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The Effect of Inputs on Poultry Production Output

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To the Graduate Council:

I am submitting herewith a thesis written by Ty M. Wolaver entitled "The Effect of Inputs on Poultry Production Output." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Economics.

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The Effect of Inputs on Poultry Production Output

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Abstract

To combat poverty and malnutrition, Feed the Future Tworore Inkoko, Twunguke (TI) has set out to teach Rwandan farmers how to grow broilers as additional income for the farmers and an additional protein source within the community to combat malnutrition. Throughout this program, the inputs and outputs of the farmers were recorded, and the goal is to determine an efficiency score for each flock raised and use that information to determine what factors contributed to a higher flock efficiency. A data envelopment analysis (DEA) is used to determine the efficiency score of each flock. Using these efficiency scores, a regression will be estimated using the characteristics of the farmers that raised the flocks and the characteristics of the farms and flocks themselves. The results show that as the program advanced, newer farmers increased in efficiency more quickly when the entire trend was observed. The main source of protein for commercial broilers is obtained from soybean meal. With a high protein percentage and low anti-nutrient properties, soybean meal is a complete, low-cost source of protein. However, solely relying on one type of protein meal leaves broiler producers open to price volatility. It is beneficial to have an alternative protein meal source available to lower the overall feed cost or reduce price volatility risk. Camelina meal offers a way to supplement the protein meal in broiler feed to solve this problem. To identify the demand of camelina meal for broiler finisher feed, a linear programming model was constructed that determines how much camelina meal would be selected for multiple price points in relation to soybean meal price. To consider the distribution of protein around both camelina meal and soybean meal, the stochastic LP model will be estimated at 5000 iterations per price point with each iteration randomly selecting from the distributions of camelina meal and soybean meal. The results show that the average amount of

camelina meal continues increasing until the price of camelina meal is 60% relative to the price of soybean meal with the maximum amount of camelina meal selected in the best-case-scenario also being reached at this price level.

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INTRODUCTION

In 2018, world poultry production rose to its highest point ever reaching 95.5 million metric tons of broiler meat which is 12 million metric tons higher than its 2012 level of 83.3 million metric tons (Statista, 2019). This rise in poultry production mirrors the growing global middle class. As people move from the lower class into the middle class, their mean animal protein consumption as a percentage of their total caloric intake increases from 2.2% of their diet to between 3.7 and 5.2% of their diet (Sans & Combris, 2015). As the middle class grows and income rises, consumers begin to demand more expensive products, and poultry meat purchases increase and outweigh red meat purchases leading to increased demand for poultry production (Senauer & Goetz, 2003). Because of this increasing demand for high value products, demand for meat products is expected to reach 455 million metric tons by 2050 which is more than double the amount produced in 2007 (Alexandratos, 2012). A substantial amount of this increased production will be poultry if current trends in meat demand continue.

Increases in poultry as a source of animal-based protein are driven by the fact that it is relatively cheap to produce and the spatial requirements are much lower than that of other meat animals (Chief, 2019). It is estimated that costs per broiler chicken within one flock cycle are only about $2.19US in large-scale, commercial operations (Chief, 2019). A broiler is a chicken harvested for meat production. However, there are some disadvantages in producing poultry. The initial capital required to start a farm can be high even though, in the long run, recurring costs are low (Chief, 2019). The houses for birds and the equipment used to maintain the houses can cost hundreds of thousands of dollars to a farmer although in the US this may vary considerably depending on location and size of the poultry operation There are also disease risks associated with the concentration of poultry production. Fowl cholera, coccidiosis, avian influenza, fowl pox, Newcastle disease virus, and salmonellosis are all risks poultry farmers face with every flock, and their tolls on productivity and profitability can be high (Chief, 2019). For example, an analysis on the impact of poultry disease in Egypt shows that Newcastle disease virus is associated with up to 80% mortality rate and a 30% loss of total income (Fasina et al., 2012).

