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Economic impact of highly pathogenic avian influenza outbreaks in Western Java smallholder broiler farms

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ABSTRACT

Highly Pathogenic Avian Influenza (HPAI) H5N1 is considered endemic in most parts of Indonesia and constitutes an important risk for broiler production, especially in Western Java which has the highest poultry population in the country. Most broiler farms in Western Java are smallholder farms that operate under different business types: independent (i.e., revenues based on market price and live bird weight), price-contract (i.e., revenues based on a contract selling price and live bird weight) or *makloon* (i.e., revenues based on a management fee per sold bird). Many studies focus on the epidemiological impacts of HPAI at the regional level, and insights into the economic impact at the farm level are scarce, especially in the Indonesian context. Meanwhile, a single HPAI outbreak could disrupt smallholder broiler farmers' primary source of income. Therefore, this study aimed to evaluate the economic impact of HPAI outbreaks under different response scenarios (i.e., no action, stamping out, and early selling) on typical Western Java smallholder broiler farms. Furthermore, the effect of different farm business types and the existence of a sick-bird market on the economic effects of HPAI outbreaks were evaluated. We developed a dynamic stochastic bio-economic simulation model to simulate epidemiological and economic impacts of HPAI outbreaks on a typical Western Java smallholder broiler farm during one production round. Our results show that the economic consequences of HPAI outbreaks for independent and price-contract farms are considerable, ranging from, on average, 1.2–62.7 million Indonesian Rupiah (IDR) losses (€76.9 to €3919), depending on the moment of and response to infection, compared to an expected gross margin of 5.3 million IDR (€331) under normal circumstances. The economic loss for m*akloon* farms was substantially lower than for other business types, reducing their incentive to implement biosecurity. The economic impacts were sensitive to changes in a diverse set of parameters, including disease transmission rate, detection threshold, and stamping-out compensation. The losses in a scenario with stamping out were higher than in other scenarios, especially when stamping out happened near the end of the production round. Moreover, reacting to an outbreak by selling chickens early gave the lowest economic losses, incentivizing farmers to engage in behavior with a high disease transmission risk. Therefore, the results of this study suggest that it is important to consider the economic perspective of individual farmers when designing HPAI mitigation programs. Financial incentives for farmers to control HPAI differ largely between farm business types.

1. Introduction

Highly pathogenic avian influenza (HPAI) is a poultry disease caused by H5 and H7 subtypes of type A influenza virus, family Orthomyxoviridae. HPAI is zoonotic, contagious, and can lead to high mortality in a poultry flock (Swayne and Suarez, 2000; Peiris et al., 2007). In addition, outbreaks with HPAI H5N1 can have a large impact on public health and the global economy.

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Thus far, Indonesia counts 168 HPAI H5N1 casualties, ranking second on global mortality charts (WHO, 2021). As the most significant sector in the Indonesian poultry industry, the broiler sector was heavily disrupted by HPAI H5N1 outbreaks, with about 11 million chickens dead or culled between the years 2003–2009. HPAI H5N1 is considered endemic in most parts of Indonesia, under which Western Java, which comprises three provinces: Jakarta, West Java, and Banten (Pramuwidyatama et al., 2019). This region has the highest poultry (60 %) and human (40 %) population in Indonesia (BPS, 2022). Consequently, broiler production is continuously at risk of HPAI infection.

The Western Java broiler production chain structure is complex with a mix of industrial, semi-industrial, small-scale, and backyard farms (Durr et al., 2016; Indrawan et al., 2018; Wibawa et al., 2018). The majority of the broiler farms in Western Java are smallholder farms (Indrawan et al., 2018), operating as independent farms, price-contract farms, or *makloon* farms (Indrawan et al., 2020). Independent farmers buy their inputs and sell their chickens autonomously. Price-contract and *makloon* farmers are under a production contract with a poultry company, such as an integrated company or a supplier. Price-contract farmers buy production inputs on a credit basis, get paid based on the delivered weight and the predetermined contract price, and settle their credit when selling their production to the nucleus company. *Makloon* farmers are provided with production inputs and are paid based on a pre-determined fee per bird (Indrawan et al., 2020; Pramuwidyatama et al., 2022).

While a large number of studies focus on the epidemiological impacts of HPAI at the regional level (Indriani et al., 2010; Loth et al., 2011; Yupiana et al., 2010; Henning et al., 2019), studies about HPAI's economic impact at the farm level are lacking, especially in the Indonesian context. Furthermore, since the implementation of HPAI control measures by the government has been lacking (Indrawan et al., 2018), the behavior of farmers towards HPAI outbreaks has become an important aspect. These farmers are more likely to respond to an outbreak based on their economic interest which may be less favorable for HPAI control. Thus, it is important to understand the consequences of farmers' behavior reacting to an outbreak of HPAI. Furthermore, there is another aspect of the Western Java broiler sector that may influence farmers' response towards an outbreak and, consequently, the economic outcome of HPAI outbreaks: the existence of sick-bird markets where infected poultry may still be sold (Indrawan et al., 2020).

This study aimed to evaluate the economic impact of HPAI outbreaks on typical Western Java smallholder broiler farms, with a particular emphasis on the effect of different broiler business models, as well as of the sick-bird market. By developing a bio-economic simulation model we studied the epidemiological and economic impacts of HPAI outbreaks in a typical Western Java smallholder broiler farm.

2. Materials and method

2.1. Model overview

A dynamic stochastic bio-economic model was developed in Microsoft Excel 2016 with @RISK add-in software (version 7.6; Palisade, Ithaca NY, USA) to simulate HPAI H5N1 infection occurrence and spread in a broiler population in one production round. A small-scale commercial broiler farm (also known as a sector 3 broiler farm; Wibawa et al., 2018) with an open house system was chosen as the epidemiological unit of interest as this is the most common type of broiler farm in Indonesia. A small-scale broiler farm usually rears 3,000 chickens per production round, in 30-days on average (Indrawan et al., 2020). Small-scale broiler farms in Western Java are most commonly operating as (extended) price-contract, *makloon*-contract, or independent businesses (Indrawan et al., 2020; Pramuwidyatama et al., 2022).

The basis for the bio-economic model is the simulation of the broiler population dynamics (in daily time steps) on the farm during one production round. During their stay on the farm, chickens can transit to different HPAI-related health states, associated with the introduction and spread of HPAI on that farm. Based on this health state, production and economics are calculated and summarized to provide the gross margin of that specific, simulated production round, reflecting the differences in returns and costs for the various farm business types. By comparing the gross margin of rounds with and without an HPAI outbreak, the epidemiological and economic effect of the HPAI outbreak can be determined for the respective farm business type. In the following paragraphs, the various elements of the simulation model will be described in detail.

2.2. Dynamics of the broiler population

Each chicken in the flock can be in one of four distinct and mutually exclusive HPAI-related health states (Fig. 1.): immune with maternally-derived antibodies (*Imm*), susceptible (*S*), infected (*Inf*); chickens that are infected but do not show clinical signs and are not infectious), and infectious/clinically ill (*I*; chickens that are infected with HPAI, clinically ill and infectious) (Bouma et al., 2009; Poetri et al., 2011; Tiensin et al., 2005; Swayne et al., 2011). Because the infectious period (γ) is assumed to last three days (Poetri et al., 2011), state *I* is divided into three sub-states (i.e., I_1, I_2, and I_3) where I_1, I_2, I_3 are the first, second, and third day of the infectious period, respectively (Fig. 1.). While on the farm, chickens may leave the flock because of death (*mort;* due to HPAI infection or other reasons), stamping out (*SO*), or sale for slaughter (*sold*). Each simulation time step (t) represents one day. The total number of chickens in each state is updated every production day based on time and decision dependent probabilities of transition from one state to the other. Potential state-transitions are shown in Fig. 1.

The probabilities of transmission are dependent on a number of stochastic processes as well as a number of predefined events (a chicken becoming infected with HPAI, E^{Intro}; an outbreak is detected in the flock in a production day, E_t^{Detect}; stamping out in case of an HPAI outbreak, E^{SO}); decisions (source of day-old-chickens (DOC), D^{DOC}; sale of the flock at a sick-bird market, D^{panic}), and time variables (duration of maternal immunity, T^{Imm}; moment of introduction of HPAI, T^{Intro}; the earliest day to sell the flock, T^{early}; the last production day in one round, T^{end}; the length of one production round, T^{cycle}). Variables representing events and decisions are binary. Chickens in state *S* can become infected with HPAI as a consequence of HPAI introduction into the flock or because of within-flock virus transmission.

The total flock population at the end of every production day is the sum of the chicken population in all states on that day

$$N_t = N_t^{Imm} + N_t^S + N_t^{Inf} + N_t^{I_1} + N_t^{I_2} + N_t^{I_3} \tag{1}$$

where N_t is the total chicken population at the end of time step t and N_t^{Imm}, N_t^S, N_t^{Inf}, N_t^I are the number of chickens in each different health state at the end of time step t.

