood must be immune to interrupt the transmission of HPAI H5N1 (ILRI, 2011). We
5 explored this immunity threshold and an alternative observed in a confined populations (67%),
6 calling them lower and higher critical threshold. Our simulations showed that the herd immunity
7 of the scavenging and mixed village chicken population quickly falls below that expected from
8 vaccine coverage. The best scenarios simulated (Figure 2), showed that protective herd immunity
9 would last about two months for the scavenging, and between two and two-and-a-half months for
10 the mixed population.

11 These observations for village chickens in the Indonesian context are similar to those reported by
12 Lesnoff *et al* (2009) for a generalized African one, *viz.* 16 weeks following mass vaccination,
13 only about 30% of either the Indonesian or African village chicken populations would remain
14 immune. Similarly, about 27% of these populations would remain immune 16 weeks after birds
15 >14 day-old were vaccinated. Notably however, the rate of reduction of herd immunity in the
16 Indonesian scavenging population is faster compared with mixed flocks due to the high rate of
17 population replacement. These results show that vaccination coverage does not guarantee control
18 of HPAI H5N1 and that the population turnover of village chickens would undermine the
19 effectiveness of interventions based on current inactivated oil-emulsified whole virus vaccines.
20 These results suggest that to achieve sustained impact, vaccination based on the current
21 technology would need to be conducted at least every second month, an unfeasible goal given the
22 limited coverage reported for the Indonesian sector 4 (Swayne *et al.*, 2011).

23 Survival probabilities of females, males, and each age-stage could impact differently on the
24 effectiveness of vaccine interventions. In this regard, the sensitivity analysis revealed the impact
25 of high survivorship of chicks (chicks P) on the vaccine scenarios simulated: in the mixed
26 population, if all birds are vaccinated, more chicks would remain contributing to sustain the herd
27 immunity; however, if only those >14 day-old are vaccinated, the high survival of chicks
28 increases both susceptible and immune, undermining the herd immunity. While the magnitude of
29 association of chick survival with the herd immunity is the same in both vaccine interventions
30 they do however have opposite effect (Figure 3). This suggests that vaccinating the whole mixed

population (scenario 1) would be the most appropriate intervention; however, this conclusion cannot be extrapolated to the scavenging population since the survivorship effect is not observed. This difference highlights the importance of accurately identifying the relevant subgroups of the village chicken population to be targeted for vaccination. In the same way, since females have higher survival probabilities and become the dominant gender in both village chicken population types modelled (> 50% of the population), gender specific immunization may be one strategy to consider both to maintain high herd immunity *within* given population and to prevent the spread of HPAI H5N1 beyond it.

In conclusion, given that vaccination efforts aim to protect poultry and humans with a major objective of preventing the emergence of a variant strain of HPAI H5N1 with pandemic potential, intervention planning should account for the turnover effect of the Indonesia's village chicken population in enzootic areas. We found that Indonesia's village chicken population has been characterized by aggregate values of multiple systems, resulting in estimated population dynamics that are not representative of traditional scavenging populations of village chickens. When vaccination is planned, it would be advisable to estimate the abundance of the scavenging and improved rearing systems in the area since different population dynamics have different effects on vaccine effectiveness; however, our simulations confirmed that vaccination based on current technology in any of these populations will still not suffice to control HPAI H5N1. Direct contact with birds remains the main route of zoonotic infection (Van Kerkhove, 2013) and vaccinating with inadequate coverage could produce a false sense of security amongst people in contact with birds. The dramatic upsurge of human cases of HPAI H5N1 in Egypt in November 2014 highlights that epidemics at the animal-human interface are possible without major changes in the virus or infection patterns, when insufficient biosecurity measures are implemented to protect humans in close contact with poultry (World Health Organization, 2015b). In Indonesia, where most people continue to purchase live or plucked scavenging-backyard birds in markets or from street vendors despite large poultry outbreaks (FAO, 2009a) the potential for such crossover event remains. These cultural nuances make evident that this disease is best approached using a One Health perspective.

