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THE EFFECTS OF FEED COSTS AND INCREASED ENERGY NEEDS ON BROILER FARM PRODUCTIVITY: A DYNAMIC PROGRAMMING APPROACH

By

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Summary

While Africa has seen a rapid growth of commercial livestock enterprises with its food systems transformation, little is known about their viability. We explore the profitability of commercial poultry enterprises facing rising input costs and increasing energy needs due to the adoption of climate mitigating technologies in Nigeria. Using a cross-sectional dataset and a one-year weekly panel of farm inputs and prices, we employ a discrete time, discrete control and state space dynamic programming model disaggregated by farm size to determine the source of economies of scale among commercial poultry farms. In the presence of high feed costs and increased energy needs, the optimal decision for medium sized farms is to sell and exit the industry. However, it remains profitable for large farms to stay in the sector. The findings are robust to various alternative model assumptions and specifications. They indicate that broiler farms need larger stock sizes to withstand negative input price shocks and expand energy consumption in the face of volatile and hotter temperatures. The sensitivity of the poultry industry to the feed prices is a major threat to the growth and survival of farms and highlight the importance of developing risk management mechanisms to stabilize prices.

Keywords: Dynamic programming, poultry production, food systems, Nigeria

With rising incomes and urbanization, food systems in Sub-Saharan Africa (SSA) have transformed rapidly over the last two decades. One key characteristic of this transformation is the diversification of diets from largely starchy staples to increased consumption of animal proteins (Tschirley et al., 2015). Nigeria has followed comparable trends to the rest of Sub-Saharan Africa, with positive and large income elasticities of demand for beef, fish, and chicken (Desiere et al., 2018; Aborisade and Carpio, 2017).

While livestock operations generally keep trending towards larger and more efficient processes, no other meat production in Africa has skyrocketed at a faster rate than poultry. For example, poultry production in Nigeria has expanded by 25% over the last two decades (Graph 1) and the industry is considered one of the most commercialized sub-sectors of agriculture[1]. The growth in poultry farms also stems from innate characteristics of the sub-sector: perceived high returns to investment, a short production cycle for broilers, and low investments needed to start a small poultry farm (Heise et al., 2015).

As poultry farmers attempt to expand their capacity, there is a rising demand for factors of production at stable prices, such as water and electricity. However, there is a lack of rigorous economic analysis on how negative price shocks to essential production inputs and changing energy needs impact farmer profitability, optimal decisions, and the structure of the industry in developing countries. In this paper, we focus on feed costs, the largest production expense in a poultry operation, and energy costs, increasing with the use of electricity intensive technologies employed to manage environmental changes.

Being a key ingredient for feed, increases in maize prices pose a severe threat to poultry farmers profitability. For example, maize prices increased from ₦132 per kg in 2015 to ₦271 in early 2016 (FewsNet, 2019)[2]. Then, prices declined to ₦122 per kg during the summer months of 2016, only to increase to ₦198 in 2017. These price spikes are typically the result

[1](Liverpool-Tasie et al., 2017) estimate that from 1980-2012, egg and chicken output grew by 300% and 220%, respectively.

[2]The current exchange rate is 1 USD = 350 Nigerian Naira (₦). The exchange rate at the beginning of the data collection process was 1 USD=305₦ (Central Bank of Nigeria). Thus ₦271 is approximate $0.75 given the current exchange rate.

of supply shortages caused by weather conditions and a reduction in imports due to the strengthening of the dollar against the Nigerian Naira (Ojosipe 2016).

As broiler operations expand, the energy needs of the farm and the share of the budget allocated to energy expenses typically rise. For poultry enterprises in developed countries, energy is one of the main operational expenses. For example, in the U.S., energy costs amount to 1.1-1.2 cents per pound of meat produced (the largest operational expense), with 54% of that calculation attributed to fuel costs for heating and 34% to electricity expenses (MacDonald, 2014)[3] In Nigeria, larger broiler farmers are starting to rely on energy intensive technologies to avoid heat stress losses and maintain optimal broiler temperatures.

This study explores the effect of current and expected input costs on the profitability of poultry farms. Specifically, we examine the role feed expenses, increasing energy needs, and farm size play in determining optimal decisions and firm survival. We employ a discrete state and control space, discrete time dynamic programming model to analyze optimal decisions of poultry farms. We compute farmers intertemporal value functions and optimal strategy choices using models parameterized using two datasets collected from southwest Nigeria, the region of the country that has experienced the most rapid growth in medium and large-scale poultry farms over the last decade (Liverpool-Tasie et al., 2017)[4]. We also explore the potential heterogeneity of farm size and its influence on optimal choice, instead of assuming a single representative farm as is common in the existing literature. Instead, we model optimal decisions for medium and large sized farms separately. By disaggregating the data by farm size, we show the source of any existing economies of scale and expand on possible policy implications for each type of farm.

We construct hypothetical feed price regimes to capture the effect of an upward shift in feed prices on farmer decisions. This analysis is relevant to the Nigerian context given that

[3]Similarly, studies about Brazilian poultry farms find electricity is the largest cost (Turco et al., 2002; Mendes et al., 2014) and suggest a 1% increase in electricity costs reduces profit by 0.46%, a larger and more significant effect than that of labor costs.

[4]In this study, medium and large-scale farms refer to poultry farms with 100-1000 birds and more than 1,000 birds, respectively. While we recognize that this might be very different from integrated poultry farms in the United States, it is specific to the reality of the emerging poultry industry in Nigeria

maize prices have recently been on an upward trajectory which is likely to continue. We hypothesize that farm size, (average flock size) is an important determinant of whether a farm can withstand a permanent feed price increase. This relates to the idea that there might be a minimum threshold investment necessary to maintain a profitable poultry enterprise because of economies of scale.

Finally, we explore the effect of an increase an electricity consumption on optimal decisions of medium and large-scale farms. Approximately 12% of our sample of Nigerian farmers have adopted new electricity intensive methods and technologies to deal with rising temperatures and heat stress. Some examples include the use of cooling fans and sprinklers to regulate bird temperature. Modifying our model in this way, we can consider scenarios that are both consistent with the realities in Nigeria and also likely to occur in the future due to climate change.

Our results suggest a negative feed price shock not only reduces the value of poultry farms, but triggers exit decisions among medium scale farms. Conversely, larger farms are better positioned to withstand these price increases; the shock reduces the value of large farms, but they can maintain positive profitability and remain in the industry. Similarly, we find that expanding energy use drives medium scale farms out of business in certain price states while large farms can profitably incorporate these higher energy costs. Our findings suggest that large poultry farms are better equipped to both handle key input price shocks and make the necessary investments to manage a successful poultry operation.

This study makes three main contributions to the literature. This is the first study to consider the dynamic, decision-making process of poultry farmers in Sub-Saharan Africa and the potential triggers of farm exit decisions. Past literature on livestock systems in Nigeria and Africa have only modeled profit flows of farmers from a static perspective (Oyakhilomen et al., 2015; Ohajianya, 2013; J. O., 2012).

Second, this is the first study in Africa (the authors are aware of) to incorporate multiple sources of energy costs into the analysis and consider the effect of changing energy needs.

Based on the data we have collected in Oyo State, farmers receive between 40 and 63 hours of electricity per week and if their operations require more electricity, they must use a petrol or diesel-powered generator to make up the difference. Thus, only accounting for the cost of electricity underestimates the true cost of energy, since alternative sources of energy are needed to offset the limits on the hours of electricity received from the grid. As farms in the developing world are transitioning from isolated, backyard farms to organized, medium and large-scale farms, reevaluation and research on the roles of various inputs across the value chain becomes essential.

Lastly, this paper contributes to the literature by reducing aggregation bias and modeling optimal policy rules for medium and large-scale producers separately. Considering the importance of farm size heterogeneity in determining the success of a firm, this extension necessary to accurately model how an industry performs (Buckwell and Hazell, 1972; Spreen and Takayama, 1980; Chen and Onal, 2012).

The paper begins with a discussion of the feed and energy context in which Nigerian poultry farms operate, followed by the theoretical framework, a discussion of the data, and the parametrization of the model. Then, we describe the results, potential extensions of the model, and conclude with a discussion of the implications of this work.

Feed and Energy costs in Nigeria

Maize as Primary Input for Feed

Currently, maize-based feed remains the largest expense item for Nigerian poultry farmers (Adebayo et al., 2015). While other feedstuffs (such as cassava root), are used in addition to (or as a partial substitute for) maize, maize remains the primary component. High-quality feed is necessary for a successful fattening process and alternative feeds that use less maize can result in decreased feed intake, slower weight gain, and a higher feed conversion ratio (Uchegbu et al., 2011). However, maize production and prices are subject to market and weather fluctuations which can adversely affect poultry farmers profitability and ability to stay in business[5]. In August 2016, the price of maize in Nigeria increased by 70% from ₦100 per kg in June to ₦170 (FewsNet, 2019). Large shocks in the price of maize affect the cost of feed, since maize accounts for between 50-70% of the cost (Olugbemi et al., 2010)[6]. In addition to feed, maize is also a staple food in Nigeria and livestock producers compete with an increasing demand for this commodity for food.

The Energy Sector in Nigeria

Although Nigeria has a plethora of energy resources (Akinbami, 2001), the power sector performs poorly and at a deficit. There is unstable energy supply, blackouts, and a weak transmission network that is privately managed but government owned. Some of the reasons the energy sector performs poorly include the declining maintenance budgets and lack of investments in capacity expansion (Oyedepo, 2012; Aliyu et al., 2013).

The Nigerian National Electric Power Authority (NEPA) has experienced significant deregulation and restructuring over the last twenty years. As part of earlier restructuring plans, NEPA evolved into the Power Holding Company of Nigeria (PHCN) in 2005. The PHCN was later privatized but the problems of the sector remain today with 60% of the population lacking access to electricity (Osunmuyiwa and Kalfagianni, 2017). Consequently, the effects of a poorly managed power sector constrain the growth of firms in other sectors. A 2009 study revealed 97% of all firms in Nigeria experienced 196 hours of outages and relied on their own generators to overcome low electricity supply (USAID 2014). With climate change and expected global temperatures rising, the electricity needs of livestock farms will increase. Hypothesizing over the effect of these potential changes on cost of production should be anticipated by researchers and policymakers alike.