At the beginning of a production round ($t = 0$), farmers will fill the barn capacity (N) with day-old chickens from a breeder:

$$N_{t=0}^{Imm} = N \times D^{DOC} \tag{2a}$$

$$N_{t=0}^{S} = N - N_{t=0}^{Imm} \tag{2b}$$

where D^{DOC} is the farmer's decision to buy day-old chickens from a certified breeder with maternal immunity ($D^{DOC} = 1$) or from an uncertified breeder without maternal immunity ($D^{DOC} = 0$) (Ka-Oud et al., 2008; Poetri et al., 2011).

For every production day t, the following transitions were evaluated: dying, becoming susceptible, being stamped out, being sold for slaughter, becoming infected with HPAI, and becoming infectious and clinically ill. In the following paragraphs, the dynamics within each state will be described.

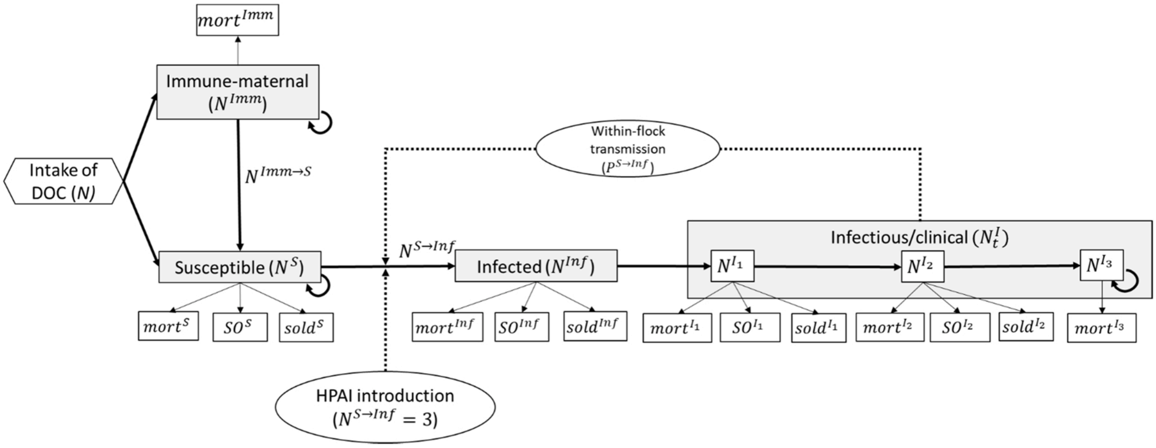

Fig. 1. HPAI state-transition model (*Imm*: immune with maternal immunity, *S*: susceptible, *Inf*: infected, *I*: infectious/clinical) in each time step of one day (t) with transition intake of DOC (N), mortality (*mort*), transitions between states (e.g., $Imm\to S$), stamping out (*SO*), HPAI introduction ($S\to Inf$), within-herd spread ($P^{S\to Inf}$), and sales (*sold*). Three chickens in state *S* will be infected in the beginning of each of production weeks (t= 8, 15, or 22). The within-flock spread was calculated using the Reed-frost model (Gani and Jerwood, 1971).

2.2.1. Immune with maternally-derived antibodies (Imm)

As a first step, the mortality is determined using a binomial distribution based on the number of chickens in state *Imm* at time $t-1$ and the probability of mortality (P^{mort}) that varies per iteration based upon a triangular distribution:

$$mort_t^{Imm} = binomial\left(N_{t-1}^{Imm}, P^{mort}\right) \tag{3a}$$

$$where: P^{mort} = TRIANG(\mu_{\min}^{mort},\ \mu_{ml}^{mort}, \mu_{\max}^{mort}) \tag{3b}$$

where $mort_t^{Imm}$ is the number of dead chickens in state *Imm* at time step t and $\mu_{\min}^{mort}$, μ_{ml}^{mort}, $\mu_{\max}^{mort}$ are the minimum, most likely, and maximum, respectively, probability of mortality used in the triangular distribution. The mortality probability differs between the first week ($t \le 7$) and the rest of the production cycle ($t > 7$).

Depending on the duration of maternal immunity (T^{Imm}) and the number of chickens in state *Imm*, the number of chickens that will move to state *S* ($N_t^{Imm\to S}$) is determined by the following equation:

$$if \quad t = T^{Imm}: N_t^{Imm\to S} = N_{t-1}^{Imm} - mort_t^{Imm} \tag{4a}$$

$$else: N_t^{Imm\to S} = 0 \tag{4b}$$

Finally, the number of chickens that stay in state *Imm* at the end of time step t is described in Eq. (5).

$$N_t^{Imm} = N_{t-1}^{Imm} - mort_t^{Imm} - N_t^{Imm\to S} \tag{5}$$

2.2.2. Susceptible (S)

The mortality in state *S* depends on the number of chickens in state *S* in time $t-1$ (N_{t-1}^S) and is determined as was described for state *Imm* (Eqs. (3a) and (3b)).

The event stamping out depends on the enforcement of governmental regulation that all chickens on a farm will be culled at the occurrence of an HPAI outbreak ($E^{SO} = 1$) and the event that an outbreak is detected ($E_t^{detect} = 1$). E_t^{detect} is determined with the following equation:

$$if \quad N_{t-1}^I \ge Detect^{Thresh} \times N_{t-1}: E_t^{detect} = 1 \tag{6a}$$

$$else: E_t^{detect} = 0 \tag{6b}$$

and the number of chickens that will be culled is determined as follows:

$$if \quad E^{SO} = 1 \quad and \quad E_{t-2}^{detect} = 1 \quad : \quad SO_t^S = N_{t-1}^S - mort_t^S \tag{7a}$$

$$else: SO_t^S = 0 \tag{7b}$$

where the outbreak can be detected when the number of infectious chicken (N_{t-1}^I) in time step $t-1$ is equal or larger than the $Detect^{Thresh}$, which is the threshold for outbreak detection at which stamping out takes place.

When the stamping out regulation is absent or not enforced ($E^{SO} = 0$), farmers may decide to sell their chickens early ($D^{panic} = 1$). The number of chickens in state *S* sold early to sick-bird markets is determined by the following equation:

$$if \quad E_{t-2}^{detect} = 1 \quad and \quad t \ge T^{early}: \quad sold_t^S = N_{t-1}^S - mort_t^S - SO_t^S \tag{8}$$

where $sold_t^S$ is the number of chickens in state *S* sold in time step *t*. Sale of chickens for slaughter may happen at two occasions: panic sale after detection of an outbreak (Eq. (8)) or final sale of the whole flock at the last day of a normal production round (T^{cyle}) (Eqs. (9a) and (9b)).

$$if \quad t = T^{cycle}: sold_t^S = N_{t-1}^S - mort_t^S - SO_t^S \tag{9a}$$

$$else: sold_t^S = 0 \tag{9b}$$

Depending on whether or not HPAI is introduced into the flock ($E^{Intro} = 1$) and the time of HPAI introduction (T^{Intro}), the model assumes that three chickens in state *S* will become infected and transit to state *Inf* at time step *t*, which is determined by the following equation.

$$if \quad E^{Intro} = 1 \quad and \quad t = T^{Intro}: N_t^{S\to Inf} = 3 \tag{10}$$

After T^{Intro}, $N_t^{S\to Inf}$ is based on a binomial distribution that depends on the number of susceptible chickens at time step t (Eq. (11a)) and the daily probability of transition from state *S* to state *Inf* at time step t ($P_t^{S\to Inf}$) which is calculated as follows:

$$if \quad t > T^{intro}: N_t^{S\to Inf} = binomial\left(N_{t-1}^S - mort_t^S - SO_t^S - sold_t^S, P_t^{S\to Inf}\right) \tag{11a}$$

$$else: N_t^{S\to Inf} = 0 \tag{11b}$$

where $P_t^{S\to Inf}$ is simulated using the Reed-Frost model (Gani and Jerwood, 1971) which is based on the virus transmission rate (β), the number of infectious chickens at time $t-1$ (N_{t-1}^I), and the number of susceptible chickens at time step *t*, in Eq. (11a). βchanges per iteration, based on a triangular distribution:

$$P_t^{S\to Inf} = 1 - \exp\left(\frac{-\beta \times N_{t-1}^{I}}{N_{t-1}}\right) \tag{12a}$$

$$where : \beta = TRIANG(\beta_{\min}, \beta_{ml}, \beta_{\max}) \tag{12b}$$

where $\beta_{\min}, \beta_{ml}, \beta_{\max}$ are the minimum, most likely, and maximum, respectively, virus transmission rate.