In this thesis, two different facets related to poultry production will be explored. The first chapter will discuss the comparative efficiencies of rural, commercial, small-scale poultry production by comparing the technical efficiencies between cohorts of farmers in similar locations and the flocks they raise, using a data envelopment analysis (DEA). The farmers used from the analysis come from a US government-funded Feed the Future program that will be explained in the first chapter. They are farmers in Rwanda that have been taught the basics of commercial production and given the opportunity to put these skills into practice with one-hundred chickens at a time. The second chapter will discuss possible replacements of the crude protein provided by soybean meal in broiler feed namely through the dry matter leftover from biofuel production.

CHAPTER 1: FACTORS CONTRIBUTING TO PRODUCTION EFFICIENCY IN SMALL-SCALE, RWANDAN BROILER FARMS

ABSTRACT CHAPTER 1

To combat poverty and malnutrition, Feed the Future Tworore Inkoko, Twunguke (TI) equips Rwandan farmers with the necessary skills and knowledge to grow broilers in flocks of 100 birds as additional income for the farmers and an additional protein source within the community to combat malnutrition. Throughout the TI program, the inputs and outputs of the farmers were recorded. The goals of this paper are to determine i) an efficiency score for each flock raised in the TI program and ii) what factors contributed to a higher flock efficiency. A data envelopment analysis (DEA) is used to determine the efficiency score of each flock within the program. Using these efficiency scores, a regression was estimated using the characteristics of the farmers that raised the flocks and the characteristics of the farms themselves. The results show that as the program advanced, newer TI program enrollees increased in efficiency more quickly than earlier enrollees when the entire trend was observed. For the regression, farmer characteristics such as gender, farmer age, and family size have some effect on the efficiency score. Farm characteristics such as elevation also influence farmer efficiency. Flock characteristics were also identified as significant factors. These included how many flocks a farmer has raised, seasonality, and what year the flocks were raised. Findings indicate that younger farmers with smaller families are the most efficient producers of broilers for this program. However, it will be important to assess the long-term commitment to the program of older farmers with large families as efficiency improves experience. Findings also indicate that the most efficient time of year to raise broilers on the year away from the seasonal rains in Rwanda. These results may be useful to other small-scale broiler operations with similar inputs and outputs and help improve other future programs.

Introduction

Despite rapid development over the past two decades, Rwanda faces many challenges including high poverty rates and malnutrition (Gill, 2018). The Government of Rwanda's Vision 2050 hopes to address these problems by propelling Rwanda into a middle-income country by the year 2020 through multifaceted programming aimed at increasing income, improving food access, and reducing malnutrition (Gill, 2018). One possible way to do this is to increase rural Rwandan poultry production. In Rwanda, the average poultry producer raises 2 to 18 free range birds per flock that were obtained solely through heritage lines, and predation and disease are substantial problems (Mbuza et al., 2016). These back-yard flocks are meant to be consumed by the grower and are often dual-purpose birds (i.e., meant for both egg and meat production). This can lead to tough meat when consumed and erratic egg production can result in irregular household revenue or nutrition. Through teaching Rwandan farmers improved husbandry and genetic selection, supplying a reliable source of birds, and increasing the amount of poultry on the market, it is possible to supply Rwandans with a low production cost protein source that will help combat malnutrition and potentially provide additional household income.

Through a US government-funded program called Tworore Inkoko, Twunguke (TI), Rwandan participants are given the opportunity to establish small scale broiler production through access to capital, field technician expertise, and concentrated marketing efforts. The goal of the program is to increase incomes and improve nutrition of smallholder households in Musanze district, Rwanda, through training and enrolling producers in these households in efficient broiler chicken production. In August 2017, 26 Rwandans from the Musanze district were selected to be trained to raise modern commercial broilers as a starter trial. The farmers went through a three-day training period where they learned how to raise broiler chickens in a closed coop environment, and how to maintain proper biosecurity. The farmers received follow-up training as needed. They were invited to visit a demonstration farm and attend nutrition training events to emphasize the value of protein in diets and provide recipes for cooking chicken which has not traditionally been a staple of Rwandan diets. Over the course of three years, the number of farmers increased from 44 by the end of 2017 to 252 in 2018 and 588 in 2019. To assist the farmers and track their progress, four broiler technicians were hired (Gill, 2018). After each flock, the input and output data from each of the farms was collected. Farmers trained in this program are divided into cohorts based mostly upon their location.