[5]Using data collected on Nigerian maize farmers in 2017, 19% of maize farmers indicated that they had experienced a significant increase in the price of fertilizer and 41% of respondents indicated the hike in price had a great negative effect on their business in 2016 About 12% of farmers coped with this price shock by reducing their farm size or exiting maize farming and 23% sold maize from the stored stock.

[6]In our data set, the average price of branded feed is ₦140 per kg.

Model

Suppose a poultry farm purchases day old chicks[7] $q^B = \{q^M, q^L\}$ at price p^D per chick, where q^M and q^L correspond to the stock size of a medium and large-scale farm, respectively. In this model, a B superscript indicates that a variable varies between medium and large farms.[8]

Each week t, the farmer decides whether to feed the broilers, sell the complete stock and restart the fattening process, or sell the stock and exit the industry permanently. Because of limited capacity, we assume that if the farmer wants to restart the growing process, he must sell his current batch of broilers.[9] In addition, we assume both medium and large-scale farms have invested in assets such as cages, chicken houses, and a generator, based on the summary statistics detailed in Table 2. Let s_t be the farmer's choice set:

$$s_t = \begin{cases} 0, & \text{Feed with no replacement} \\ 1, & \text{Sell with replacement (restart the growing process)} \\ 2, & \text{Sell without replacement (exit the sector)} \end{cases}$$

The farmer will stop the process at a time that maximizes the discounted expected sum of farm profits. The reward function, conditional on s_t, is:

$$\pi_t = \begin{cases} \text{-c}(\text{p}_t^f, q_t^f, a_t)q^B - e(z_t, h_t^B, q^B) - l(p_t^w, x_t^B) - m^B & \text{if } s_t = 0 \quad (1) \\ (\text{r}(\text{w}_t, p_t^b) - p^D - c(p_t^f, q_t^f, a_t))q^B - e(z_t, h_t^B, q^B) - l(p_t^w, x_t^B) - m^B & \text{if } s_t = 1 \quad (2) \\ \text{r}(\text{w}_t, p_t^B)q^B & \text{if } s_t = 2 \quad (3) \end{cases}$$

[7] The quantity purchased of day-old chicks is the same as total stock sold when the bird reaches maturity. This assumption is supported by the fact farms do not report significant losses. On average, medium and large-scale farms report on average 5 and 33 broilers die before sale, respectively.

[8] While the analysis focuses on medium and large scale farms in the study context, we also analyze small, household farms for completeness. These results can be found in Appendix C.

[9] This is consistent with anecdotal evidence from the field which indicates most poultry farms tend to sell their birds in batches.

$$c(p_t^f, q_t^f, a_t) = q_t^f p_t^f \tag{4}$$

$$q_t^f = (\beta_1 a_t + \beta_2 a_t^2 + \beta_3 a_t^3) \tag{5}$$

Equation (1) represents the profit function (π_t) conditional on continuing the feeding process ($s_t = 0$), equation (2) is the profit if the farmer chooses to restart the growing process ($s_t = 1$), and (3) when the farmer decides to sell and exit the sector, ($s_t = 2$). Under $s_t = 0$ and $s_t = 1$, the farm incurs the cost of feeding (4), a function increasing in the price of feed vector (p_t^f), quantity of feed bought (q_t^f), and the age of the batch (a_t). We allow for the feed price and their conditional transition probabilities [10] to vary by farm size to account for the possibility that size might influence the likelihood of experiencing different feed prices. Equation (5) is the feed quantity cubic function changing in the age of the batch (a_t). We assume the farmer always provides the optimal amount of feed. While this is a simplification, it allows us to focus on the replacement and exit decisions which are the main focus here. A potential extension and future area of research from this work is to study the effect of feed price increases on optimal feed quantity decisions. The farmer also incurs energy expenses $e_t^B(z_t, h_t^B, q^B)$ and labor costs $l^B(p^w, q^B)$ under $s_t = 0$ and $s_t = 1$. We define a vector of energy prices (z_t) such that $z_t = \{\alpha_t, \gamma_t, \delta_t\}$, where α_t corresponds to the price of electricity from the grid, γ_t is the price of fuel, and δ_t is the price of diesel. Each energy price is multiplied by the corresponding element in the vector of energy quantities (h_t^B). The variation in total energy expenses between medium and large-scale farms comes from the quantity of energy used: $e_t^B = h_t^M z_t, h_t^L z_t$ and is a function of the stock size. The labor function depends on the quantity of broilers and the fixed wage rate (p^w). We expect energy expenses and the labor function to be the source of economies of scale driving different optimal decisions between medium and large-scale farms:

$$\frac{\partial \overline{l(p_t^w, q^B)}}{\partial q^B} \text{ and } \frac{\partial \overline{e(z_t, h_t^B, q^B)}}{\partial q^B} < 0$$

[10] In this article, a transition probability refers to the likelihood of facing a price in $t + 1$ conditional on the realizing certain price in time t

Finally, we assume the farmer incurs fixed vaccination and medical costs (m^B) every period. Based on the prophylactic measures Nigerian farmers employ, having weekly medical expenses is a reasonable assumption.

Equation (2) corresponds to the reward function when the farmer chooses to restart the growing process ($s_t = 1$). Under this option, the farmer receives a return $r(w_t, p_t^b)$ that is a function of the broiler price (p_t^b) and the weight of the bird (w_t). Weight each period evolves following a Richard's growth function[11]:

$$w_t = \frac{A}{(1 - \delta e^{-\lambda a_t})^{\frac{1}{m}}} \tag{6}$$

Lastly, equation (3) represents the exit option of the firm ($s_t = 2$). Here the farmer receives a return only for the sale of the stock of broilers $r(w_t, p_t^b)$. We assume the farmer is not able to sell his farm assets and machinery. This is a conservative assumption as it makes the exit decision less appealing and a last resort to farmers.

The farmer's objective function Π_t is:

$$\max_{s_t} \Pi_t = \sum_{t=1}^{\infty} \beta^{t-1} E\Big\{\{\pi_t|(s_t = 0)\}\mathbb{1}_{s_t=0} + \{\pi_t|(s_t = 1)\}\mathbb{1}_{s_t=1} + \{\pi_t|(s_t = 2)\}\mathbb{1}_{s_t=2}\Big\}$$

$$\text{s.t.} \quad a_{t+1} = p(a_t, s_t) \tag{7}$$

$$Pr(p_{t+1}^{fB} = i | p_t^{fB} = j) = p_{ij}^{fB} \tag{8}$$

$$Pr(p_{t+1}^{b} = m | p_t^{b} = n) = p_{mn}^{b} \tag{9}$$

$$\{p_t^b = 0\}\mathbb{1}_{a_t < 5} \tag{10}$$

where β is the discount factor, (7) is a state transition equation for age, equations (8) and (9) represent the conditional feed and broiler price transition probabilities, (10) is a market constraint for sale of birds less than 5 weeks, as previously discussed.

[11]See appendix for complete description. A = the asymptotic weight as age approaches infinity, k = the instantaneous relative growth rate (or maturing rate), B= constant, m = is the Richards function shape parameter.

Equation (7) depends on the decision of the farmer:

$$a_{t+1} = p(a_t, s_t) = \begin{cases} \mathrm{a}_t + 1, & s_t = 0 \\ 1, & s_t = 1 \\ 0, & s_t = 2 \end{cases}$$

The transition probabilities for feed and broiler prices are derived from the one-year panel data set by assuming a Markov transition process[12]. For states $i = 1, 2, ...K$ and $j = 1, 2, ...K$, the feed transition probabilities vary by farm size and follow (8) to make up the $K \times K$ matrix[13] P^f :

$$P^{fB} = \begin{pmatrix} p^f_{1,1} & p^f_{1,2} & \cdots & p^f_{1,j} & \cdots & p^f_{1,K} \\ p^f_{2,1} & p^f_{2,2} & \cdots & p^f_{2,j} & \cdots & p^f_{2,K} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ p^f_{i,1} & p^f_{i,2} & \cdots & p^f_{i,j} & \cdots & p^f_{i,K} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ p^f_{K,1} & p^f_{K,2} & \cdots & p^f_{K,j} & \cdots & p^f_{K,K} \end{pmatrix}$$

Similarly, the broiler price transition matrix P^b is composed of the one-step state transition probabilities also computed using the one-year panel data set. For $m = 1, 2, ...L$ and $n = 1, 2, ...L$ (m and n indexing broiler price states), the $L \times L$ matrix P^b:

[12]The probabilities are derived using the Markov command in STATA. Markov tabulates "one-step transition frequencies, carries out a chi-square test for independence, and tabulates a transition probability matrix" (Cox, 1998)

[13]The size of this matrix varies between medium and large scale firms, but it is always a square matrix.

$$P^b = \begin{pmatrix} p^b_{1,1} & p^b_{1,2} & \cdots & p^b_{1,n} & \cdots & p^b_{1,L} \\ p^b_{2,1} & p^b_{2,2} & \cdots & p^b_{2,n} & \cdots & p^b_{2,L} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ p^b_{m,1} & p^b_{m,2} & \cdots & p^b_{m,n} & \cdots & p^b_{m,L} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ p^b_{L,1} & p^b_{L,2} & \cdots & p^b_{L,n} & \cdots & p^b_{L,L} \end{pmatrix}$$

To create a joint conditional probability matrix for feed and broiler prices, we use the Kronecker product operator to create the $LM \times LM$ full transition probability matrix:

$$P^b \otimes P^f = \begin{pmatrix} p^b_{1,1}P^f & \cdots & p^b_{1,L}P^f \\ \vdots & \ddots & \vdots \\ p^b_{m,1}P^f & \cdots & p^b_{m,L}P^f \\ \vdots & \ddots & \vdots \\ p^b_{L,1}P^f & \cdots & p^b_{L,L}P^f \end{pmatrix}$$

We begin with a zero-value function and iterate to convergence on Bellmans equation:

$$\upsilon(k_t) = \max_{s_t} \left\{ \{\pi_t|(s_t = 0)\}\mathbb{1}_{s_t=0} + \{\pi_t|(s_t = 1)\}\mathbb{1}_{s_t=1} + \{\pi_t|(s_t = 2)\}\mathbb{1}_{s_t=2} + \beta E_t[\upsilon(k_{t+1})] \right\}$$

where $k_t = [w_t, a_t, p^b_t, p^f_t]$ is a vector of state variables. We solve this infinite horizon problem recursively in MATLAB using the dynamic programming algorithm developed by (Miranda and Fackler, 2002). We apply the Newton Method to solve the optimization problem.