At the end of time step t, the number of animals in state S is determined in Eq. (13).

$$N_t^S = N_{t-1}^S - mort_t^S - SO_t^S - sold_t^S - N_t^{S\to Inf} + N_t^{Imm\to S} \tag{13}$$

2.2.3. Infected (Inf)

The infected (*Inf*) state represents the incubation period of infected chickens which is assumed to be one day (Poetri et al., 2011). Since chickens in state *Inf* are not clinically ill, all transitions and probabilities in this state are equal to transitions for state S (Eq. (6a) to Eq. (13)). The only difference is that chickens will transit to state I_1 after 1 day. At the end of time step t, the number of chickens in state *Inf* is determined using the following equation:

$$N_t^{Inf} = N_{t-1}^{Inf} - mort_t^{Inf} - SO_t^{Inf} - sold_t^{Inf} - N_t^{Inf\to I_1} + N_t^{S\to Inf} \tag{14}$$

2.2.4. Infectious (I)

The infectious (I) state represents the infectious period of clinically ill chickens which is assumed to be, on average, three days (Poetri et al., 2011). Each infectious sub-state is denoted by γ. The number of chickens in state I at time step t is the sum of the number of chickens in each infectious period in time t (Eq. (1b)). Chickens will transit to the next infectious period every time step t (i.e., $I_1 \to I_2$, $I_2 \to I_3$), and those in the last infectious period (I_3) will stay in this sub-state until they eventually die. All transitions and probabilities in this state are equal to transitions for state *Inf* (Eq. (14)). As in other states, chickens in state I can die. However, the daily probability of mortality for infectious chickens is higher because of clinical illness:

$$for \quad \gamma = 1,2,3 : mort_t^{I_\gamma} = binomial\left(N_{t-1}^{I_\gamma}, P^{mort_\gamma}\right) \tag{15}$$

where P^{mort_γ} is the probability of mortality in each infectious sub-state where P^{mort_3} is one. The probability of mortality in state I was assumed to increase linearly from the first to the last infectious sub-state.

2.3. Production and economic performance

In order to assess the economic impact of a single HPAI outbreak on a farm, a gross margin (*GM*) calculation was carried out. The returns and variable costs were calculated for every time step of the production round and summed to obtain the gross margin for that production round. Costs that are fixed (e.g., cleaning & disinfection of the barn after a production cycle) or paid by the government (e.g., surveillance and quarantine) were not included in the model.

2.3.1. Returns

In general, broiler farmers receive returns from selling their chickens to traders at the end of the production round or, in the event of panic selling, to a sick-bird market. These returns depend on the business type of the farm.

The returns of *Makloon* farmers in one production round ($R^{makloon}$) are based on chicken sales and depend on the total number of chickens in state S ($sold_t^S$) and *Inf* ($sold_t^{Inf}$) sold at time t. The live bird weight at time t (BW_t) is based on unpublished daily body weight data of broiler chickens from an integrated poultry company in Western Java and the *makloon* price per chicken and per kilogram of live weight ($\Pr^{makloon}$):

$$if \quad t = T^{end} or \quad t = T^{cycle} : R^{makloon} = \left(sold_t^S + sold_t^{Inf}\right) \times BW_t \times \Pr^{Makloon} \tag{16}$$

Returns for independent and price-contract farmers ($R^{Indie-price}$) for one production round are based on returns from the sales of the flock or on the compensation received when stamping out. Sales returns depend on the price of one kilogram live bird weight on the day of sales ($\Pr_t$) and were calculated as in Eq. (16). Since we assumed two types of sales, $\Pr_t$ can vary. Under normal circumstances, $\Pr_t$ is the market price ($\Pr^{market}$). However, when an outbreak is detected, $\Pr_t$ is based on the selling price at the sick-bird market, which is lower than the market price (i.e., small: $BW \leq 1$ kg; large: $BW > 1$ kg). The selling price is determined with the following equation:

$$if \quad E_{t-2}^{detect} = 1 \quad and \quad t \geq T^{early} and \quad BW_t \leq 1kg : \Pr_t = \Pr^{panic-S} \tag{17a}$$

$$if \quad E_{t-2}^{detect} = 1 \quad and \quad t \geq T^{early} and \quad BW_t > 1kg : \Pr_t = \Pr^{panic-L} \tag{17b}$$

$$else : \Pr_t = \Pr^{market} \tag{17c}$$

where $\Pr^{panic-S}$ and $\Pr^{panic-L}$ are the sick-bird market prices for one kilogram of live bird weight for respectively small and large birds. In the event of stamping out, there will be no returns from chicken sales. Instead, farmers may receive returns in the form of compensation (*comp*), based on the number of asymptomatic chickens culled, i.e. chickens in state S (SO_t^S) or *Inf* (SO_t^{Inf}). Only independent and price-contract farmers will receive compensation due to stamping out on their farm, because *makloon* farmers do not own the chickens. Thus, returns for independent and price-contract farmers were calculated using the equation below.

$$\begin{aligned} if \quad t = T^{end} or \quad t = T^{cycle} : R^{Indie-price} \\ = \left(sold_t^S + sold_t^{Inf}\right) \times BW_t \times \Pr_t + \left(SO_t^S + SO_t^{Inf}\right) \times comp \end{aligned} \tag{18}$$

2.3.2. Costs

The total variable costs of a broiler farm in a production round are determined by the following components: production costs (DOC, feed, animal health, utility, and labor) and HPAI outbreak costs (disposal, HPAI test, and disinfection).

2.3.2.1. Production costs. Day-old-chickens costs (C^{DOC}) are costs from the purchase of DOC at the beginning of the production round. The price of a DOC ($\Pr^{DOC}$) depends on the source of DOC (D^{DOC}) which is determined by the following equations:

$$if \quad D^{DOC} = 1 : \Pr^{DOC} = \Pr^{certDOC} \tag{19a}$$

$$else : \Pr^{DOC} = \Pr^{uncertDOC} \tag{19b}$$

where $\Pr^{certDOC}$ and $\Pr^{uncertDOC}$ are the price of DOC from a certified and uncertified breeder, respectively. C^{DOC} is calculated based on the barn capacity (N) and $\Pr^{DOC}$:

$$C^{DOC} = N \times \Pr^{DOC} \tag{20}$$

Feed costs (C^{feed}) are the total feed costs in a production round and are based on the total population at time $t-1$ (N_{t-1}), the daily feed intake per chicken at time t (DFI_t) is based on the same source of data for the body weight in Eq. (16), and the commercial feed price per kilogram ($\Pr^{feed}$).

$$C^{feed} = \sum_{t=1}^{T^{end}} \left(N_{t-1} \times DFI_t \times \Pr^{feed}\right) \tag{21}$$

Animal health costs (C^{AH}) relate to the cost of products for chicken health (e.g., vitamins and antimicrobials) in one production round. The costs are determined by the total population at time $t-1$ (N_{t-1}), the average body weight at time $t-1$ (BW_{t-1}), and the average price of the animal health product per housed chicken per kilogram live bird weight (Pr^{AH}).

$$C^{AH} = \sum_{t=1}^{T^{end}} (N_{t-1} \times BW_{t-1} \times \mathrm{Pr}^{AH}) \tag{22}$$

Utility costs ($C^{utility}$) comprise the electricity and heating required for one production round and were calculated using the same Eq. (22), based on the average price of utility per housed chicken per kilogram live bird weight ($\mathrm{Pr}^{utility}$). Labor costs (C^{labor}) were calculated the same way as in Eq. (22) and were based on the price of labor per housed chicken per kilogram live bird weight (Pr^{labor}).

Total production costs ($C^{production}$) are the sum of all cost components:

$$C^{production} = C^{DOC} + C^{feed} + C^{AH} + C^{utility} + C^{labor} \tag{23}$$

2.3.2.2. Outbreak-related costs. In order to reduce the spread of diseases, dead chickens are disposed of by burning and burying the carcass which is usually done by farmers or farm staff. Disposal costs ($C^{disposal}$) depend on the number of infectious birds remaining (i.e., that are not sold to the market at the end of the production round:, $sold_t^{I_1}$, $sold_t^{I_2}$, $sold_t^{I_3}$) and total mortality at every time step t ($mort_t$). Disposal costs from stamping-out were not included since these costs are paid by the government or the large integrated poultry company. Consequently, the number of birds that are stamped out was not included in the calculation for disposal costs. $mort_t$ is determined by the following equation:

$$mort_t = \sum_{t=1}^{T^{end}} (mort_t^{Imm} + mort_t^{S} + mort_t^{Inf} + mort_t^{I_1} + mort_t^{I_2} + mort_t^{I_3}) \tag{24}$$

as well as on the cost associated with disposing one chicken ($\mathrm{Pr}^{disposal}$), including both labor and material:

$$C^{disposal} = \sum_{t=1}^{T^{end}} (mort_t + sold_t^{I_1} + sold_t^{I_2} + sold_t^{I_3}) \times \mathrm{Pr}^{disposal} \tag{25}$$

Upon recognition of an outbreak, an HPAI test would be performed through necropsy and a one-time rapid test in the production round. The cost of the HPAI test (C^{test}) was determined by the price of the test provided by the government or private companies (Pr^{test}).