Using data from the TI program, a data envelopment analysis (DEA) was used to determine the average technical efficiencies across all the flocks of every cohort and determine the flocks that do best across every cohort. Finally, a regression model was estimated to explain the effects of farmer, farm, and flock characteristics on the efficiency in which the flock was raised. The results presented later in this chapter will provide some insights into how the TI program affected small-scale broiler production efficiency and the speed to efficient production, and what factors contribute to their production efficiency.

Literature Review

Nutritional benefits of protein

Low-income populations face a significant burden of undernourishment, with nutritionally incomplete diets which can lead to substantial health issues. Animal sourced foods play a huge part in human development. A diet missing or low in the micronutrients animal protein provides can result in developmental complications or health problems including anemia, low birth weight, blindness, stunted growth, lowered immune responses, lethargy, decreased life expectancy, and decreased physical and cognitive capacity (Demment et al., 2003). Although it is possible to reach the nutrient requirements through an all plant or mostly plant based diet, animal products continue to be the best source of the six micro nutrients that are considered to be of most concern: iron, zinc, vitamin B-12, riboflavin, calcium, and vitamin A (Murphy & Allen, 2003). From this, it can be inferred that an increase in human consumption of animal-based proteins in low-income countries may lead to improved physical and cognitive development, and a source of food that may improve immune health and life expectancy.

There are several reasons for considering poultry production when aiming to increase animal protein production and consumption in low-income countries to address mal- and undernourishment. The first of these reasons is the relatively short time to maturity and high number of offspring of poultry when compared to other livestock species. Chickens take just 147 days to begin reproducing compared to 730 days for cattle or 333 days for swine (Peters et al., 2014). Chickens also produce 157 offspring per breeding cycle for meat type birds (250 for breeds selected for egg laying rates) versus just 0.92 per breeding cycle for cattle and 10.90 for swine (Peters et al., 2014). Another reason poultry is considered is its efficient feed conversion ratio (FCR). FCR measures how many kilograms of feed it takes to produce one kilogram of meat. The lower the FCR the more animal weight produced for every kilogram of feed consumed by the animal. Farm weight FCR, which measures the FCR based on the live weight of the chickens, is often the most used as it gives farmers feedback on how well, or efficiently, they are using their resources. Broilers, birds produced for human consumption, have the lowest farm weight FCR when compared to other sources with only 1.89kg of feed used to produce 1kg of live poultry weight whereas beef cattle take 14.30kg and swine take 2.63kg of feed to produce 1kg of live weight (Peters et al., 2014). This low FCR means that a smaller amount of crop resources, and therefore capital, must be used to raise poultry when compared to other livestock.

The scale of poultry production

In the United States and other high-income countries, large-scale poultry production is prominent as poultry products have a high demand. In lower income countries, these large-scale operations are not as feasible for multiple reasons. Some of these reasons include: i) the lack of genetic lines selected for optimal growth that are prevalent in other countries, ii) feed and environmental constraints in lower income countries that are not conducive to large scale production, and iii) a lack of necessary technology and finance to raise a large volume of poultry (Sonaiya, 1990). However, the role of small-scale poultry production is well established in low-income countries, and nearly all families at the village level have poultry - even resource-poor individuals that own little land (Mack et al., 2005). The role of these families owning a few poultry helps increase food security and reduce poverty by making use of locally available resources (Mack et al., 2005). An example of this is the Bangladesh Poultry Development Model. In the 1980s, a poultry production system meant to mirror large-scale commercial operations was implemented in Bangladesh (Mack et al., 2005). The main effort of this program was to provide services that taught women to use the inputs around them to produce chickens as a tool to alleviate poverty and hunger, and it has made an important contribution to poverty alleviation and is considered essential to improving rural livelihood moving forward despite its current, continued need for improvement. (Mack et al., 2005).