Data

This paper uses two primary data sources from Ibadan, Oyo State, Nigeria. The first is a 2017 cross-sectional dataset including questions on farmers input purchasing decisions, chicken farm activities, input and output prices, sale locations, maize procurement and feed production, labor use, energy consumption, and shocks and coping strategies.

The survey respondents include 365 farms that either produce only broilers or both broilers and layers from the 11 main poultry-producing Local Government Areas (LGAs)[14] in Greater Ibadan. This paper only uses the information from broiler farms with a stock size greater than 100 broilers. We assume that households with fewer than 100 broilers are not part of the commercial industry, but instead hold birds for consumption and informal sale to neighbors and family members. A household model might be better suited to analyze the decisions of these small, household-farms.

Partitioning the data by flock size in 2016, there are 70 small farms with a stock size of less than 100 birds, 118 medium-sized farms with 100-1,000 broilers, and 177 large farms with a stock size of more than 1,000 birds[15]. Medium and large-scale farms vary in terms of production practices and assets. A higher percentage of large-scale farms keep records and own freezers, trucks, bore holes, and generators (Table 2).

The second data set covers input purchases and prices as well as chicken prices and sales of 100 poultry farmers in Ibadan (Table 1). The data was collected weekly for one year between June 1st, 2017 and June 30th, 2018. This panel data set is randomly selected sample from the total list of non-household farms in the study area.

Parameterization of the Model

The base values of the parameters in the sell-feed model are summarized in Table 6. Each period represents a week and the maximum life of the chicken is set at 10 weeks[16]. We assume the weekly discount factor is between 0.98-0.995. The Central Bank of Nigeria (CBN) reports the interest rate is between 17.53% and 31.40% as of February 2018; if the maximum interest rate were imposed, that would still yield a weekly discount factor of 0.993. However, to allow

[14] Local Government Areas (LGAs) are the third tier of government in Nigeria, equivalent to a US county.

[15] This farm size classification is specific to Nigeria and we recognize that in other economies, the farms we consider to be large here might still be considered small or medium.

[16] Most of the farmers in our sample slaughter the bird when it reaches 5-8 weeks, so we determine the terminal period T to equal 10 weeks.

for the possibility of informal credit at a higher interest rate than the one reported by CBN, we expand the range to include slightly smaller discount factors.

To have a rich state space but limit the curse of the dimensionality, we specify 14 different feed prices for medium farms and 12 for large scale farms in ₦ per kg[17]:

$$p_t^{fM} = [112, 120, 125, 130, 138, 140, 144, 150, 156, 160, 164, 168, 176, 180] \tag{11}$$

$$p_t^{fL} = [110, 120, 125, 128, 130, 136, 140, 144, 150, 160, 170, 200] \tag{12}$$

Both vectors include the lowest, the median, and the highest feed prices from the one-year panel data set. The feed transition probabilities demonstrate high state persistence with a high probability of realizing the same broiler price in period $t+1$ as in period t. Specifically, for all feed prices (for both medium and large-scale farms), the probability of realizing the same price in $t+1$ as in period t is greater than 0.8. However, comparing overlapping prices[18], medium sized farms have higher persistence among lower feed price states than large-scale farms. For example, if the feed price in period t is $p_t^{fM} = 140$₦, then $Pr(p_{t+1}^{fM} = 140 | p_t^{fM} = 140) = 0.97$, but for large farms this probability equals 0.5. The full list of feed price conditional probabilities are listed in Appendix A.

Since there is less variation across the observed broiler prices and we want to keep the state space manageable, we specify 7 broiler prices (₦ per kg) from our data set:

$$p_t^b = [900, 1000, 1150, 1200, 1250, 1350, 1500] \tag{13}$$

These probabilities also display high persistence and tend towards higher broiler prices. For example, if $p_t^b = 900$₦, then $Pr(p_{t+1}^b = 900 | p_t^{fM} = 900) = 0.83$ and $Pr(p_{t+1}^b = 900 | p_t^{fM} = 1500) = 0.17$. Under this broiler price state, the farm can only realize a price of ₦900 or the

[17]The current exchange rate is 1 USD = 350 Nigerian Naira (₦). The exchange rate at the beginning of the data collection process was 1 USD=305₦ (Central Bank of Nigeria).

[18]Overlapping in this context refers to prices that are reported by both medium and large scale farms.

highest price of ₦1,500. The likelihood of remaining in a certain price state or switching to a much higher output price will affect the farm optimal decisions. For example, we might not see exit decisions among the highest feed price-lowest broiler price state ($p_t^{fM} = 180$, $p_t^b = 900$) due to high future expected broiler prices and/or lower expected future feed prices.

We use a fixed price of day-old chicks equal to ₦200, the median price reported in the cross-section data set, and a combined cost of medication and veterinary services from the cross-sectional data. The parameters we use for hours of electricity and liters of fuel and diesel are mean values from our weekly, year-long panel data set. We maintain fixed energy prices to reduce the dimensionality of the optimization problem. For the labor parameters, we utilize the average of workers hired per week and the average wage from the cross-sectional data set.

Results

A dynamic optimization model is applied to capture how constraints, costs, and prices affect farmers' decisions for a representative medium and large farm[19]. This disaggregation by farm size addresses one of the limitations of traditional dynamic models and allows us to explore how current conditions and potential negative price shocks induce different behaviors for farms of different sizes.

Medium vs. Large-Scale Farms

One key finding stands out when optimal behavior by firm size is considered. In the absence of negative feed price shocks, exit decisions are optimal for medium-scale farm under price states: $p_t^f = 164$, and $p_t^b = 1,000$ or $1,150$ (Table 5). Conversely, the optimal decision for large-scale farms is always to sell and restock (Table 6). This indicates that the average, medium-sized poultry farm in Nigeria is not profitable under certain input-output price combinations but large farms are. These findings are driven by economies of scale from

[19]The results of optimal decisions for small farms are located in Appendix B. They confirm the inadequacy of this model to elicit realistic optimal decision for household, non-commercial operations.

labor and energy expenses, the inherent low profit margins of the sector, and the differences in transition probabilities faced by medium and large farms.

There are potential strategies firms could be adopting in lieu of an exit decision and we discuss the feasibility of those decisions in the extensions section of the paper. Interestingly, when $p_t^b = 900$, both medium and large firms have a delayed optimal sale and restock decisions among the lower tail of feed price vector space. This suggests farms strategically delay sales and opt to have a longer fattening period when the expected input and output prices are low.

Hypothetical Feed Price Regimes

We model the effect of feed price increase through new price regimes, where the current feed price vector in the state space shifts upward by 20% and 50% with the same transition probabilities as the baseline model. For medium-scale farms, the price vectors are:

$$p^{fM}_{20\%} = [134, 144, 150, 156, 166, 168, 173, 180, 187, 192, 197, 202, 211, 216] \tag{14}$$

$$p^{fM}_{50\%} = [168, 180, 188, 195, 207, 210, 216, 225, 234, 240, 246, 252, 264, 270] \tag{15}$$

A 20% hike in feed price for the representative medium-sized farm results in a decision to sell and exit the industry in states with high feed-low/med broiler prices. For example, if broiler price is ₦1000 per kg, it is optimal to sell and exit for all feed prices above 187₦ per kg[20] (Table 7). If broiler price increases to ₦1,250 per kg, it is optimal to exit if feed prices exceed ₦197 per kg. On the other hand, when broiler prices increase to ₦1,350 and ₦1,500, it is optimal sell and restock when the batch is five weeks old for all feed prices.

If prices were to increase by 50%, exit decisions are optimal for medium farms even at the highest broiler prices. For example if the broiler price reached ₦1,500 per kg, it is optimal to exit if feed prices reach ₦246 (Table 8).

[20]There are some optimal exit decisions for lower feed prices if the batch is kept past 6 weeks

Similarly for large-scale operations, the price vectors are (16) and (17) below:

$$p^{fL}_{20\%} = [132, 144, 150, 154, 156, 163, 168, 173, 180, 192, 204, 240] \quad (16)$$

$$p^{fL}_{50\%} = [165, 180, 188, 192, 195, 204, 210, 216, 225, 240, 255, 300] \quad (17)$$

For large scale farms, a 20% increase in feed prices has a small effect, resulting in exit decisions only at the highest feed price state of ₦240. For all other prices, it is optimal for the farm to sell and restock. This result is primarily driven by the feed price conditional transition probabilities for large farms. For example, the feed price transition matrix for large farm demonstrates certainty if feed price in time t is ₦240: $Pr(p^{fB}_{t+1} = 240 | p^{fB}_{t} = 240) = 1$. This explains why exit decisions for large farms in the presence of a shock are likely when feed price equals ₦240. However, as output price increases, the effect of a feed price hike diminishes (Table 9).

With a 50% feed price increase and when broiler price is ₦900, large farms sell the batch sooner than in the prior scenarios. For example, at the lowest feed price state, sale and replacement is optimal when $a_t = 6$ (Table 10) while with a 20% shock, if feed price is the lowest (₦132), it is optimal decision to sell and restock when the batch age equals 8 weeks (Table 9). Exit decisions occur at every broiler price, but only when the feed price is the highest ($p^f_t = 300$). Otherwise, it is always optimal to sell and restock.

The results from hypothetical changes in the feed price regime demonstrate that medium-scale farms are more susceptible to negative feed price shocks than large farms.These differences are attributed to economies of scale from labor expenses and the slim profit margins that are alleviated by maintaining a larger stock size[21]. Lastly, we attribute the optimality of some decisions to high persistence in both feed and broiler price states. This confirms the importance of modeling the effects of dynamic price trends and transitions on farm behavior

[21] Differences stemming from farm size are also confirmed with the results of small scale farms in Appendix C. For this type of farm, exit decisions are much more common in all cases (baseline, 20% and 50% shock) and result in exit decisions in every price state with a 50% shock.

and profitability, as opposed to using a static budget analysis.