A common response of Western Java smallholder farmers when they have recognized a sudden increase of mortality in the flock would be disinfection of the barn. Based on this information, we assumed that every day between initial recognition of an outbreak and the sale or stamping out of the flock, the farmer will disinfect the barn by spraying a disinfectant agent to reduce further disease spread. The daily costs of reactive barn disinfection at every time step t ($C_t^{disinfection}$) equals the price of disinfection per day ($\mathrm{Pr}^{disinfection}$) which includes both labor and material.

$$if \quad E_t^{Detect} = 1 : C_t^{disinfection} = \mathrm{Pr}^{disinfection} \tag{26a}$$

$$else : C_t^{disinfection} = 0 \tag{26b}$$

The cost of reactive disinfection ($C^{disinfection}$) is the sum of $C_t^{disinfection}$ in one production round.

$$C^{disinfection} = \sum_{t=1}^{T^{end}} C_t^{disinfection} \tag{27}$$

Thus, control costs ($C^{control}$) are the sum of all three mentioned costs.

$$C^{control} = C^{disposal} + C^{test} + C^{disinfection} \tag{28}$$

2.3.2.3. Total costs. The total variable costs in a production round are different for *makloon* farms versus independent and price-contract farm business types. Since in case of the former, production costs are paid by the company, only disease control costs are at the expense of the farm owner. Therefore, the total variable costs for *makloon* farms ($C^{makloon}$) are equal to the costs of disease control. For independent and price-contract farms ($C^{indie-price}$), the total calculated variable costs in a production round is the sum of all cost components.

$$C^{makloon} = C^{control} \tag{29}$$

$$C^{indie-price} = C^{production} + C^{control} \tag{30}$$

2.3.3. Gross margin

The gross margin (GM) is the difference between the returns and total variable costs which depends on the business type and was calculated using the following equations:

$$GM^{makloon} = R^{makloon} - C^{makloon} \tag{31a}$$

$$GM^{indie-price} = R^{indie-price} - C^{indie-price} \tag{31b}$$

where $GM^{makloon}$ and $GM^{indie-price}$ are the gross margin for *makloon* farms, and independent and price-contract farms, respectively.

2.4. Model parameterization

Input parameters for epidemiology and economics are presented in Tables 1–2 and were derived from scientific literature and expert opinion. Input parameters were chosen to mimic smallholder broiler farms in the Western Java situation as close as possible. Literature consisted of peer-reviewed papers as well as working papers that were focused on the Indonesian context. If data about the Indonesian context were unavailable, we used data or literature from other Southeast Asian countries (e.g., Thailand, Vietnam). When information about input parameters was unavailable in existing literature, we relied on expertise of the authors and other experts.

2.5. Model validation, scenarios and sensitivity analysis

As a first step in the validation approach, the computations in the model were checked by running several simulations with and without HPAI infection. Afterwards, the model was validated using face and expert validation. Face validity was carried out internally. Expert validation was performed through discussion within the author team as well as with an outside expert with research experience in Indonesia.

Different scenarios were developed based on the day of HPAI infection, specific events and farmer decisions. HPAI infection was assumed to occur at the beginning of the second, third and fourth week, that is T^{intro}: 8, 15, or 22. Three possible action scenarios regarding farmers' and the government responses to an HPAI outbreak were applied in the simulation: no action (*none*), panic selling (*early*), and stamping out (*stamp*). The no action scenario serves as baseline scenario for this study. Panic selling is defined as farmers selling their birds as early as possible

Table 1
Parameter inputs for HPAI infection dynamics.

Parameter	Default input (s)	Source
P_t^{mort}	$t \leq 7$, *TRIANG* (0.003, 0.004, 0.005) $t > 7$, *TRIANG* (0.001, 0.002, 0.003)	Indrawan et al. (2020) Expert opinion
T^{Imm}	7	Ka-Oud et al. (2008)
$Detect^{Thresh}$	1 %	Glanville et al. (2010)
T^{early}	19	CENTRAS, unpublished
β	*TRIANG* (1.1, 1.4, 1.9)	Poetri et al. (2011)
P^{mort_i}	for γ =1, 2, 3 (0.33, 0.67, 1)	Expert opinion

to sick bird markets when they detect a disease outbreak on their farm. Selling birds early is a known practice in the Southeast Asia region (Delabouglise and Boni, 2020) and is relatively common in Western Java situation where control measures are lacking (Indrawan et al., 2018). The decision to follow governmental advice and stamp out was included as an ideal scenario for an HPAI outbreak. However, the government has stopped supporting the program since 2007 (Azhar et al., 2010). The stamping out scenario was adjusted to the Indonesian context where farmers do not get compensated for stamping out.

Each scenario is denoted by using the name of the action and the day of HPAI introduction, for instance, *none-8* means that the scenario assumed that farmers decided to not taking any action to the outbreak (*none*) and HPAI introduction happened on day 8. In total, 10 scenarios were simulated, consisting of nine scenarios with HPAI infection and one scenario of production in normal circumstances without HPAI.

A univariate sensitivity analysis was performed to assess the effect of changing a specific epidemiological or economic parameter to the mean gross margin for all scenarios. Epidemiological inputs studied in the sensitivity analysis were the virus transmission rate, probability of mortality of infectious birds, and outbreak detection threshold. The virus transmission rate was doubled and halved (i.e., 2.8 and 0.7) to depict an outbreak with a more or less infectious viral strain (Bouma et al., 2009). The probability of mortality of infectious chickens was decreased by 10% (i.e., 90%). The detection threshold was doubled and halved (i.e., 2% and 0.5%) which depicts the detection threshold in industrialized poultry farms and vaccinated flock in Indonesia (Glanville et al., 2010). Economic parameters inputs changed in the sensitivity analysis were market price of chickens, feed price, and stamping out compensation. Changes in prices were based on the most likely fluctuation of the market price for chickens and feed (Pr^{market}: ± 500 IDR/kg; Pr^{feed}: ± 250 IDR/kg). The change in stamping out compensation was based on a combination of DOC and feed prices (*comp*: 13000 IDR/culled bird), an approach that has been used in the past. In order to assess the economic impact of a single HPAI outbreak on a farm, a gross margin (*GM*) calculation was carried out. The returns and costs were calculated for every time step or for one production round and summed to obtain the total returns and costs.

3. Results

Overall, HPAI H5N1 outbreaks decreased returns, total variable costs, and, consequently, gross margins in all business types in all scenarios. Detailed calculations of returns, costs, and gross margins for different farmers' decisions are presented in Table 3. The economic consequences of outbreaks were larger for independent and price-contract farmers (Table 4) than for *makloon* farmers (Table 5) as also visualized in Fig. 2. The smaller economic consequences for *makloon* farmers was because the economic burden is allocated to the poultry integrator company that made a *makloon* contract with the farmers.

3.1. No-action scenarios

The results in a no-action scenario were used as the reference point to measure the economic impact of HPAI H5N1 outbreaks at different times for all farm business types. Fig. 3 shows how the mean value of gross margins in no-action scenarios increases for outbreaks towards the

Table 2

Economic inputs and parameters used for production and economic calculations. Parameters that are in IDR are valued at thousand IDR.

Parameter	Description	Value	Unit	Source
$Pr^{makloon}$	Management fee paid to *makloon* farmers	1	IDR/sold bird/kg	Expert opinion
Pr^{market}	Contract/market price of live birds	19	IDR/sold bird/kg	Ministry of Industry, 2019
$Pr^{panic-S}$	Sick bird market price of live bird weight ≤ 1 kg	10	IDR/sold bird/kg	CENTRAS, unpublished
$Pr^{panic-L}$	Sick bird market price of live bird weight > 1 kg	14	IDR/sold bird/kg	CENTRAS, unpublished
Comp	Stamping out compensation	0	IDR/culled bird	Expert opinion
$Pr^{certDOC}$	Average vaccinated day-old-chick (DOC) price	6.25	IDR/DOC	Author calculation
$Pr^{uncertDOC}$	Average unvaccinated DOC price	6	IDR/DOC	Author calculation
Pr^{feed}	Average commercial feed price	7.25	IDR/kg	Author calculation
Pr^{AH}	Average animal health price	0.54	IDR/housed bird/kg	van Horne et al. (2020)
$Pr^{utility}$	Average utility price (e.g., electricity, heating)	0.7	IDR/housed bird/kg	van Horne et al. (2020)
Pr^{labor}	Average minimum wage in Western Java	0.75	IDR/housed bird/kg	Author's calculation
$Pr^{disposal}$	Gasoline and labor for burning and burying birds	0.25	IDR/dead bird	Expert opinion
Pr^{test}	HPAI test: necropsy, rapid test, service fee	200	IDR/round	Author calculation
$Pr^{disinfection}$	Disinfectant price and labor	50	IDR/day	Expert opinion

Table 3

Components of returns and costs included in the calculation of gross margin (in million IDR) for independent and price-contract business types, for each action scenario. Results are for one round of production when the introduction of virus was assumed in production day 15.