When looking for areas best suited for the implementation of small-scale, commercial broiler operations, it is important to find an area that is capable of growing poultry, has nutritional deficiencies that could possibly be alleviated with the introduction of affordable animal protein, and is already familiar with poultry so a greater volume would not be an unknown product that would not sell. The high human population density, lack of available arable land, high protein malnutrition, and government commitment to agricultural-led economic development were all factors that led to Rwanda being a good candidate to pilot the TI broiler production model. A full layout of the Rwanda TI program model can be found in Figure 1.1 with the rest of the tables and figures in the Appendix.

Model assessment

To measure how farmers are performing compared to their peers, a DEA can be used. DEA is a way to evaluate the performance of similar producers with a measure of efficiency in turning their inputs into outputs with respect to one another (Cooper et al., 2004). Using this analysis, each farmer's efficiency related to the other producers can be evaluated. The DEA can also be used to look at what inputs each producer is failing to use efficiently compared to the rest of the producers in the analysis (Cooper et al., 2004). The main measurement of the DEA is described as comparative efficiency which falls between 0 and 1. Once comparative efficiencies have been estimated for all the different farms in the system, there needs to be a way to determine what factors effect that comparative efficiency. The most popular way that this is done is through a second-stage analysis where the first stage is the DEA, and the second stage is a regression on the comparative efficiencies produced by the DEA (Simar & Wilson, 2011). While there are different econometric models for estimating the regression after the data-generating process that DEA creates, it is possible to draw valid inferences from the second-stage regression that is completed from them (Simar & Wilson, 2011). It is possible to use multiple inputs to estimate the efficiency of multiple outputs which is why this two-stage method is the most ideal model for when measuring efficiency of complicated systems such as agricultural production (Ji & Lee, 2009).

Conceptual Framework

In order to make assumptions about the output of the DEA, it must be assumed that producers want to minimize their inputs in order to maximize their outputs (Tohidi & Razavyan, 2013). The reason for this is a producer's assumed goal of maximizing profitability. In this analysis, a producer's profitability can be viewed as maximized when the sum of the weight of the outputs multiplied by the real value of the outputs is equal to 1 or a comparatively efficient use of inputs turned into outputs, which is represented by Equation 1.1:

(1.1) $$\text{Max Profit} = \sum_{j=1}^{\infty} W_{j,k} * Y_{j,k} = 1$$
$$\text{s.t. } W_{j,k}, Y_{j,K} \geq 0$$

where W_{jk} are the weights of output and Y_{jk} are the real output j for farmer k. This model compares a farmer to the other farmers that have similar inputs and outputs. In this equation, the equation does not have to equal 1, but rather, 1 is the highest level of comparative efficiency. Having a comparative efficiency of 1 means that a farmer is perfectly using inputs to make outputs compared to their peers. This does not mean a perfect use of inputs, just a comparatively perfect use. Because of this, it is assumed a farmer will continue to produce if the marginal cost of adding one more of any additional input is less than the marginal revenue attained by the addition of the input. Once marginal cost equals marginal revenue, the farmer will discontinue the addition of any more inputs to their farm (Nicholson & Snyder, 2012). The weight for an output is determined endogenously by the DEA model which is defined in objective one of the methodology section.

Methodology

The analysis of the Rwandan farmer data will be accomplished with two objectives in mind. The first objective will be to identify the comparative efficiency of each flock in the dataset. This will be accomplished with a DEA. The second objective aimed to determine how different factors affect the comparative efficiency scores. This will be accomplished with a truncated regression on the DEA output from the first objective.

Objective (1)

The first objective will be completed through a DEA. To run the DEA, first a linear programming model should be formulated to represent the analyzed situation. In this type of model, the goal is to maximize the sum of virtual output, obtained by multiplying the weights of the outputs by the number of all the actual outputs of each farm which relies on the assumption that the farmer uses all of the inputs provided. Production possibilities follow a set of microeconomic assumptions including no free production where the set of possible outcomes must include reflective inputs, or that there cannot be something produced with no inputs. For this analysis, that assumption translates that the virtual output must be less than or equal to zero when it is differenced by the virtual input that is the sum of multiplication of the weights of the inputs and number of actual inputs of each farm. The virtual inputs must equal 1 as it is assumed that all inputs listed are used in production of the outputs. While it is possible for free disposal in production because producers are interested in maximizing their possible profitability as discussed in the conceptual framework, we assume that they will produce as efficiently as possible, i.e., using their full resources without waste. Finally, any weight of the inputs multiplied by any weight of the outputs must be greater than or equal to 0. The usage of this objective and its constraints can be found in the source "Data Envelopment Analysis" (Cooper et al., 2004). The general form of these constraints can be found below in Equation 1.2:

(1.2) $$Maximize\ Z = \sum_{j=1}^{2} W_{jk} \times Y_{jk}$$

$$\text{Subject to: } \sum_{j=1}^{2} W_{jk} \times Y_{jk} - \sum_{i=1}^{3} V_{ik} \times X_{ik} \leq 0$$

$$\sum_{i=1}^{3} V_{ik} \times X_{ik} = 1$$

$$V_{ik} \times X_{ik} \geq 0$$

V_{ik} = weights of inputs i for farmer k (i = 1 to 3; k = 1 to 44)

W_{jk} = weights of outputs j for farmer k (j = 1 to 2; k = 1 to 44)

X_{ik} = amount of inputs used i for farmer k

Y_{jk} = amount of outputs obtained j for farmer k

The inputs in this DEA are made up of bags of charcoal used, the kilograms of feed used, and the sale age in days. The outputs are made up of the live weight of the whole flock when it is taken for harvest in kilograms and the livability.

For this analysis, the DEA was estimated in three ways. The first included eight separate iterations for each flock while keeping the flock constant. For this to happen, within each cohort, the corresponding flock for that DEA was selected. In this way, all matching numbered flocks are used for one DEA. For example, each farmer's first flock, within every cohort, was selected for a single DEA. Similarly, this was done for flocks two through eight. In the same fashion, twelve separate iterations for each cohort were estimated. For example, all the observations in the first cohort were selected for a single DEA. Similarly, this will be done for cohorts two through twelve. Finally, a single DEA was estimated which include all observations from every cohort and every flock. This final DEA is used for the second objective. Although the described DEA models with flock held constant or cohort held constant are beneficial for analysis, they cannot be used cumulatively for an econometric model because comparative efficiency scores cannot be compared across DEA models due to comparative efficiency scores being a measure of relative efficiency with that relativity being encased within that model. For a model to be estimated, as described in the second objective, this all-inclusive model is necessary.

Objective (2)

After the comparative efficiency scores are obtained from each farmer, an econometric decomposition was applied to the factors, besides input use, affecting efficiency of production will be estimated. These factors include characteristics of the farmer, farm, and flock. The variables that correspond to farmer characteristics are gender, age, and family size. The variables that correspond with farm characteristics include elevation in kilometers and distance from another farmers in kilometers. The variables that correspond with flock characteristics include flock number, harvest month, and harvest year.

The dependent variable for this regression is generated by the model in objective 1, where the DEA only generates comparative efficiency scores between 0 and 1. An ordinary least squares model is inappropriate for this as it would fit data beyond the limits of 0 and 1. The econometric model needs to account for the truncation of the dependent variable. A truncated model is used when the sample is only available for observable data, i.e., y and x are only observable when y is less than (or greater than) a given constant (c). In this analysis, the data available are truncated on both sides and limited to producers with comparative efficiency scores between 0 and 1 such that there could be other producers in the population that could go beyond 1 (our maximum efficiency observed) or below 0. This model can be represented as:

(1.3) $$(y_i^* | 0 \leq y_i \leq 1) = x_i^{`}\beta + \sigma\lambda(\frac{c - x_i{'}\beta}{\sigma}) + \varepsilon_i$$

where y^* is the dependent variable and is only observable when y is less than or equal to 1 and greater than or equal to 0, x are the independent variables including farmer, farm, and flock characteristics, β represent the estimated parameters, $\sigma\lambda(\frac{c-x_i{'}\beta}{\sigma})$ is the truncation correction (σ is the standard deviation), and ε_i represents the error term. The truncated model is estimated as a maximum likelihood model and the log likelihood is represented in equation 1. 4 where a is the lower limit and b is the upper limit (0 and 1 in this analysis), Φ is the standard normal distribution, and all other variables previously defined (StataCorp, 2005).