Hypothetical Changes in Energy Needs

One advantage of dynamic programming models is the ease with which hypothetical scenarios can be implemented and optimal decisions can be computed. This flexibility is particularly advantageous when studying the growing importance of an input to a farm or industry. Here we are interested in modeling the effect of increased consumption of energy on optimal firm decisions. The expected rise in energy consumption is consistent with expansion as well as the adoption of electricity-intensive technologies used to mitigate the effect of rising temperatures. Cooling fans, sprinklers, and water pumps are becoming increasingly important tools utilized to counteract heat stress in developing countries. We find that 12% of our cross-sectional sample of poultry farms in Oyo State report using these technologies. These farms are also more likely to have higher energy consumption compared to the average farm (Table 11). This is consistent with the expectation that in the next 10 years, Nigeria's economic sector will transition towards more mechanized operations (Asoegwu and Asoegwu, 2007) that will require more energy. In addition, we would expect that consumption of diesel and fuel might increase if electricity from the grid is absent or insufficient, as occurs in Nigeria. If these adapting technologies are necessary to operate a successful farm, the lack of electricity from the grid could be augmented by using a diesel or fuel powered generator.

We consider the case of an increase in the weekly fuel consumption of medium and large poultry farms based on the difference in consumption between all farms and those using climate adapting technologies in our survey data. We found that medium (large) farms using climate adaptation technologies used 127%(180%) more fuel and 99% (212%) more electricity than the average farm of that size. For medium farms, a 127% increase in fuel consumption and 99% increase in electricity consumption result in some exit decisions when broiler prices equal ₦1,000, 1150, and 1,250 per kg and feed price is ₦164 (Table 12). For large-scale farms, there are no changes to the baseline results (Table 6) given a 180% increase in fuel consumption and a 212% increase in electricity use. The results for medium-scale farms suggest that while some exit decisions are optimal, restock decisions predominate. Both medium and large farms are positioned to evolve into electricity-intensive operations, barring any negative feed and energy price shocks to which medium scale farms are highly susceptible.

Discussion/Extensions

In this section we discuss the robustness of our analysis to relaxing certain assumptions, particularly the assumption that there are no alternative options/coping strategies that might allow firms to stay in the industry instead of exiting.

Credit: The use of credit to purchase inputs is a potential alternative to exiting the sector when a feed price shock occurs. Using credit, farms could purchase the inputs necessary to grow their broilers to a sellable weight, sell the chicken, and repay the loan. This is not likely in the Nigerian context. Only about 5% of farmers in our sample of over 1,000 farms report using credit to buy feed and/or medicines. The reason for the limited credit use is an issue that merits further discussion in future research.

Reducing other production costs: If a farmer is facing high feed prices and/or low broiler prices, a potential coping strategy would be to reduce the quantity of inputs used such as feed, antibiotics and medicines. However, reducing these production inputs can negatively affect the growth and survival rate of the broiler, resulting in ever slim profit margins. One input cost that might be amenable to reduction is labor. A medium-scale farm could substitute hired labor with family labor at a wage rate equal to zero to reduce the total labor bill. However, the opportunity cost for family labor is not zero, given the off-farm employment options of the individual. Farms with over 100 broilers need at least two employees: one laborer to handle broiler operations and a security person, with the latter being hired, non-family labor. We account for the possibility that farms will operate with one worker instead of two, but even in this scenario we find exit decisions at low broiler/high feed price states for medium farms. In the case of farms with more than 1,000 birds, it is highly unlikely cutting labor would be an efficient strategy unless the entire farm were downsizing. Then the farm would be smaller and more vulnerable to shocks as our analysis suggests.

Self-compounded feed vs. branded feed: Since feed is the largest cost of a broiler farm, accounting for 48% of total costs of production (Adetola and Simeon, 2013), a logical solution would be to switch from buying branded feed to self-made feed. On average, self-made feed is 10% cheaper than branded feed (Table 3), but its primary component is still maize. Feed price would still be subjected to negative shocks and fluctuations in connection with maize prices. A farmer could change feed composition, but as discussed in the parametrization section, this is currently an unlikely situation due to the negative effect this has on the fattening process and poultry health.

Contracts: Another potential coping strategy that could influence optimal decisions but is not accounted for in our model is the use of contracts. This form of arrangement (formal or informal) between a potential buyer and a farm reduces production risk of farmers, search and transaction costs, and can potentially increase the bargaining power. For example, a farmer can use production contracts to secure a broiler price or transfer a large portion of the risk to a vertically integrated firm and manage only the broiler growth, as happens in the broiler industry in the United States. However, the majority of Nigerian poultry farms do not secure neither input nor production contracts. We find that only about 5% of farmers use contracts to secure a market for their stock. It is expected that institutional change including contract farming could become a structure under which livestock production can flourish and systems can integrate.

Conclusion

This article employed a discrete state and control space, discrete time dynamic programming model to analyze the effect of high feed costs and changes in energy needs on the optimal decisions of poultry farms in Nigeria by scale of operation. We find that medium poultry farms in Nigeria are not resilient to input price shocks. However, large poultry farms are equipped to handle both key input price shocks and make the necessary investments to manage a successful poultry operation. The findings of this paper have three key implications. First, as food systems transform in Africa and the number of commercialized farms expands, proper accounting of input and output prices as well as their fluctuations will be crucial to ascertain firm profitability and continued growth within the sector. Consequently, the development of accounting and financial training programs is essential for farmers to properly assess farm performance.

Second, the results highlight the importance of stabilizing maize prices. The sensitivity of the sector to increases in feed prices is a major threat to the growth farms have enjoyed thus far. We confirm that large increases in the price of feed switch the optimal decision from sale and restock to sale and exit, especially among medium scale farmers. This reveals a need for risk management mechanisms, such as input contracts, to regulate maize prices.

Third, our results emphasize the effects of increases in energy consumption on cost of production. We argue that the energy needs of farms will change to adjust to volatile and hotter temperatures, without necessarily increasing stock size. We find that to make investments to become an energy-intensive operation and remain profitable, farms must realize some economies of scale.

Though the analysis detailed in this work focuses on the poultry sector in Nigeria, it is applicable to livestock industries in other countries, particularly other developing countries where these livestock farms are rapidly expanding. The findings are relevant to the broader debate on food systems transformation in developing countries. As the domestic supply in these countries responds to rapid growth in animal protein consumption, the insights from this study can be applied in the development of appropriate programs and strategies to promote job creation, business development, and economic growth.

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Tables

Table 1: Summary Statistics (One-year data set)

VARIABLES	Oyo State Mean	Oyo State Std. Dev.
Price per broiler (₦/bird)	2342.91	759.47
Price of branded feed (₦/kg)	140.3	13.03
Price of self-made feed (₦/kg)	126.94	21.21
Price of diesel (₦/liter)	181.87	24.85
Price of fuel (₦/liter)	154.26	18.57
Price of electricity from the grid (₦/kwh)	23.5	0.24
Number of liters needed to power the generator for an hour	1.47	0.5
Number of hours of electricity received per week	51.54	13.44

Note: 1 USD = 360 Nigerian Naira (₦)

Table 2: Summary Statistics of Broiler Farmers by Farm Size in 2016

	Medium-Sized Farms (101-1000 birds)		Large Farms (1000 birds)	
VARIABLES	Mean	Std. Dev.	Mean	Std. Dev.
Management Characteristics				
Sex (Male=1, Female=0)	0.49	0.5	0.56	0.5
Age	50.05	13.55	47.94	11.06
Year business started	2011	0.41	2010	0.45
Keep records of expenditures (0/1)	0.2	0.4	0.56	0.5
Training in chicken production (0/1)	0.2	0.4	0.38	0.49
Production Practices				
Buy inputs, assemble own feed (0/1)	0.26	0.44	0.26	0.44
Buy chicken feed (0/1)	0.76	0.43	0.87	0.33
Freeze and store chicken meat (0/1)	0.01	0.1	0.04	0.2
Contract with poultry processor (0/1)	0.04	0.19	0.17	0.38
Deliver chicks to market or buyer (0/1)	0.51	0.5	0.38	0.49
Package chicken meat to retail (0/1)	0	0	0.05	0.23
Use vitamins (0/1)	0.47	0.5	0.71	0.46
Use medicines (0/1)	0.47	0.5	0.74	0.44
Chicken Characteristics				
Flock size in 2016	330.14	240.68	3,325.00	2,288.87
Average weight of broiler sold (kg)	2.47	1.32	2.87	1.13
Minimum weight of broiler sold (kg)	1.88	0.71	2.33	0.74
Maximum weight of broiler sold (kg)	2.32	0.9	3	0.7
Selling Channels				
Sold to neighbors (%)	35.91	41.05	14.9	23.96
Sold to rural retailers (%)	23.43	35.4	23.82	30.95
Sold to town retailers (%)	35.61	40.98	39.96	39.63
Sold to processors (%)	2.78	15.07	10.12	26
Sold to supermarkets (%)	1.01	10.05	0.66	2.9
Sold to northern wholesalers (%)	0	0	0.54	5.19
Sold to southern wholesalers (%)	1.26	9.02	10	26.37
Private Assets				
Own cages (0/1)	0.22	0.42	0.5	0.5
Number of trucks owned	0.03	0.17	0.4	0.83
Number of freezers owned	0.02	0.14	0.13	0.39
Number of freezers rented	0	0	0.02	0.13
Own well (0/1)	0.89	0.31	0.69	0.47
Own bore hole (0/1)	0.06	0.24	0.35	0.48
Own a bird slaughtering facility (0/1)	0.01	0.1	0.04	0.19
Own a generator (0/1)	0.15	0.36	0.6	0.49
Own a solar panel (0/1)	0	0	0.01	0.08
N	118		177	

Table 3: Summary Statistics of Energy Build-up of Broiler Farmers by Farm Size in 2016