Independent & price-contract farms	*none-15*		*early-15*		*stamp-15* with compensation	
	mean	95% C.I.	mean	95% C.I.	mean	95% C.I.
Returns	**64.32**	**41.37 – 79.08**	**45.67**	**27.69 – 56.41**	**36.23**	**35.01 – 36.07**
Sales of chickens	64.32	41.37 – 79.08	45.67	27.69 – 56.41	0.90	
Stamping out compensation					35.33	34.96 – 36.34
Production costs	**75.93**	**73.57 – 77.60**	**61.36**	**53.11 – 73.76**	**58.22**	**52.61 – 69.96**
DOC	18.75		18.75		18.75	
Feed	49.82	48.38 – 50.84	36.39	29.09 – 47.33	33.61	28.66 – 43.97
Animal health	2.00	1.75 – 2.19	1.69	1.43 – 2.09	1.59	1.41 – 1.97
Utility	2.59	2.27 – 2.84	2.19	1.85 – 2.70	2.06	1.82 – 2.55
Labor	2.78	2.44 – 3.04	2.34	1.99 – 2.90	2.21	1.95 – 2.73
Control costs	**0.73**	**0.44 – 1.01**	**0.37**	**0.36 – 0.39**	**0.31**	**0.30 – 0.32**
Disposal	0.21	0.09 – 0.40	0.07	0.06 – 0.09	0.06	0.05 – 0.07
HPAI test	0.20	0.20 – 0.20	0.20	0.20 – 0.20	0.20	0.20 – 0.20
Disinfection	0.32	0.15 – 0.45	0.10	0.10 – 0.10	0.05	0.05 – 0.05
Gross margin	**–12.34**	**–33.13 – 1.19**	**–16.05**	**–25.64 – –14.62**	**–22.30**	**–34.76 – –16.92**

Table 4
Summary of returns, costs, and gross margin (in million IDR) for independent and price-contract business types, for all simulated days of HPAI H5N1 introduction and three action scenarios during one production round.

Decision/event	Default	No action (*none*)			Early selling (*early*)			Stamping out (*stamp*)		
Day of introduction	No HPAI	8	15	22	8	15	22	8	15	22
Independent and price-contract farms										
Returns										
Mean	83.39	11.59	64.32	82.17	21.31	45.67	80.96	0.17	1.15	57.73
5%	81.84	0.06	41.37	80.28	19.15	27.69	60.59	0.00	0.00	0.00
95%	84.89	45.29	79.08	83.93	25.48	56.41	83.93	0.00	0.00	83.90
Production costs										
Mean	78.06	63.96	75.93	77.95	43.78	61.36	77.93	39.84	58.19	77.71
5%	77.31	55.92	73.57	77.20	42.22	53.11	77.17	36.10	50.29	74.50
95%	78.78	72.49	77.60	78.68	49.86	73.76	78.68	47.32	69.93	78.67
Control costs										
Mean	0.05	1.52	0.73	0.14	0.42	0.37	0.14	0.30	0.30	0.14
5%	0.04	1.09	0.44	0.05	0.36	0.36	0.05	0.29	0.30	0.05
95%	0.07	1.70	1.01	0.36	0.51	0.39	0.36	0.31	0.32	0.32
Gross margin										
Mean	5.28	–53.89	–12.34	4.07	–22.89	–16.05	2.89	–39.97	–57.35	–20.11
5%	4.44	–61.97	–33.13	2.66	–24.61	–25.64	–17.74	–47.62	–69.75	–78.56
95%	6.12	–27.89	1.19	5.31	–22.23	–14.62	5.31	–36.40	–50.39	5.31

Table 5
Summary of returns, costs, and gross margins (in million IDR) for all HPAI H5N1 introduction and action scenarios in one production round of a *makloon* business type.

Decision/event	Default	No action (*none*)			Early selling (*early*)			Stamping out (*stamp*)		
Day of introduction	No HPAI	8	15	22	8	15	22	8	15	22
Makloon farms										
Returns										
Mean	4.39	0.61	3.39	4.32	2.10	3.27	4.32	0.01	0.06	3.04
5%	4.31	0.00	2.18	4.23	1.91	2.77	4.22	0.00	0.00	0.00
95%	4.47	2.38	4.16	4.42	2.55	4.03	4.42	0.00	0.00	4.42
Control costs										
Mean	0.05	1.52	0.73	0.14	0.42	0.37	0.14	0.30	0.30	0.14
5%	0.04	1.09	0.44	0.05	0.36	0.36	0.05	0.29	0.30	0.05
95%	0.07	1.70	1.01	0.36	0.51	0.39	0.36	0.31	0.32	0.32
Gross margin										
Mean	4.34	–0.91	2.66	4.18	1.68	2.91	4.18	–0.29	–0.24	2.90
5%	4.24	–1.70	1.17	3.89	1.40	2.41	3.89	–0.31	–0.32	–0.32
95%	4.43	1.29	3.72	4.37	2.18	3.65	4.37	–0.29	–0.30	4.37

end of the production round. Furthermore, the relative increase of the gross margins follows the same pattern for all business types.

Taking no action to control HPAI outbreaks (*none*) leads to considerable losses for both independent and price-contract farmers. The average gross margin in the earliest HPAI introduction scenario on day 8, *none-8* was the lowest compared to all other scenarios. The gross margins in *none-8* and *none-15* (Table 4) show that taking no action to address HPAI outbreaks could lose independent and price-contract farmers, on average, − 53.9 and − 12.3 million IDR (−€3368 to −€771) (1 Euro = 16,000 IDR), respectively. These losses equate to 10 and two times the gross margin of a normal round (i.e., *Default*), respectively. Meanwhile, taking no action when infection occurred in the beginning of the fourth week (*none-22*) resulted in a positive but lower gross margin compared to the default scenario.

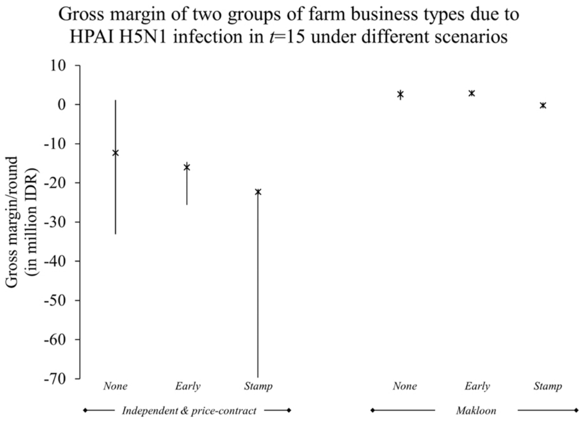

Fig. 2. A comparison of gross margins in one production round for different action scenarios for independent, price-contract, and *makloon* business types when HPAI H5N1 introduction occurs in the beginning of the second week of the round ($t=15$).

For *makloon* farmers, taking no action on HPAI outbreaks also leads to economic losses in all three scenarios. When the infection occurred in the beginning of the second week (*none-8*) (Table 5), the losses were the largest, although only about a quarter of the gross margin under the default scenario.

3.2. *Early selling decision reduces the losses*

Selling birds to the sick-bird market (early/panic selling) leads to the highest and least variable gross margins in most scenarios and in all business types. The graph (Fig. 3.) shows a similar pattern compared to the no-action scenario, with average gross margins increasing as the time of the outbreak is delayed. However, the increase was less strong compared to the no-action scenario, especially for a *makloon* business type.

Table 4 shows that early selling to the sick-bird market reduced the losses of independent and price-contract farmers as shown in *early-8* and *early-15*. The average losses were − 22.9 and − 16 million IDR, approximately four and three times the gross margin of a default production round, respectively. For *makloon* farmers, early selling also leads

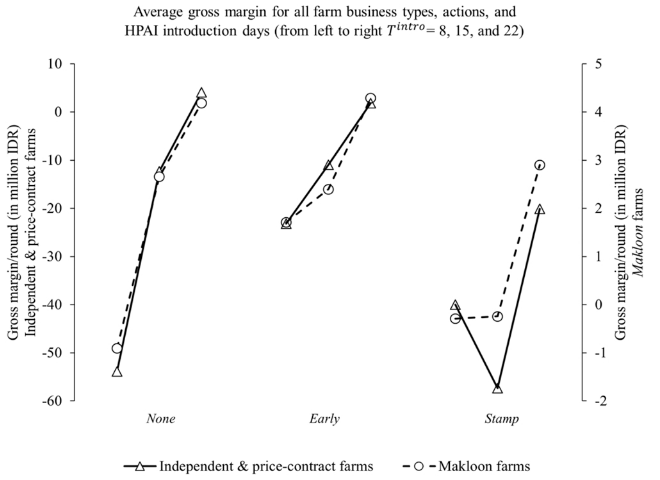

Fig. 3. Effects of the time of introduction of HPAI H5N1 (T^{intro}) and actions taken by farmers to the average gross margin in one round of production for all farm business types.

to lower gross margins compared to the default situation, but they are still higher than under other scenarios (Table 5).