References

- 1 Aini, I., 1990: Indigenous chicken production in South-east Asia. *World Poultry Sci. J.* 46, 51-
2 57.
- 3 Alders, R. G. and R. A. E. Pym, 2009: Village poultry: still important to millions, eight thousand
4 years after domestication. *World Poultry Sci. J.* 65, 181-190.
- 5 Bouma, A., A. T. Muljono, A. Jatikusumah, A. Nell, S. Mudjiartiningsih, I. Dharmayanti, E. S.
6 Siregar, I. Claassen, G. Koch and J. Stegeman, 2008: Field trial for assessment of avian
7 influenza vaccination effectiveness in Indonesia. *Rev. Sci. Tech.* 27, 633-642.
- 8 Caswell, H., 2001: *Matrix population models: construction, analysis, and interpretation*. Sinauer
9 Associates, Sunderland, Massachusetts.
- 10 Crouse, D. T., L. B. Crowder and H. Caswell, 1987: A stage-based population model for
11 loggerhead sea turtles and implications for conservation. *Ecology* 68, 1412-1423.
- 12 Cumming, R.B., 1992: Village chicken production: problems and potential. In: *Proceedings of an*
13 *international workshop on Newcastle disease in village chickens: control with thermostable oral*
14 *vaccines*. Kuala Lumpur, Malaysia, 6-10 October 1991, p. 21-24.
- 15 De Vriese, J., M. Steensels, V. Palya, Y. Gardin, K. M. Dorsey, B. Lambrecht, S. Van Borm and
16 T. Van Den Berg, 2010: Passive protection afforded by maternally-derived antibodies in
17 chickens and the antibodies' interference with the protection elicited by avian influenza-
18 inactivated vaccines in progeny. *Avian Dis.* 54, 246-252.
- 19 Diwyanto, K. and S. Iskandar, 1999: *Kampung chickens: A key part of Indonesia's livestock of*
20 *sector*. Central Research Institute for Animal Sciences and Research Institute for Animal
21 *Production*. Bogor, Indonesia.
- 22 EMPRES-i FAO, 2015: H5N1 HPAI disease events in Indonesia. Food and Agriculture
23 Organization of the United Nations. Available at: <http://empres-i.fao.org/eipws3g/#> (accessed
24 on 03 Jun 2015).

- 1 EMPRES/FAO-GLEWS, 2012: H5N1 HPAI global overview April-June 2012. Food and
2 Agriculture Organization of the United Nations. Available at:
3 <http://www.fao.org/docrep/016/ap387e/ap387e.pdf> (accessed on 31 Mar 2014).
- 4 EMPRES/FAO, 2012: Focus on. Update on the continuous spread and expansion of H5N1
5 highly pathogenic avian influenza. Food and Agriculture Organization of the United Nations.
6 Available at: <http://www.fao.org/docrep/019/i3610e/i3610e.pdf> (accessed on 6 Jan 2015).
- 7 FAO, 2008a: Biosecurity for highly pathogenic avian influenza. Issues and options. FAO Animal
8 Production and Health Paper. FAO, Rome, Italy.
- 9 FAO, 2008b: Local chicken genetic resources and production systems in Indonesia. Prepared by
10 Muladno Muladno. GCP/RAS/228/GER Working paper No. 6. Rome, Italy.
- 11 FAO, 2009a: Consumer preferences for poultry products in Indonesia. Prepared by Muladno
12 Muladno and O. Thieme. GCP/RAS/228/GER Working paper No. 12. Rome, Italy.
- 13 FAO, 2009b: Production systems and poultry genetic resources utilized by small producers in
14 areas of West Java and Central Java, Indonesia. Prepared by Muladno Muladno and O. Thieme.
15 GCP/RAS/228/GER Working paper No. 11. Rome, Italy.
- 16 FAO/OIE/WHO, 2010a: Executive summary. The 2008 FAO-OIE-WHO joint technical
17 consultation on avian influenza at the human animal interface. Influenza Other Respir. Viruses
18 4 Suppl 1, ii-ii.
- 19 FAO/OIE/WHO, 2010b: FAO/OIE/WHO joint scientific consultation and other emerging
20 zoonotic diseases at the human-animal interface. Meeting summary and key findings, Verona,
21 Italy.
- 22 Farnsworth, M. L., S. Fitchett, M. M. Hidayat, C. Lockhart, C. Hamilton-West, E. Brum, S.
23 Angus, B. Poermadjaja and J. Pinto, 2011: Metapopulation dynamics and determinants of
24 H5N1 highly pathogenic avian influenza outbreaks in Indonesian poultry. Prev. Vet. Med. 102,
25 206-217.