	Medium-Sized Farms (101-1000 birds)		Large Farms (>1000 birds)	
VARIABLES	Mean	Std. Dev.	Mean	Std. Dev.
Total spent on electricity from the grid (₦)	1,279.5	1,470.4	2,462.3	3,021.3
Quantity of electricity used (kWh/month)	69.5	100.1	81.0	122.9
Price of electricity from the grid (₦/kWh)	23.3	3.2	23.4	3.5
Keep track of fuel expenses for generator (0/1)*	0.1	0.3	0.4	0.5
Percent of total monthly expenditures that go to diesel for generator* (%)	3.5	14.0	10.6	18.2
Average monthly expenditure on fuel for generator (₦)*	2,736.1	3,356.0	8,926.5	9,655.4
Price of fuel (₦/Liter)	144.1	15.5	143.4	12.4
Average monthly expenditure on fuel for transportation (₦)	1,333.3	2,737.9	6,554.6	6,574.3
Average monthly expenditure on diesel for generator*	525.0	3,162.2	7,504.6	12,416.1
Price of diesel (₦/Liter)	172.5	17.7	170.9	35.5
Average monthly expenditure for solar energy supply	0.0	0.0	0.0	0.0
Price of solar energy supply (₦/kWh)			25.0	.
Farms that use electricity (%)	0.5	0.5	0.3	0.5
Electricity needs/consumption that comes from the grid (%)	67.2	33.4	41.4	28.7
Electricity needs/consumption that comes from generator (%)	28.6	31.3	49.1	31.0
Share of electricity from the grid used to power freezers (%)	4.2	11.5	9.5	19.1
Hours a day generator runs*	4.1	4.1	5.4	3.6
Capacity of generator (KVA)	9.5	8.3	9.5	6.9
Have petrol costs (0/1)	0.2	0.4	0.4	0.5
Diesel costs from running generator for maize dryer (%)	0.0	0.0	0.0	0.0
Diesel costs from running generator for pumping water for birds (%)	16.0	35.8	18.8	23.9
Diesel costs from running generator for lighting (%)	74.0	37.2	62.5	25.0
Diesel costs from running generator for your freezers (%)	0.0	0.0	6.3	12.5
Diesel costs from running generator for other activities (%)	10.0	22.4	2.7	14.6
N	118		177	

Table 4: Parametrization of Sell-Feed Model

Description	Value
Weekly discount rate	0.993
Maximum age of the bird (weeks)	10
Price of the day-old chick (₦)	200
Average total medical cost for medium farms (₦/week)	892
Average total medical cost for large farms (₦/week)	1,820
Labor wage rate (₦/week)	3000
Average number of employees hired by medium farms	2
Average number of employees hired by large farms	6
Asymptotic weight of the bird (kg)	5.97
Average stock size for medium farms in 2016 (# of broilers)	430
Average stock size for large farms in 2016	3,898
Price of diesel (₦/liter)	186.37
Price of fuel (₦/liter)	142.17
Price of electricity from the grid (₦/kWh)	30.5
Electricity from the grid used by medium farms (kWh/week)	32
Electricity from the grid used by large farms (kWh/week)	16.51
Diesel used by medium farms (liters/week)	16.26
Diesel used in large farms (liters/week)	32.91
Fuel used per week in medium farms (liters/week)	6.8
Fuel used per week in large farms (liters/week)	17

Note: 1 USD = 360 Nigerian Naira (₦)

Table 5: Results for Medium-Scale Farms (Baseline)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If p_t^f =112, 120 or 125, then $s_t = 0$ for $a_t \leq 8$ and $s_t = 1$ for $a_t > 8$ If p_t^f =130 or 138, then $s_t = 0$ for $a_t \leq 7$ and $s_t = 1$ for $a_t > 7$ If $140 \leq p_t^f \leq 156$, then $s_t = 0$ for $a_t \leq 6$ and $s_t = 1$ for $a_t > 6$ If $p_t^f \geq 160$, then $s_t = 0$ for $a_t \leq 5$ and $s_t = 1$ for $a_t > 5$
1,000	If p_t^f =164, then $s_t = 0$ for $a_t \leq 4$, $s_t = 1$ for $a_t = 5$, and $s_t = 2$ for $a_t > 5$ Otherwise, $\forall\ p_t^f$, $s_t = 1$ for $a_t \geq 5$
1,150	If p_t^f =164, then $s_t = 0$, for $a_t \leq 4$, $s_t = 1$ for $a_t = 5$, and $s_t = 2$ for $a_t > 5$ Otherwise, $\forall\ p_t^f$, $s_t = 1$ for $a_t \geq 5$
1,200	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,250	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,350	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,500	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 6: Results for Large-Scale Farms (Baseline)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If p_t^f =110 then $s_t = 0$ for $a_t \leq 7$ and $s_t = 1$ for $a_t > 7$ If $120 \leq p_t^f \leq 130$, then $s_t = 0$ for $a_t \leq 6$ and $s_t = 1$ for $a_t > 6$ If $136 \leq p_t^f \leq 150$, then $s_t = 0$ for $a_t \leq 5$ and $s_t = 1$ for $a_t > 5$ If $p_t^f \geq 160$, then $s_t = 0$ for $a_t \leq 5$ and $s_t = 1$ for $a_t > 5$
1,000	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,150	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,200	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,250	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,350	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,500	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 7: Results for Medium-Scale Farms (20% Negative Feed Price Shock)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If $p_t^f = 134$, then $s_t = 0$ for $a_t < 8$ and $s_t = 1$ for $a_t \geq 8$
	If $144 \leq p_t^f \leq 156$, then $s_t = 0$ for $a_t \leq 6$ and $s_t = 1$ for $a_t > 6$
	If $p_t^f = 160, 168$, then $s_t = 0$, for $a_t < 6$ and $s_t = 1$ for $a_t \geq 6$
	If $p_t^f = 197$, then $s_t = 0$, for $a_t < 7$ and $s_t = 2$ for $a_t \geq 7$
	If $187 \leq p_t^f \leq 216$, then $s_t = 0$ for $a_t \leq 4$ and $s_t = 1$ for $a_t > 4$
1,000	If $134 \leq p_t^f \leq 156$, then $s_t = 0$ for $a_t \leq 4$ and $s_t = 1$ for $a_t > 4$
	If $p_t^f = 160, 168$, then $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $5 \leq a_t \leq 7$, and $s_t = 2$ for $8 \leq a_t \leq 10$
	If $p_t^f = 173, 180$, then $s_t = 0$ for $a_t \leq 4$, $s_t = 1$ for $a_t = 5, 6$, and $s_t = 2$ for $a_t > 6$
	If $p_t^f \geq 187$, then $s_t = 0$, for $a_t \leq 4$ and $s_t = 2$ for $a_t \geq 5$
1,150	If $p_t^f = 134$, then $s_t = 0$, for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	$\forall\, p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,200	If $134 \leq p_t^f \leq 192$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f \geq 197$, then $s_t = 0$ for $a_t \leq 4$ and $s_t = 2$ for $a_t \geq 5$
1,250	If $134 \leq p_t^f \leq 192$, then $s_t = 0$ for $a_t \leq 4$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f \geq 197$, then $s_t = 0$ for $a_t \leq 4$ and $s_t = 2$ for $a_t \geq 5$
1,350	$\forall\, p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,500	$\forall\, p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 8: Results for Medium-Scale Farms (50% Negative Feed Price Shock)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If $p_t^f = 168$, then $s_t = 0$ for $a_t < 6$ and $s_t = 1$ for $a_t \geq 6$ If $p_t^f = 180$, then $s_t = 0$ for $a_t < 6$, $s_t = 1$ for $a_t = 6$, and $s_t = 2$ for $a_t \geq 7$ If $p_t^f = 188, 195$, then $s_t = 0$ for $a_t \leq 4$, $s_t = 1$ for $a_t = 5, 6$, and $s_t = 2$ for $a_t \geq 7$ If $p_t^f \geq 207$, then $s_t = 0$, for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,000	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,150	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,200	If $p_t^f = 168$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f = 180$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$ If $p_t^f = 188$, $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $a_t = 5$, and $s_t = 2$ for $a_t \geq 6$ If $p_t^f \geq 198$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,250	If $p_t^f = 168$, then $s_t = 0$ for $a_t \leq 4$, $s_t = 1$ for $a_t = 5, 6, 7$, and $s_t = 1$ for $a_t > 7$ If $p_t^f \geq 180$, then $s_t = 0$ for $a_t \leq 4$ and $s_t = 2$ for $a_t \geq 5$
1,350	If $168 \leq p_t^f \leq 195$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f = 207, 210$, $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $a_t = 5, 6$, and $s_t = 2$ for $a_t \geq 7$ If $p_t^f \geq 216$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,500	If $168 \leq p_t^f \leq 210$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f = 216, 225$, $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $5 \leq a_t \leq 8$, and $s_t = 2$ for $a_t = 9, 10$ If $p_t^f = 234$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$ If $p_t^f = 240$, $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $5 \leq a_t \leq 7$ and $s_t = 2$ for $a_t \geq 8$ If $p_t^f \geq 246$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 9: Results for Large-Scale Farms (20% Negative Feed Price Shock)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If p_t^f =132 then $s_t = 0$ for $a_t \leq 7$ and $s_t = 1$ for $a_t > 7$ If $144 \leq p_t^f \leq 156$, then $s_t = 0$ for $a_t \leq 6$ and $s_t = 1$ for $a_t > 6$ If $163 \leq p_t^f \leq 180$, then $s_t = 0$ for $a_t \leq 5$ and $s_t = 1$ for $a_t > 5$ If $p_t^f \geq 192$, then $s_t = 0$ for $a_t \leq 5$ and $s_t = 1$ for $a_t > 5$
1,000	If $p_t^f \neq 240$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f = 240$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,150	If $p_t^f \neq 240$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f = 240$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,200	$\forall$ p_t^f, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,250	$\forall$ p_t^f, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,350	$\forall$ p_t^f, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,500	$\forall$ p_t^f, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 10: Results for Large-Scale Farms (50% Negative Feed Price Shock)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If p_t^f =165, 180 then $s_t = 0$ for $a_t \leq 5$ and $s_t = 1$ for $a_t > 5$
	If $188 \leq p_t^f \leq 255$, then $s_t = 0$ for $a_t \leq 4$ and $s_t = 1$ for $a_t > 4$
	If $p_t^f = 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,000	If $p_t^f \neq 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f = 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,150	If $p_t^f \neq 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f = 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,200	If $p_t^f \neq 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f = 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,250	If $p_t^f \neq 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f = 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,350	If $p_t^f \neq 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f = 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,500	If $p_t^f \neq 300$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f = 300$, then $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $a_t = 5$, and $s_t = 2$ for $a_t > 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 11: Average Energy Use of Broiler Farms

	Medium Farms	Medium Farms*	%Δ	Large Farms	Large Farms*	%Δ
Electricity used (kWh/week)	31.43	62.62	**99%**	16.51	51.5	**212%**
Fuel used (Liters/week)	6.8	15.42	127%	16.99	47.65	180%
Diesel used (Liters/week)	16.26	15.97	-2%	32.91	70.38	114%

*These farms use energy intensive technologies to deal with temperature changes, such as automated sprinklers, fans, and cooling systems.