(1.4) $$lnL = -\frac{n}{2}\log(2\pi\sigma^2) - \frac{1}{2\sigma^2}\sum_{i=1}^{n}(y_i - x_i\beta)^2 - \sum_{i=1}^{n} log\left\{\Phi\left(\frac{b-x_i\beta}{\sigma}\right) - \Phi\left(\frac{a-x_i\beta}{\sigma}\right)\right\}$$

A truncated regression estimator accounts for the data and will allow for adjusted, bootstrapped standard error calculations. This is consistent with Simar and Wilson (2011) who, along with a truncated regression, use bootstrapped standard errors. The bootstrapped errors are used to account for the bias in the error term (Simar & Wilson, 2011). Stata is used to run the truncated regression model and estimate the errors.

Data

The data for this analysis were collected between October 2017 and April 2020 in Rwanda through the TI program's small-scale, commercial poultry flocks (USAID, 2020). The data includes production inputs, output, and producer demographics. Summary statistics can be found in Table 1.1 and Table 1.2

Table 1.1 is representative of all the inputs and outputs used in the DEA analysis. Inputs include the *Feed Quantity* in kilograms, the *Charcoal Usage* which was measured by the bag, and the *Sale Age* which is measured in days. *Sale Age* is considered an input instead of an output because, unlike most livestock like pigs and cattle, poultry is sold at a certain age rather than at a certain weight. This age can be modified to maximize efficiency or profitability for either the processing center or the farmer. Some of the inputs had observations deleted due to mistype issues such as negative values entered. The outputs are made up of *Livability* which is the percentage of chickens that survived to harvest and the live weight of the flock that was taken to be harvested.

The first variable in Table 1.2 is Gender which is broken down by *Male* (49%) and *Female* (51%). Following *Gender* is *Farmer Age* which shows the age range of the farmer at the time the flock was harvested of 18 to 76 years old with an average farmer age of 39 years old. This variable had some observations deleted if the age was not present. Then there is *Family Size* which shows how many members live with the farmer in his or her household. The average family size is 4 members. These four variables make up the farmer characteristics.

The first variable for the Farm Characteristics in Table 1.2 is *Elevation.* This variable is measured in kilometers. *Elevation* shows that there is less than one kilometer between the lowest farmer and highest farmer with an average elevation of 2,103 meters. The next variable is *Distance from the Farmer* which is measured in kilometers. This shows that the average farmer is only 0.08 kilometers (80 meters) away from their closest peer with the furthest being only 3.197 kilometers away.

Flock Characteristics in Table 1.2 have all been made into categorical variables to view each flock's, month's, and year's individual effect on comparative efficiency rather than the magnitude of movement between them. The first flock characteristic is *Flock Number.* Flock number is representative of the number of flocks each farmer has raised. In this analysis, each farmer has up to 11 flocks, but only 10% of the farmers have five or more flocks, and only 1% of farmers have a ten or more flocks. For *Harvest Month* there is not much difference in the number of birds that are harvested in each month with the most birds being harvested in October with

12% and the least being harvested in September with 5%. There is no known reason that more or fewer flocks would be harvested in any given month except that it might be related to the fact that the program harvested its first flocks in October of 2017. The last variable is *Harvest Year*. The most flocks were harvest in 2019 with 55% and the least in the inaugural year of 2017 with only 3%. Only 2018 and 2019 would have flocks harvested in every month as the program started in 2017, and the data collection was not complete through the year of 2020. This might explain some of the percentage variation in *Harvest Year*.

Results

Individual DEA analyses

To understand trends in flocks and cohorts individually, subsets of data were used to estimate individual DEAs by cohort (1 through 12) or by flock (1 through 8). Altogether, 20 individual DEAs were estimated. For example: all the inputs and outputs for all flocks that fall under cohort 1 were used to estimate a DEA, which will provide a granular understanding of how the efficiency of cohort 1 changed over their different flocks. These individual DEAs show similarities in trends within efficiency of flocks or of cohorts. It is important to note that comparative efficiency scores across DEAs cannot be compared as a DEA only shows comparative efficiency from flocks within the system, but their results do show patterns.