3.3. Stamping out might lead to bigger losses

On average, stamping out without compensation leads to the highest losses for all scenarios. Fig. 3 shows a different pattern of the gross margins between groups of business types. For independent and price-contract farms, the lowest gross margin is when the virus was introduced to the flock in the middle of the production round (t = 15). Table 4 shows that the gross margin of *stamp-15* (−57.4 million IDR) was lower than of *stamp-8* (−39.9 million IDR) because of increasing costs. These losses are approximately 11 and eight times the normal gross margin in a round. However, the average gross margin in *stamp-22* was higher (−20 million IDR) because birds might already have been sold before detecting the outbreak.

For a *makloon* business type farm, the average gross margin increased when the outbreaks occurred later in the production cycle (Fig. 3.). Similar to early selling scenarios, outbreaks of HPAI lead to higher losses when the infection occurs earlier, as shown in *stamp-8* (Table 5).

3.4. How changes in parameters affect the impact of HPAI

Based on the sensitivity analysis results in Tables 6 to 8, the gross margins were sensitive to changes of three parameter inputs: disease transmission rate, detection threshold, and stamping out compensation. An increase or decrease in disease transmission rate resulted in the biggest changes in gross margins for all business types. For independent and price-contract farmers, a more virulent type of virus led to a more severe economic impact as indicated by a significant decrease of the gross margins due to higher mortality (e.g., *none-15*: −54.1 million IDR) and the likelihood of outbreaks to be detected earlier (e.g., *early-22*: −19.4 million IDR; *stamp-22*: −51.2 million IDR) (Tables 6 and 7). In contrast, a less virulent virus significantly increases the gross margins, especially for *none-8*: 56 million IDR and *stamp-15*: 53.7 million IDR.

A higher or lower outbreak detection threshold was more sensitive to

Table 6
Changes of the mean value of the gross margin of independent and price-contract farms (in million IDR) from the sensitivity analysis based on disease transmission rate, probability of mortality of infectious birds, and detection threshold in all scenarios.

Independent & price-contact	Changes in the mean value of the gross margin (in million IDR)					
	Default (mean value)	Disease transmission rate		Probability of mortality infectious birds	Detection threshold	
		0.5x	2x	−10%	0.5%	2%
No Action						
none-8	−53.89	55.99	5.87	−1.59	–	–
none-15	−12.34	16.53	−54.12	−2.22	–	–
none-22	4.07	0.86	−4.05	−0.09	–	–
Early selling						
early-8	−22.89	18.82	−6.15	−0.04	0.21	−0.56
early-15	−16.05	18.95	−8.10	0.05	−3.06	−0.66
early-22	2.89	2.04	−19.35	−0.32	−8.87	1.25
Stamping out						
stamp-8	−39.97	17.88	6.26	0.68	3.48	−3.57
stamp-15	−57.35	53.65	8.19	0.58	4.22	−3.68
stamp-22	−20.11	25.04	−51.17	−5.21	−32.70	22.56

Table 7
Changes of the mean value of the gross margin of *makloon* farms (in million IDR) from the sensitivity analysis based on disease transmission, probability of mortality in infectious state, and detection threshold in all scenarios.

Makloon	Changes in the mean value of the gross margin (in million IDR)					
	Default (mean value)	Disease transmission rate		Probability of mortality infectious birds	Detection threshold	
		0.5x	2x	−10%	0.5%	2%
No Action						
none-8	−0.91	4.82	−0.69	−0.16	–	–
none-15	2.66	1.56	−3.92	−0.16	–	–
none-22	4.18	0.13	−0.49	−0.02	–	–
Early selling						
early-8	1.68	2.09	−1.12	−0.04	−0.11	0.16
early-15	2.91	1.30	−0.63	−0.06	−0.27	0.22
early-22	4.18	0.13	−0.45	−0.02	−0.16	0.07
Stamping out						
stamp-8	−0.29	2.71	0.00	0.01	0.01	0.02
stamp-15	−0.24	4.03	−0.06	−0.02	−0.04	0.10
stamp-22	2.90	1.41	−3.16	−0.29	−1.95	1.26

Table 8

Changes in the mean value of the gross margin of independent and price-contract farms (in million IDR) from the sensitivity analysis based on changes on the market price, feed price, and stamping out compensation (in '000 s IDR) in all scenarios.

Independent & price-contact	Changes in the mean value of the gross margin (in million IDR)					
	Default	Market price		Feed price		Compensation
		– 0.5 IDR/kg	+ 0.5 IDR/kg	+ 0.25 IDR/kg	– 0.25 IDR/kg	13 IDR/culled bird
Default	5.28	–2.20	2.19	–1.76	1.76	–
No Action						
none-8	–53.89	0.06	1.23	–0.82	2.38	–
none-15	–12.34	–1.83	1.66	–1.78	1.51	–
none-22	4.07	–2.16	2.15	–1.76	1.75	–
Early selling						
early-8	–22.89	–0.07	0.12	–0.75	0.78	–
early-15	–16.05	0.12	0.31	–1.10	1.58	–
early-22	2.89	–1.88	1.93	–1.74	1.68	–
Stamping out						
stamp-8	–39.97	–0.04	–0.06	–0.69	0.64	36.07
stamp-15	–57.35	0.40	0.35	–0.52	1.52	35.05
stamp-22	–20.11	0.60	1.85	–1.03	3.51	10.87

later outbreaks, from day 22 onwards. A higher sensitivity detection threshold resulted in lower gross margins for scenarios where the infection occurred later in the production round. For instance, gross margins of *early-22* and *stamp-22* decreased by nine and 32.7 million IDR (Table 6), respectively. In contrast, a less sensitive detection threshold increased the gross margins, but the effect was more significant for stamping out compared to early selling scenarios (Tables 6 and 7).

When stamping out compensation was assumed, the gross margins in *stamp-8* and *stamp-15* increased considerably: by about 36 and 35 million IDR, respectively (Table 8). The gross margin for the earliest scenario might be higher than early selling scenarios.

4. Discussion

In this study, a stochastic bio-economic model was developed to estimate the economic impact of highly pathogenic avian influenza (HPAI) outbreaks on a typical Western Java smallholder broiler farm. We focused on these smallholder broiler farms because those farms play an important role in the transmission of HPAI in the Indonesian poultry sector and human population/HPAI-cases (Glanville et al., 2010; Wibawa et al., 2018). This study is not the first study on the economics of HPAI outbreaks. However, other economic studies (e.g., Otte et al., 2008; Akunzule et al., 2009; Basuno et al., 2010; Govindaraj et al., 2018) were aimed at eradication of HPAI in epidemic outbreak situations and at the regional-level. In contrast, in this study, we emphasized on the economic losses for smallholder poultry farmers as a result of HPAI outbreaks in several farm business types and of short-term decision options that these farmers have, under an assumption of an endemic situation.

Our bio-economic model allows the comparison of the economic impact of an HPAI outbreak in independent, price-contract, and *makloon* business types, and for different farmer decisions: no-action, early selling, and stamping out. We integrated available epidemiological and economic data, scientific literature, and expert opinion for the basis of our model parameters inputs. Sensitivity analysis pointed out that there were significant effects on the changes in gross margins when the disease transmission rate, detection threshold, and stamping out compensation were altered.

Additionally, despite the effort in developing a representative and reliable bio-economic simulation model, some simplifications were used. For instance, feed cost may have been overestimated since we assumed that sick birds have the same feed intake as healthy birds during the first and second infectious periods. Moreover, in our model, we based detection of an HPAI outbreak on the daily morbidity, while in practice, farmers base the detection on daily mortality (Glanville et al., 2010). So, in our model, detection of HPAI may have been one to two days earlier than sometimes would occur in a field situation, which led to, for instance, a lower mortality and losses per round. Furthermore, early selling and stamping out were assumed to be implemented the day after outbreak detection, which could under- or overestimate the effect of these decisions. However, the consequences of these simplifications are relatively small compared to the overall consequences of an HPAI outbreak, and therefore, have relatively small effects on the main results of our bio-economic model.

In this discussion, three aspects will be discussed: the role of business types, farm economic impact, and the role of sick-bird market.