Table 12: Results for Medium-Scale Farms (Increased Energy Consumption Scenario)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If p_t^f =112, 120 or 125, then $s_t = 0$ for $a_t \leq 8$ and $s_t = 1$ for $a_t > 8$ If p_t^f =130 or 138, then $s_t = 0$ for $a_t \leq 7$ and $s_t = 1$ for $a_t > 7$ If $140 \leq p_t^f \leq 156$, then $s_t = 0$ for $a_t \leq 6$ and $s_t = 1$ for $a_t > 6$ If $p_t^f \geq 160$, then $s_t = 0$ for $a_t \leq 5$ and $s_t = 1$ for $a_t > 5$
1,000	If p_t^f =164, then $s_t = 0$ for $a_t \leq 4$, $s_t = 1$ for $a_t = 5$, and $s_t = 2$ for $a_t > 5$ Otherwise, $\forall\ p_t^f$, $s_t = 1$ for $a_t \geq 5$
1,150	If p_t^f =164, then $s_t = 0$, for $a_t \leq 4$, $s_t = 1$ for $a_t = 5$, and $s_t = 2$ for $a_t > 5$ Otherwise, $\forall\ p_t^f$, $s_t = 1$ for $a_t \geq 5$
1,200	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,250	If p_t^f =164, then $s_t = 0$, for $a_t \leq 4$, $s_t = 1$ for $a_t = 5$, and $s_t = 2$ for $a_t > 5$ Otherwise, $\forall\ p_t^f$, $s_t = 1$ for $a_t \geq 5$
1,350	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,500	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Figures

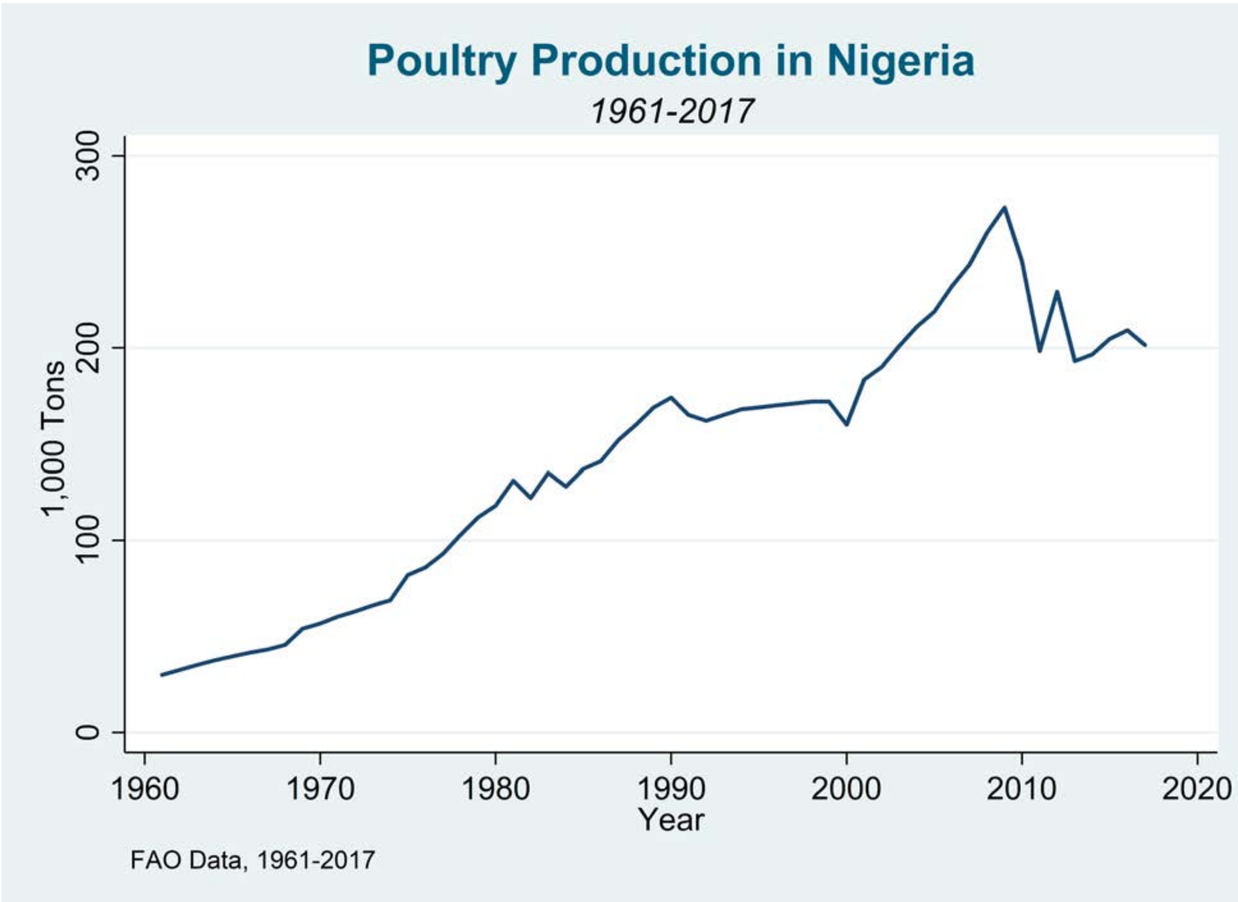

Figure 1: Over the past 50 years, there has been a steady increase in chicken production with a decline in 2009 due to an avian flu outbreak. The importance of poultry continues to rise, in a similar matter than it has all over the world.

Appendix A Feed and Broiler Transition Probabilities

Table 1A: Feed Price Transition Probability Matrix for Medium-Sized Farms

	112	120	125	130	138	140	144	150	156	160	164	168	176	180
112	1	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0.857	0.036	0.071	0	0	0	0	0	0	0	0	0	0.036
125	0	0.024	0.951	0.024	0	0	0	0	0	0	0	0	0	0
130	0	0.003	0.006	0.983	0	0.003	0	0.006	0	0	0	0	0	0
138	0	0	0	0	0.933	0.067	0	0	0	0	0	0	0	0
140	0	0.002	0	0.011	0.004	0.971	0.009	0.002	0	0	0	0	0	0
144	0	0	0.008	0	0	0.048	0.92	0.008	0	0.008	0.008	0	0	0
150	0	0	0	0	0	0.136	0.045	0.818	0	0	0	0	0	0
156	0	0	0	0	0	0.032	0	0	0.968	0	0	0	0	0
160	0	0.045	0	0	0	0.045	0	0.045	0.045	0.818	0	0	0	0
164	0	0	0	0	0	0	0	0	0	0.048	0.952	0	0	0
168	0	0	0	0.043	0	0	0.043	0	0	0	0	0.87	0.043	0
176	0	0	0	0	0	0	0	0	0	0	0	0.222	0.778	0
180	0	0	0	0	0	0.091	0	0.091	0	0	0	0	0	0.818

Table 2A: Feed Price Transition Probability Matrix for Large-Sized Farms

	110	120	125	128	130	136	140	144	150	160	170	200
110	0.833	0.167	0	0	0	0	0	0	0	0	0	0
120	0	0.875	0.063	0	0	0	0.063	0	0	0	0	0
125	0	0	0.929	0	0.071	0	0	0	0	0	0	0
128	0	0	0.059	0.882	0.059	0	0	0	0	0	0	0
130	0	0.009	0.009	0.009	0.938	0.018	0.018	0	0	0	0	0
136	0	0	0	0	0.024	0.951	0	0	0	0.024	0	0
140	0	0	0	0	0.375	0.125	0.5	0	0	0	0	0
144	0	0	0	0	0	0	0	1	0	0	0	0
150	0	0	0	0	0.091	0	0	0	0.909	0	0	0
160	0	0	0	0	0.02	0.02	0	0	0	0.959	0	0
170	0	0	0	0	0	0.033	0	0	0	0	0.967	0
200	0	0	0	0	0	0	0	0	0	0	0	1

Table 3A: Broiler Price Transition Probability Matrix

	900	1000	1150	1200	1250	1350	1500
900	0.833	0	0	0	0	0	0.167
1000	0	0.92	0	0	0.04	0	0.04
1150	0	0	0.962	0	0.038	0	0
1200	0	0	0	0.909	0.027	0	0.064
1250	0	0	0.005	0	0.976	0.002	0.017
1350	0	0	0	0	0.021	0.915	0.064
1500	0	0	0.004	0.006	0.029	0.006	0.955

Appendix B Growth Function Estimations

Non-linear models are used to describe weight as a function of age for different breeds of chicken. The growth pattern tends to have a sigmoid shape and as such, many different functional forms can capture this relationship. There are two main types of growth functions: those with a fixed point of inflection[22] and those with a variable point of inflection (Yang et al., 2006; Kaplan and Gurcan, 2018). To parametrize the weight gain function in the simulation, we empirically estimate the logistic, Gompertz, Bertalanffy, and Richards functions (Table B1). These are the four most commonly used functions in the poultry literature, with Bertalanffy and Richards having a flexible point of inflection.

Previous literature determines the goodness of fit of growth models using the coefficient of determination R^2, the adjusted R^2, the root mean square error (RMSE), and the graphical depiction of each of the curves (Selvaggi et al., 2015; Darmani Kuhi et al., 2010). Based on these criteria, the Richards function seems to be the best fit for our data, followed by the Bertalanffy growth curve (Table B2). The fitted lines for each of the functions (Graphs B1-B5) also suggest the Richards curve is a better fit than the other growth curves.