- 1 Fine, P., K. Eames and D. L. Heymann, 2011: 'Herd immunity': a rough guide. Clin. Infect. Dis.
2 52, 911-916.
- 3 Gunaratne, S., A. Chandrasiri, W. M. Hemalatha and J. Roberts, 1993: Feed resource base for
4 scavenging village chickens in Sri Lanka. Trop Anim Health Prod. 25, 249-257.
- 5 Handaka, 2009: Towards sustainable agricultural mechanization in Indonesia. Tech Monitor.
6 Available at: http://www.techmonitor.net/tm/images/d/d4/09jan_feb_sf4.pdf (accessed on 15
7 Jan 2016).
- 8 ILRI, 2011: Operational research in Indonesia for more effective control of highly pathogenic
9 avian influenza. ILRI project report. ILRI, Nairobi, Kenya.
- 10 Kingston, D., 1980: The productivity of scavenging chicken in some villages of West Java,
11 Indonesia. In: Proceedings of the South Pacific Poultry Science Convention. Auckland, New
12 Zealand, 13-16 October 1980, p. 228-237.
- 13 Kingston, D., B. Gunawan and D. Creswell, 1982: Indigenous Chickens in Indonesia: Population
14 and production characteristics in five villages of West Java. Report No. 2. Research Institute for
15 Animal Production, Bogor, Indonesia.
- 16 Lefkovitch, L., 1965: The study of population growth in organisms grouped by stages.
17 Biometrics 21, 1-18.
- 18 Leslie, P., 1948: Some further notes on the use of matrices in population mathematics.
19 Biometrika 35, 213-245.
- 20 Leslie, P. H., 1945: On the use of matrices in certain population mathematics. Biometrika 33,
21 183-212.
- 22 Lesnoff, M., M. Peyre, P. C. Duarte, J. F. Renard and J. C. Mariner, 2009: A simple model for
23 simulating immunity rate dynamics in a tropical free-range poultry population after avian
24 influenza vaccination. Epidemiol. Infect. 137, 1405-1413.

- 1 Maas, R., S. Rosema, D. Van Zoelen and S. Venema, 2011: Maternal immunity against avian
2 influenza H5N1 in chickens: limited protection and interference with vaccine efficacy. *Avian*
3 *Pathol.* 40, 87-92.
- 4 Marino, S., I. B. Hogue, C. J. Ray and D. E. Kirschner, 2008: A methodology for performing
5 global uncertainty and sensitivity analysis in systems biology. *J. Theor. Biol.* 254, 178-196.
- 6 McKay, M. D., R. J. Beckman and W. J. Conover, 1979: Comparison of three methods for
7 selecting values of input variables in the analysis of output from a computer code.
8 *Technometrics* 21, 239-245.
- 9 Parker, T. H. and K. Winker, 2005: No evidence for adaptative differential sex allocation in Red
10 Junglefowl (*Gallus gallus*). *The Auk* 122, 1161-1168.
- 11 R Development Core Team, 2014: R: A language and environment for statistical computing. R
12 Foundation for Statistical Computing, Vienna, Austria.
- 13 Sims, L., J. Domenech, C. Benigno, S. Kahn, A. Kamata, J. Lubroth, V. Martin and P. Roeder,
14 2005: Origin and evolution of highly pathogenic H5N1 avian influenza in Asia. *Vet. Rec.* 157,
15 159-164.
- 16 Siregar, E. S., J. W. Darminto and A. Bouma: The vaccination programme in Indonesia. *Dev.*
17 *Biol. (Basel)* 130, 151-158.
- 18 Skalski, J. R., K. E. Ryding and J. Millspaugh, 2010: Wildlife demography: analysis of sex, age,
19 and count data. Academic Press, Burlington , MA.
- 20 Swayne, D., G. Pavade, K. Hamilton, B. Vallat and K. Miyagishima, 2011: Assessment of
21 national strategies for control of high-pathogenicity avian influenza and low-pathogenicity
22 notifiable avian influenza in poultry, with emphasis on vaccines and vaccination. *Rev. Sci.*
23 *Tech.* 30, 839-870.
- 24 Tiensin, T., M. Nielen, H. Vernooij, T. Songserm, W. Kalpravidh, S. Chotiprasatintara, A.
25 Chaisingh, S. Wongkasemjit, K. Chanachai and W. Thanapongtham, 2007: Transmission of the