4.1. HPAI outbreak economic impact in different business types

In general, the economic consequences of an HPAI outbreak at the farm level are large. For instance, for an independent farm, in a round with an HPAI outbreak, the farm's modest gross margin of 5.28 million IDR is changed into losses varying from, on average, − 57.4 to − 12.3 million IDR, depending on the timing of the outbreak, business type, and farmers' short-term decision. These losses were two to eleven times higher than the gross margin of a default round without HPAI, and were mostly caused by a decrease in returns. For price-contract farms, the losses are more or less similar to those in independent farms, due to their similar system of payment and cost allocation. The consequences of an HPAI outbreak were estimated to be even worse when a more virulent AI virus infected the farm. Such potential of severe economic losses explains the farmers' decision to stop their poultry farming activities during the HPAI H5N1 epidemic in 2003–2004 (Basuno et al., 2010).

For *makloon* farms, HPAI outbreaks resulted in a considerably lower decrease in the farms' gross margin. The largest loss for *makloon* farms due to an HPAI outbreak was − 0.9 million IDR, which is a quarter of the normal gross margin. Since *makloon* farmers are highly dependent on their broiler farming activities (Pramuwidyatama et al., 2020), the outbreaks still heavily impact their income.

Overall, our results showed that the economic impact of an HPAI outbreak was much more severe for independent and price-contract farmers than for *makloon* farmers. However, this does not mean that for the *makloon* business type, lower economic effects occur. Instead, the economic burden is allocated to another stakeholder in the value chain: the company that made a *makloon* contract with the farmers. However, the farmers make decisions on the biosecurity on the farm, and because of the lower economic consequences of HPAI outbreaks (or other diseases), *makloon* farmers will have reduced incentives to maintain a high level of biosecurity. This is confirmed by earlier work that showed lower levels of biosecurity on *makloon* farms (Indrawan et al., 2020). The company could use contract regulations that incentivize farmers to improve biosecurity measures (Rimi et al., 2017), for instance, through contract bonus systems (Komaladara et al., 2016). Moreover, poultry companies could also establish improved communication with their farmers regarding biosecurity through their technical support staff (Jayawinangun et al., 2019; Pramuwidyatama et al., 2020).

4.2. Effects of farmers' decision on the economic impact of HPAI outbreaks

Besides differences in farm business types, we also showed that farmers' response to after an outbreak of HPAI have large consequences for the economic impact of outbreaks. Stamping out, a standard control measure to mitigate the regional effects of disease outbreaks, was the most expensive reactive measure, especially when the outbreak was detected earlier, either due to a lower detection threshold or a more virulent AI virus. With the current voluntary stamping out policy, the option to stamp out the flock is expensive for farmers. This might lead to under-reporting of HPAI outbreaks to the authorities, which would explain why stamping out programs in Indonesia were thus far not successful (Azhar et al., 2010).

Our results indicate that stamping out compensation could largely reduce the economic consequences of an HPAI outbreak. By compensating farmers, stamping out was an economically better decision in early infection scenarios than the early (panic) selling of the flock to the sick bird market, as was shown in the sensitivity analysis results. However, offering compensation to farmers might not necessarily increase the willingness of farmers to join stamping out programs, as a previous study showed (Pramuwidyatama et al., 2020). This option is also expensive for the government, as there is limited capacity to give a fair compensation for farmers. Thus, it is important to design funding mechanisms to support future stamping out programs, for example through public-private partnerships between the government and private companies (Albrechtsen et al., 2009; Swayne et al., 2011).

4.3. Effects of early selling of the flock to a sick-bird market

Typical for the situation in Western Java is the existence of a sick-bird market to which farmers can sell their sick flock for a cheaper price. In addition to taking no action or reporting an outbreak of HPAI to the authorities for stamping out, farmers have a third option: selling early. As a reaction to an HPAI outbreak, the decision to sell sick and not full-grown poultry early resulted in the lowest economic burden for farmers, especially when the outbreak occurs at the beginning of the production round. This was also observed for the Vietnamese situation (Delabouglise and Boni, 2020). In the worst situation, with a more virulent virus and lower selling price, the early selling option still offered the lowest economic losses for farmers. Since control along the poultry value chain in Western Java has been lacking, early selling occurs quite commonly (Indrawan et al., 2018). As other actors in the value chain (e.g., traders) will also benefit from early selling, they may support farmers in this decision. Although early selling during HPAI outbreaks is often the best option from the farmers' perspective, especially when the outbreak is detected near the selling day, this practice is unfavorable from the local government's point of view, since there is a larger risk of spread of HPAI throughout the region due to the increased transportation of infected birds (Indriani et al., 2010; Loth et al., 2011; Yupiana et al., 2010; Henning et al., 2019).

5. Policy implications

Our results suggest that economic consequences from an HPAI outbreak are influenced by farmers' response which is dependent on the business type and the existence of a sick-bird market. Stamping out or other control measures are not financially attractive for farmers as long as the sick-bird market still offers the lowest economic consequences. As a consequence, the uptake of control measures by farmers will likely remain low, hamper HPAI control, and maintain the risks of HPAI to the public health.With smallholder poultry farms largely making up the poultry industry in Western Java, the involvement of farmers, companies, and policymakers is needed to increase the implementation of control measures.

If the government aims to "revive" and increase farmers' participation on the stamping out program in the future, the compensation has to offer better economic outcomes for farmers compared to alternatives. Furthermore, ensuring a timely and fair compensation might help to increase and maintain farmers' involvement in the stamping out program. At the same time, more rigorous measures are also needed to disincentivize farmers and traders from trading sick birds. These measures could include monitoring of live birds trades, establishing penalties, and closing down live bird markets. Lastly, financial incentives might also be needed to increase farmers' involvement in taking up control measures on their farms. Incentives could be in many forms and could also be included in the production contract, for instance, through bonuses, the selling price, or a subsidized vaccination program. Thus, we suggest that the epidemiological and economic effects of control measures on a smallholder broiler farm context need to be studied and, ultimately, communicated to create more understanding between stakeholders involved in HPAI mitigation.

6. Conclusions

The economic consequences of HPAI outbreaks for smallholder poultry farmers in Western Java are considerable, ranging from, on average, − 62.7 to − 0.16 million IDR (−€3919 to −€10) (1 Euro = 16,000 IDR), depending on the business type, reaction of the farmer and moment of infection, and in comparison with an expected gross margin of 5.3 million IDR (€331) and 4.3 million IDR (€271) for independent and price-contract, and *makloon* farms under normal circumstances, respectively. Farmers in a *makloon* business type suffered substantially lower economic losses than other farmers, reducing their incentives to implement biosecurity measures. Stamping out, in general, led to higher losses in the absence of compensation, especially when stamping out occurred near the end of the production round. Early selling of chickens to a sick-bird market as a reaction to an HPAI outbreak, resulted in the lowest economic losses, incentivizing farmers to partake in behavior with high disease transmission risks. Overall, these aspects of the Western Java poultry infrastructure are unfavorable for the control of HPAI at the regional level. Finally, the study results suggest that a wider regional economic perspective should be compared to the individual farmers' economic perspective. Special attention should be paid to (financial) incentives for farmers to react to HPAI outbreaks on their farm in a way that supports mitigation of HPAI at the regional level.

Conflict of interest statement

All authors declare that we have no conflicts of interest.

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References

Akunzule, A.N., Koney, E.B.M., Tiongco, M., 2009. Economic impact assessment of highly pathogenic avian influenza on the poultry industry in Ghana. World's Poult. Sci. J. 65 (3), 517–528. https://doi.org/10.1017/S0043933909000385.

Albrechtsen, L., Saade, M., Riviere, A., Rushton, J., 2009. Pro-active engagement in compensation and rehabilitation policy formulation and implementation: the case of

HPAI in Egypt. World's Poult. Sci. J. 65 (2), 225–230. https://doi.org/10.1017/S0043933909000178.

Azhar, M., Lubis, A.S., Siregar, E.S., Alders, R.G., Brum, E., McGrane, J., Roeder, P., 2010. Participatory disease surveillance and response in Indonesia: strengthening veterinary services and empowering communities to prevent and control highly pathogenic avian influenza. Avian Dis. 54 (s1), 749–753. https://doi.org/10.1637/8713-031809-Reg.1.

Basuno, E., Yusdja, Y., Ilham, N., 2010. Socio-economic impacts of avian influenza outbreaks on small-scale producers in Indonesia. Transbound. Emerg. Dis. 57 (1–2), 7–10. https://doi.org/10.1111/j.1865-1682.2010.01121.x.

Bouma, A., Claassen, I., Natih, K., Klinkenberg, D., Donnelly, C.A., Koch, G., Van Boven, M., 2009. Estimation of transmission parameters of H5N1 avian influenza virus in chickens. PLoS Pathog. 5 (1), e1000281 https://doi.org/10.1371/journal.ppat.1000281.