Table B1: Growth Curves

Logistic	$W_T = \frac{A}{1+Be^{-kt}}$
Gompertz	$W_T = Ae^{-Be^{-kt}}$
Bertalanffy	$W_T = A(1+Be^{-kt})^3$
Richards	$W_T = \frac{A}{(1-Be^{-kt})^{\frac{1}{m}}}$

Table 1: A is the asymptotic weight as age approaches infinity, k is the instantaneous relative growth rate (or maturing rate), B is a constant, m equals the Richards function shape parameter determining the inflection point when the acceleration growth phase moves to the retardation phase (Tompic et al., 2011; Goliomytis et al., 2003; Darmani Kuhi et al., 2003)

[22] Point at which the growth rate is the highest (Segura-Correa et al., 2017)

Table B2: Estimated Parameters for Nonlinear Growth Curves

	(1) Logistic	(2) Gompertz	(3) Bertalanffy	(4) Richards
A	3.14***	3.78***	4.39***	5.97**
	-0.11	-0.18	-0.28	-1.877
k	0.49***	0.26***	0.18***	0.09*
	-0.01	-0.01	-0.01	-0.047
B	15.41***	3.64***	0.77***	1.00***
	-0.8	-0.07	-0.01	-0.0392
m				-0.65***
				-0.159
Observations	646	646	646	646
R-squared	0.9805	0.9818	0.982	0.9822
Adjusted R-Squared	0.9781	0.9795	0.9798	0.9799
Root MSE	0.2438	0.236	0.2342	0.2337

Table 2: Robust standard errors: $^{***}p < 0.01,^{**} p < 0.05,^{*} p < 0.1$

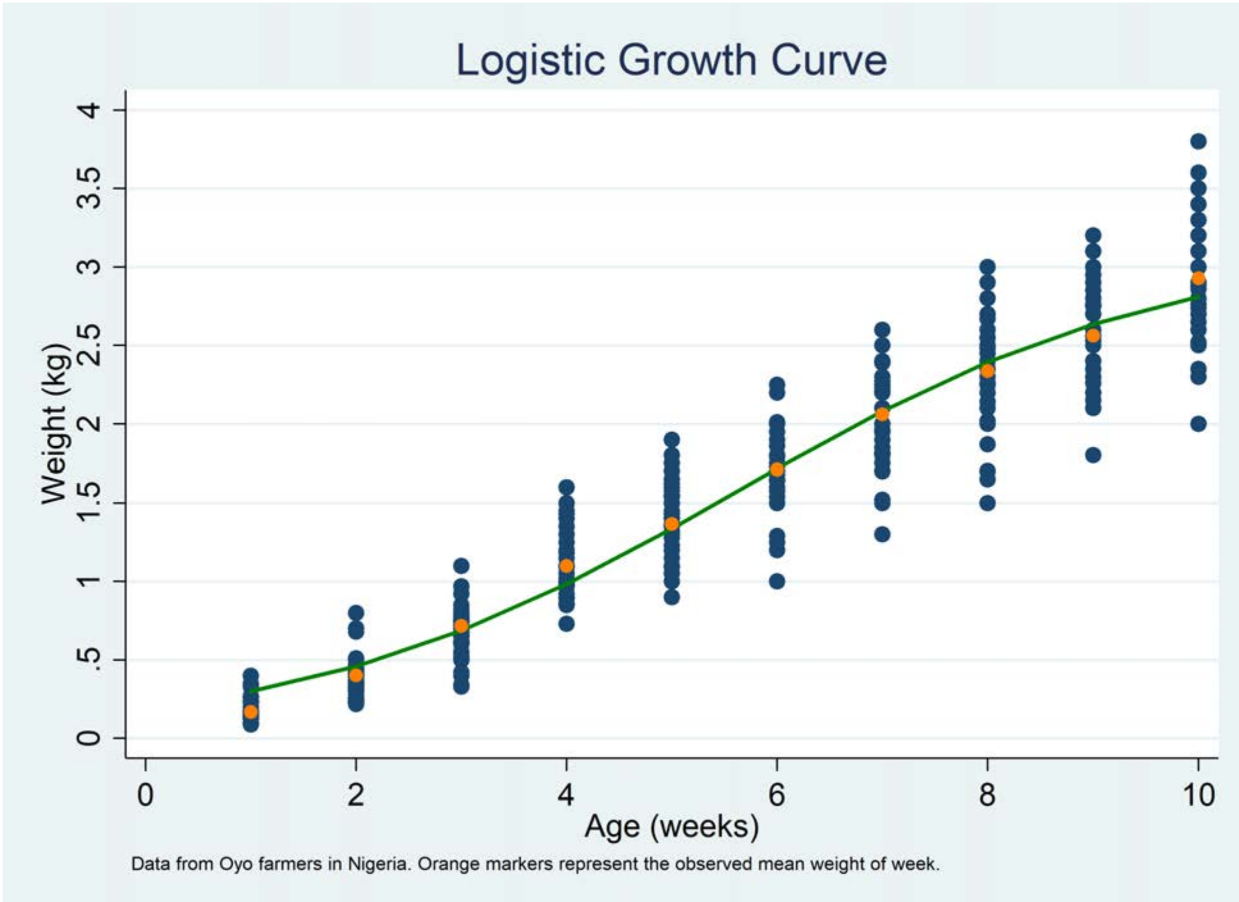

Figure B1: Visual display of the logistic growth curve for farmers in Oyo State. Orange markers represent median prices.

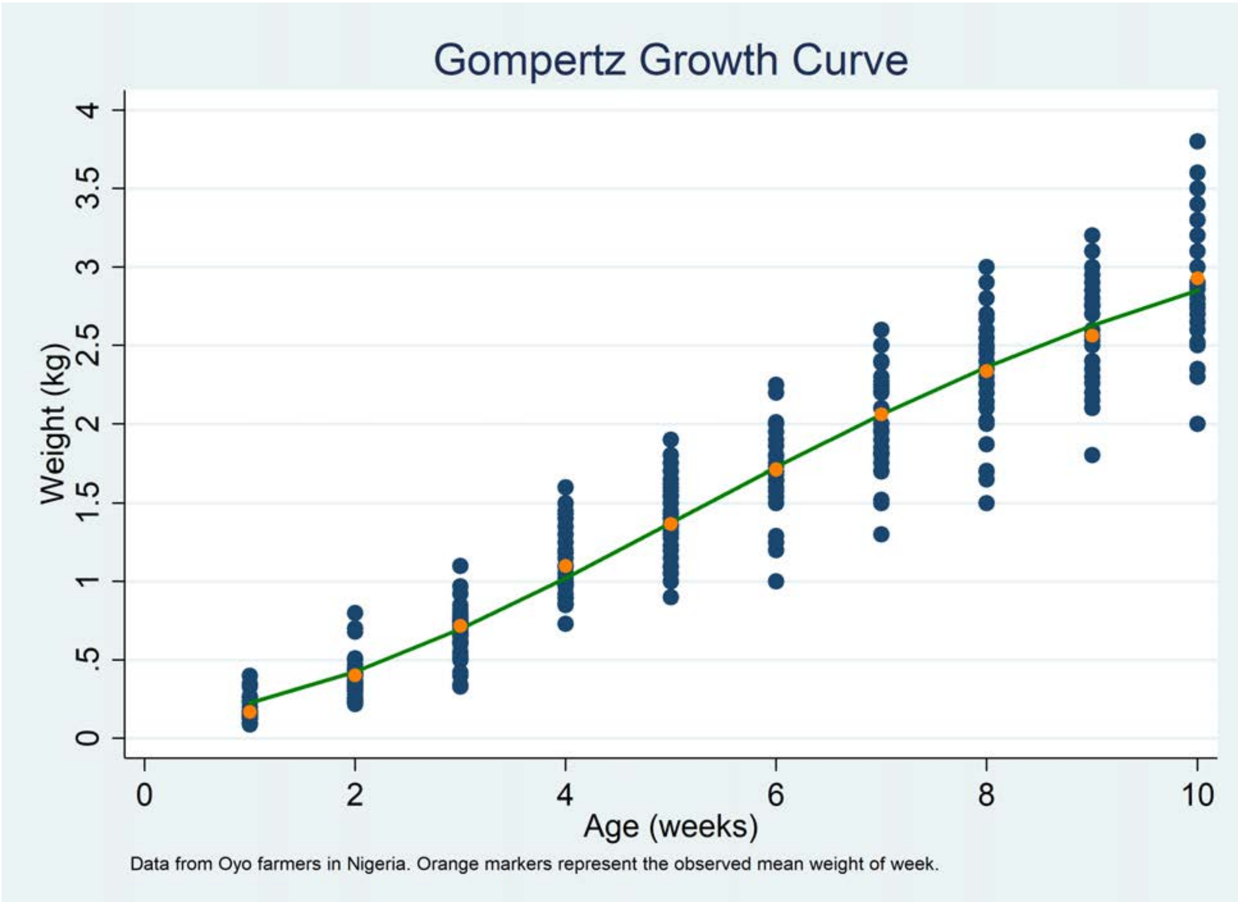

Figure B2: Visual display of the Gompertz growth curve for farmers in Oyo State. Orange markers represent median prices.