- highly pathogenic avian influenza virus H5N1 within flocks during the 2004 epidemic in Thailand. *J. Infect. Dis.* 196, 1679-1684.
- Unger, F., W. Priyono, E. Siregar, M. Azhar, B. Bett, M. McLaws, C. Jost and J. Mariner, 2012: Population dynamics in kampong chicken and consequences for HPAI vaccination: results of a field trial in Java. In: *Proceedings of the 13th conference of the International Society for Veterinary Epidemiology and Economics*. Maastricht, Netherlands, 20-24 August 2012, p. 288
- Van Kerkhove, M. D., 2013: Brief literature review for the WHO global influenza research agenda—highly pathogenic avian influenza H5N1 risk in humans. *Influenza Other Respir. Viruses* 7, 26-33.
- Ward, M., D. Maftai, C. Apostu and A. Suru, 2009: Estimation of the basic reproductive number (R_0) for epidemic, highly pathogenic avian influenza subtype H5N1 spread. *Epidemiol. Infect.* 137, 219-226.
- World Health Organization, 2013: Update on human cases of influenza at the human-animal interface, 2012. *Wkly. Epidemiol. Rec.* 88, 137-144.
- World Health Organization, 2015a: Cumulative number of confirmed human cases of avian influenza A(H5N1) reported to WHO. Available at: http://www.who.int/influenza/human_animal_interface/EN_GIP_20150106CumulativeNumberH5N1cases.pdf (accessed on 13 Jan 2015).
- World Health Organization, 2015b: Egypt: upsurge in H5N1 human and poultry cases but not change in transmission pattern. Available at: <http://www.emro.who.int/egy/egypt-news/upsurge-h5n1-human-poultry-cases-may-2015.html> (accessed on 30 May 2015).
- Zinsstag, J., E. Schelling, D. Waltner-Toews, M. Whittaker and M. Tanner, 2015: *One Health: the theory and practice of integrated health approaches*. CABI, Boston, MA.

Table 1. Demographic parameters for the Indonesia's Scavenging and Mixed village chicken population, and those of village chickens in the African context.

<i>Parameter</i>	<i>Scavenging</i>	<i>Mixed</i>	<i>African free-range ♦</i>
<i>Eggs/Hen/Year</i>	70.4	45	35
<i>Duration of egg stage (weeks)</i>	3	3	5
<i>Duration of chicks stage (weeks)</i>	4	4	10
<i>Duration female grower stage (weeks)</i>	20	20	14
<i>Duration male grower stage (weeks)</i>	20	20	10
<i>Maximum survival hens (years)</i>	2	1	4
<i>Maximum survival cocks (years)</i>	1.5	1	2
<i>Survival Eggs* (weekly %)</i>	88.6	93.0	87.3
<i>Survival chicks (weekly %)</i>	69.9	93.5	88.0
<i>Survival female growers (weekly %)</i>	94.0	94.0	95.0
<i>Survival male growers (weekly %)</i>	92.0	92.0	86.1
<i>Survival hens (weekly %)</i>	97.6	93.0	98.6
<i>Survival Cocks (weekly %)</i>	95.7	91.5	98.3

*After eggs used, broken, and hatchability. ♦ Calculated from Lesnoff *et al* (2009)

Table 2. Model's steady-state relative age-stage abundance for the Scavenging and Mixed Indonesia's village chicken population compared to field data reported by ILRI (2011).

Age-stage	Scavenging	Mixed	ILRI*
Chicks (f & m)	38%	25%	25%
Female growers	21%	32%	57%**
Male growers	18%	28%	
Hens	16%	10%	12%
Cocks	7%	6%	6%
Total	100%	100%	100%

*Abundance of growers and adults recalculated from ILRI to fit duration of these age-stages as defined in the model. ** Female and male growers together.

Figure 1. Herd immunity after a perfect vaccination of a population of scavenging (left) or semi-commercial village chickens (right). Dashed lines represent the higher and lower critical herd immunity thresholds that would prevent H5N1 reemergence.

Figure 2. Weeks for the herd immunity to reach the higher (67%) and lower (50%) critical thresholds after a perfect vaccination of a scavenging (left) or semi-commercial (right) population of village chickens.

Figure 3. Partial rank correlation coefficient between parameters and herd immunity when all (left), or those over 14 day-old (right) were vaccinated in a scavenging (black) or a semi-commercial (grey) population of village chickens.

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Villanueva-Cabezas, JP;Campbell, PT;McCaw, JM;Durr, PA;McVernon, J

Title:

Turnover of Village Chickens Undermines Vaccine Coverage to Control HPAI H5N1

Date:

2017-02-01

Citation:

Villanueva-Cabezas, J. P., Campbell, P. T., McCaw, J. M., Durr, P. A. & McVernon, J. (2017).
Turnover of Village Chickens Undermines Vaccine Coverage to Control HPAI H5N1.
ZOOZOSES AND PUBLIC HEALTH, 64 (1), pp.53-62. <https://doi.org/10.1111/zph.12282>.

Persistent Link:

<http://hdl.handle.net/11343/291462>