Delabouglise, A., Boni, M.F., 2020. Game theory of vaccination and depopulation for managing livestock diseases and zoonoses on small-scale farms. Epidemics 30, 100370. https://doi.org/10.1016/j.epidem.2019.100370.

Durr, P.A., Wibowo, M.H., Tarigan, S., Artanto, S., Rosyid, M.N., Ignjatovic, J., 2016. Defining "Sector 3" Poultry Layer Farms in Relation to H5N1-HPAI—An Example from Java, Indonesia. Avian Dis. 60 (1s), 183–190. https://doi.org/10.1637/11134-050815-reg.

Gani, J., Jerwood, D., 1971. Markov chain methods in chain binomial epidemic models. Biometrics 591–603. https://doi.org/10.2307/2528598.

BPS. (2022). Populasi Ayam Ras Pedaging menurut Provinsi (Ekor), 2019–2021. Accessed on August 1st, 2022 on ⟨https://www.bps.go.id/indicator/24/478/1/populasi-ayam-ras-pedaging-menurut-provinsi.html⟩.

Glanville, W.A.D., Idris, S., Costard, S., Unger, F., & Pfeiffer, D.U. (2010). A quantitative risk assessment for the onward transmission of highly pathogenic avian influenza H5N1 from an infected small-scale broiler farm in Bogor, West Java, Indonesia.

Govindaraj, G., Sridevi, R., Nandakumar, S.N., Vineet, R., Rajeev, P., Binu, M.K., Rahman, H., 2018. Economic impacts of avian influenza outbreaks in Kerala, India. Transbound. Emerg. Dis. 65 (2), e361–e372. https://doi.org/10.1111/tbed.12766.

Henning, J., Hesterberg, U.W., Zenal, F., Schoonman, L., Brum, E., McGrane, J., 2019. Risk factors for H5 avian influenza virus prevalence on urban live bird markets in Jakarta, Indonesia—Evaluation of long-term environmental surveillance data. PLoS One 14 (5), e0216984. https://doi.org/10.1371/journal.pone.0216984.

Indrawan, D., Rich, K.M., van Horne, P., Daryanto, A., Hogeveen, H., 2018. Linking supply chain governance and biosecurity in the context of HPAI control in Western Java: a value chain perspective. Front. Vet. Sci. 5, 94. https://doi.org/10.3389/fvets.2018.00094.

Indrawan, D., Cahyadi, E.R., Daryanto, A., Hogeveen, H., 2020. The role of farm business type on biosecurity practices in West Java broiler farms. Prev. Vet. Med. 176, 104910 https://doi.org/10.1016/j.prevetmed.2020.104910.

Indriani, R., Samaan, G., Gultom, A., Loth, L., Indryani, S., Adjid, R., Kelly, P.M., 2010. Environmental sampling for avian influenza virus A (H5N1) in live-bird markets, Indonesia. Emerg. Infect. Dis. 16 (12), 1889 https://doi.org/10.3201%2Feid1612.100402.

Jayawinangun, R., Indrawan, D., Sutarman, D.C., 2019. How to communicate livestock hazard? An approach to improve farmers'risk preparedness, 165-165 J. Manaj. Agribisnis 16 (3). https://doi.org/10.17358/jma.16.3.165.

Ka-Oud, H.A., Zakia, M.A., Kamel, M.M., 2008. Evaluation of the immune response in AI vaccinated broiler chickens: effect of biosecurity faults on immune response. Int. J. Poult. Sci. 7 (4), 390–396. https://doi.org/10.3923/ijps.2008.390.396.

Komaladara, A.A.S.P., Patrick, I., Hoang, N., 2016. Contract bonus systems to encourage biosecurity adoption on small-scale broiler farms in Indonesia. Anim. Prod. Sci. 58 (3), 595–600. https://doi.org/10.1071/AN15845.

Loth, L., Gilbert, M., Wu, J., Czarnecki, C., Hidayat, M., Xiao, X., 2011. Identifying risk factors of highly pathogenic avian influenza (H5N1 subtype) in Indonesia. Prev. Vet. Med. 102 (1), 50–58. https://doi.org/10.1016/j.prevetmed.2011.06.006.

Otte, J., Hinrichs, J., Rushton, J., Roland-Holst, D., Zilberman, D., 2008. Impacts of avian influenza virus on animal production in developing countries. CAB Rev.: Perspect. Agric. Vet. Sci. Nutr. Nat. Resour. 3 (080), 18. https://doi.org/10.1079/PAVSNNR20083080.

Peiris, J.M., De Jong, M.D., Guan, Y., 2007. Avian influenza virus (H5N1): a threat to human health. Clin. Microbiol. Rev. 20 (2), 243–267. https://doi.org/10.1128/cmr.00037-06.

Poetri, O., Bouma, A., Claassen, I., Koch, G., Soejoedono, R., Stegeman, A., van Boven, M., 2011. A single vaccination of commercial broilers does not reduce transmission of H5N1 highly pathogenic avian influenza. Vet. Res. 42 (1), 1–12 https://doi.org/10.1186%2F1297-9716-42-74.

Pramuwidyatama, M.G., Hogeveen, H., Saatkamp, H.W., 2019. A systematic evaluation of measures against highly pathogenic avian influenza (HPAI) in Indonesia. Front. Vet. Sci. 6, 33 https://doi.org/10.3389%2Ffvets.2019.00033.

Pramuwidyatama, M.G., Hogeveen, H., Saatkamp, H.W., 2020. Understanding the motivation of western java smallholder broiler farmers to uptake measures against highly pathogenic avian influenza (HPAI). Front. Vet. Sci. 7, 362. https://doi.org/10.3389/fvets.2020.00362.

Pramuwidyatama, M.G., Indrawan, D., Saatkamp, H.W., Hogeveen, H., 2022. Smallholder broiler farmers' characteristics to uptake measures against highly pathogenic avian influenza in western java. Front. Vet. Sci. *9* https://doi.org/10.3389%2Ffvets.2022.727006.

Rimi, N.A., Sultana, R., Muhsina, M., Uddin, B., Haider, N., Nahar, N., Luby, S.P., 2017. Biosecurity conditions in small commercial chicken farms, Bangladesh 2011–2012. EcoHealth 14 (2), 244–258. https://doi.org/10.1007/s10393-017-1224-2.

Swayne, D.E., Suarez, D.L., 2000. Highly pathogenic avian influenza. Rev. Sci. Et. Tech. -Off. Int. Des. Epizoot. 19 (2), 463–475. https://doi.org/10.20506/rst.19.2.1230.

Swayne, D.E., Pavade, G., Hamilton, K., Vallat, B., Miyagishima, K., 2011. Assessment of national strategies for control of high-pathogenicity avian influenza and low-pathogenicity notifiable avian influenza in poultry, with emphasis on vaccines and vaccination. Rev. Sci. Et. Tech. -OIE 30 (3), 839. https://doi.org/10.20506/rst.30.3.2081.

Tiensin, T., Chaitaweesub, P., Songserm, T., Chaisingh, A., Hoonsuwan, W., Buranathai, C., Stegeman, A., 2005. Highly pathogenic avian influenza H5N1, Thailand, 2004. Emerg. Infect. Dis. 11 (11), 1664. https://doi.org/10.3201/eid1111.050608.

van Horne, P., van Emous, R., Joosten, F., Tacken, G., & Leenstra, F. (2020). Dutch-Indonesian programme on Food Security in the livestock sector (DIFS-live): poultry meat: Results of the poultry meat programme 2014–2018; main report (No. 1259). Wageningen Livestock Research. https://doi.org/10.18174/525324.

WHO. (2021). Cumulative number of confirmed human cases for avian influenza A (H5N1) reported to WHO, 2003–2021. Accessed on January 10th, 2022 on ⟨https://www.who.int/publications/m/item/cumulative-number-of-confirmed-human-cases-for-avian-influenza-a(h5n1)-reported-to-who-2003–2021-15-april-2021⟩.

Wibawa, H., Karo-Karo, D., Pribadi, E.S., Bouma, A., Bodewes, R., Vernooij, H., Stegeman, A., 2018. Exploring contacts facilitating transmission of influenza A (H5N1) virus between poultry farms in West Java, Indonesia: a major role for backyard farms? Prev. Vet. Med. 156, 8–15. https://doi.org/10.1016/j.prevetmed.2018.04.008.

Yupiana, Y., de Vlas, S.J., Adnan, N.M., Richardus, J.H., 2010. Risk factors of poultry outbreaks and human cases of H5N1 avian influenza virus infection in West Java Province, Indonesia. Int. J. Infect. Dis. 14 (9), e800–e805. https://doi.org/10.1016/j.ijid.2010.03.014.