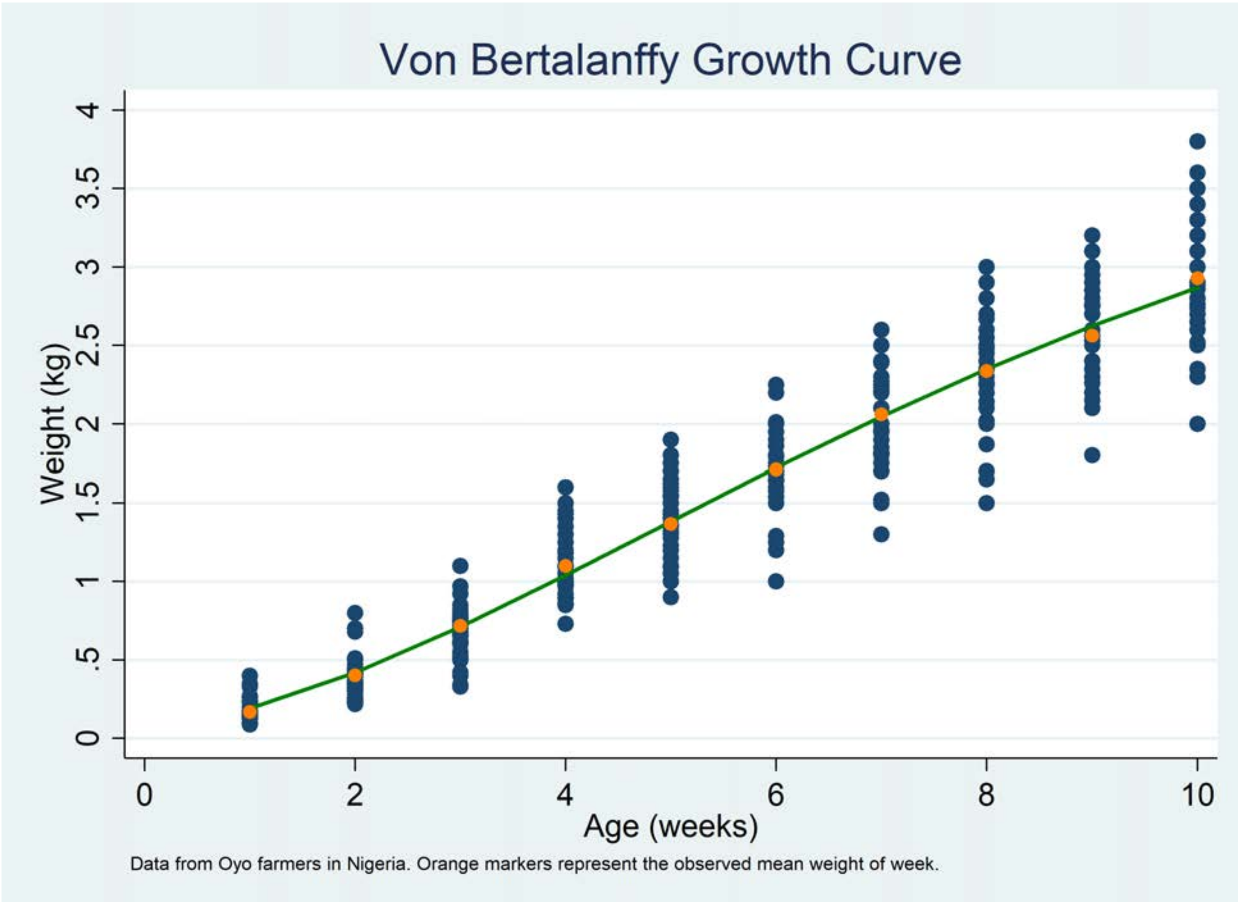

Figure B3: Visual display of the Von Bertalanffy growth curve for farmers in Oyo State. Orange markers represent median prices.

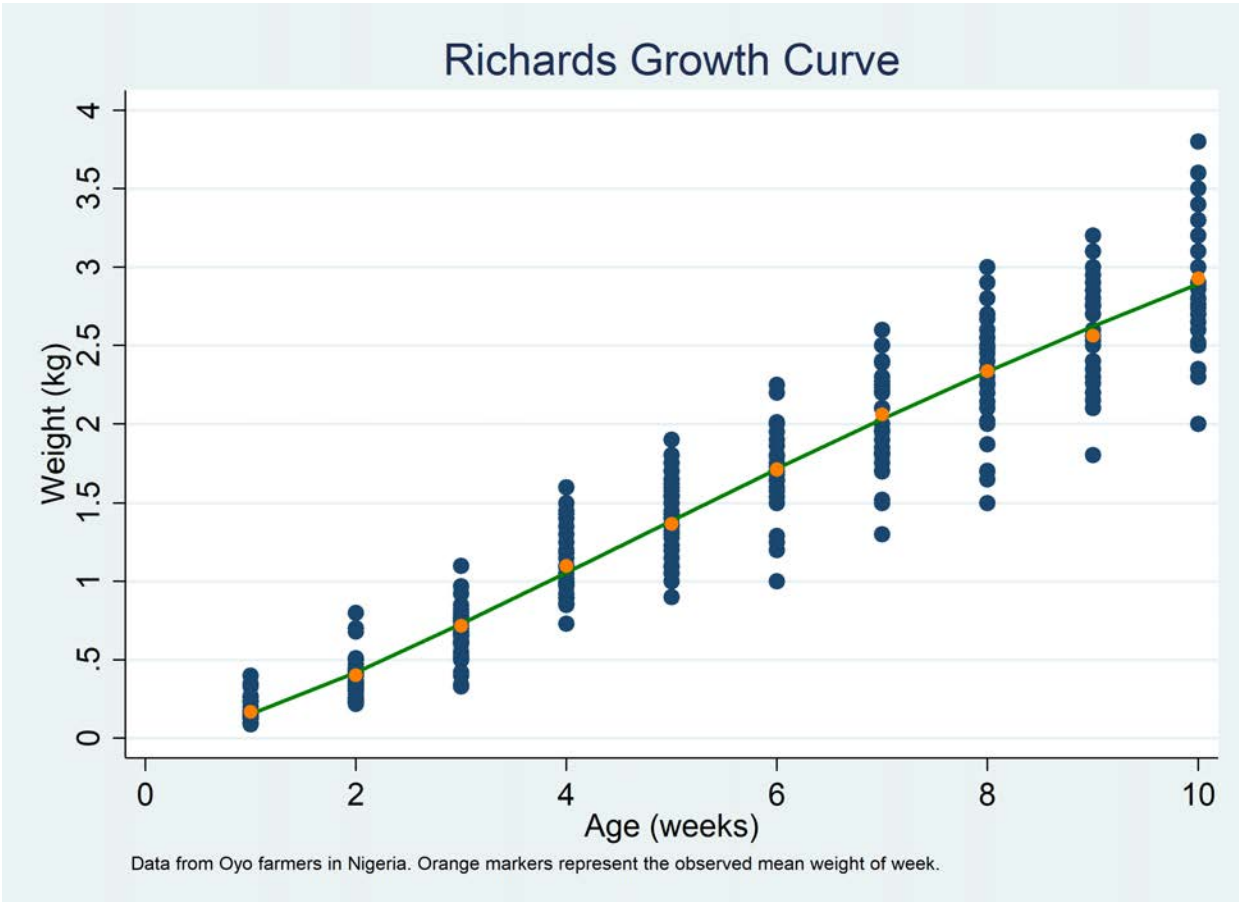

Figure B4: Visual display of the Richards growth curve for farmers in Oyo State. Orange markers represent median prices.

Appendix C Results for Small, Household Farms

Table C1: Parametrization of Sell-Feed Model for Small Households

Description	Value
Weekly discount rate	0.993
Maximum age of the bird (weeks)	10
Average total medical cost for small farms (₦/week)	0
Labor wage rate (₦/week)	2500
Average number of employees hired by small farms	0
Asymptotic weight of the bird (kg)	5.97
Average stock size for small farms in 2016 (# of broilers)	57
Price of diesel (₦/liter)	186.37
Price of fuel (₦/liter)	142.17
Price of electricity from the grid (₦/kWh)	30.5
Electricity from the grid used by small farms (kWh/week)	13
Diesel used by small farms (liters/week)	8
Fuel used per week in small farms (liters/week)	0

Note: 1 USD = 360 Nigerian Naira (₦)

Table 2C: Results for Small-Scale Farms

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If $p_t^f \leq 116$, then $s_t = 0$ for $a_t < 10$ and $s_t = 1$ for $a_t = 10$
	If $p_t^f = 120, 130$, then $s_t = 0$ for $a_t < 9$ and $s_t = 1$ for $a_t \geq 9$
	If $p_t^f = 135, 136$, then $s_t = 0$ for $a_t < 8$ and $s_t = 1$ for $a_t \geq 8$
	If $140 \leq p_t^f \leq 154$, then $s_t = 0$ for $a_t < 7$ and $s_t = 1$ for $a_t \geq 7$
1,000	If $p_t^f \leq 120$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f > 120$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,150	If $p_t^f \leq 120$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f > 120$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,200	If $p_t^f < 160$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f = 160$, then $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $5 \leq a_t \leq 9$, and $s_t = 2$ if $a_t = 10$
	If $p_t^f = 164, 168$, then $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $5 \leq a_t \leq 7$ and $s_t = 2$ if $a_t > 7$
1,250	If $p_t^f < 160$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f \geq 160$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,350	$\forall\, p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
1,500	$\forall\, p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 3C: Results for Small-Scale Farms (20% Feed Price Shock)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If $p_t^f \leq 116$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f > 116$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,000	, $\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,150	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,200	If $p_t^f \leq 116$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f > 116$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,250	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,350	If $p_t^f \leq 148$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for$a_t \geq 5$ If $p_t^f = 150, 154$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f > 154$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,500	If $p_t^f \leq 154$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$ If $p_t^f > 154$, then $s_t = 0$ for $a_t < 5$, $s_t = 1$ for $5 \leq a_t \leq 6$ and, $s_t = 2$ for $a_t > 6$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.

Table 4C: Results for Small-Scale Farms (50% Feed Price Shock)

Broiler Price p_t^b (₦/kg)	Optimal Decisions
900	If $p_t^f \neq 1$, then $s_t = 0$ for $a_t < 5$ and $s_t = 1$ for $a_t \geq 5$
	If $p_t^f >$, then $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
	If $p_t^f = 135, 136$, then $s_t = 0$ for $a_t < 8$ and $s_t = 1$ for $a_t \geq 8$
	If $140 \leq p_t^f \leq 154$, then $s_t = 0$ for $a_t < 7$ and $s_t = 1$ for $a_t \geq 7$
1,000	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,150	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,200	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,250	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,350	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$
1,500	$\forall\ p_t^f$, $s_t = 0$ for $a_t < 5$ and $s_t = 2$ for $a_t \geq 5$

Note: 1 USD = 360 Nigerian Naira (₦), $s_t = 0$ is the choice to feed, $s_t = 1$ is sell and restock, and $s_t = 2$ means sell and exit the sector.