In general, across cohorts with flock held constant, the DEAs start high, dip low within the next couple of flocks, then climb back to higher efficiency levels over the remaining cohorts with some variation across flocks. Most flocks have a higher comparative efficiency at the last cohorts, but it is not a consistent rise from cohort to cohort. As cohorts are generally selected from the same village, these trends across flocks may show that individual cohorts are affected by location, timing of production, and heterogeneity across cohorts. To see these trends, the plots of the averages across cohorts for each flock can be seen in Figure 1.2. It can be observed that the flocks follow the same basic pattern.

In general, across flocks with only cohort held constant, comparative efficiency dips lower in flocks after flock one and rise for subsequent flocks, following that pattern across most cohorts. Across flock numbers with cohort held constant, seasonality may play a role in efficiency that can be similarly noticed for all cohorts. The pattern of decreasing after the first cohort might be due to the help of the flock technicians with the first flock. After the first flock, the farmers have a small struggle on their own with the subsequent flock, but the trend begins upward from there to generally being higher than the first flock's comparative efficiency. To see these trends, the plots of the averages across flocks for each cohort can be seen in Figure 1.3. Just like with flock number, these cohorts follow the same basic pattern. All these graphs show some consistency across flocks and across cohorts that are affected by other variables.

Factors affecting efficiency results

Using the full set of flocks and cohorts, the full DEA dataset was generated, and the factor regression analysis was estimated. For the regression, the dependent variable was the comparative efficiency score that was estimated from the full DEA. There was a total of 2,202 comparative efficiency scores generated ranging from 0.4658 to 1, with a mean of 0.7498, and a standard deviation of 0.0991. Results from the factor regression model are presented in Table 1.3.

Farmer characteristics, which include gender, age, and family size, may explain some of the farm level efficiency. For gender if the farmer is male, there is a decrease in comparative efficiency by 0.0065 which while is a small difference still shows that females in the program are producing flocks more efficiently than the males in the program. There were almost an equal number of males and females selected with 51.43% of the participants female and 48.57% male. With a significant difference between the two genders, it could speak to the social structure of the families selected for the program. Women could be more traditionally responsible for the workings at the home and spend more time at home, where the poultry are placed, and the men potentially spend more time away from home and tend to do less labor at home.

For farmer age and family size, there is a significant, negative coefficient of -0.0008 and -0.0176 respectively. However, when these two variables are interacted with one another, there is a statistically significant, positive coefficient of 0.0002. Also, when family size is squared, there is a positive coefficient of 0.0012. The minimum age in the regression is 18 years old, and at the lowest family size 0, which counts the number of people beyond the enrollee. There is still a negative effect of age and family size, but as both variables grow, the effect decreases at a decreasing rate. This might indicate that younger individuals with smaller families are more willing to put their time into raising poultry; whereas older individuals with larger families, might have less time to devote to their backyard flock.

In addition to farmer characteristics, farm characteristics are also important which include elevation (km) and distance from other farmers (km). Cohort is not included in this model as cohorts were selected in regions with members of the same cohort being closely clustered to one another so that cohort and elevation can be used interchangeably. For elevation, there is a minimum of 1.69km and a maximum of 2.53km with a mean of 2.1km. With every 1km increase in elevation, there is a decrease in comparative efficiency of 0.1012. The higher in elevation a farm is located, the air is thinner which implies lower oxygen levels and reduced productivity (Pillman, 2018). However, there is not a total effect from elevation on comparative efficiency of

-0.1012 as there is not a one-kilometer change in elevation from the lowest to the highest located farm.

For distance from other farmers, there is no statistical significance of the effect of the parameter on comparative efficiency. This was initially surprising as it was expected to show that the closer two farmers are to one another, the more information that would be shared between them, but the insignificance behind the coefficient seemed to indicate otherwise. However, after looking at the summary on distance, it can be noted that the average farmer is only 78 meters away from their nearest peer in the program, and the furthest one farmer is located from another is only 3km. Because of this, it may be possible that any new, more efficient production practices that are developed can spread throughout the farmers in the TI program quickly, and the movement of helpful information may be quickened with the aid of the flock technicians that stay in contact with all the farmers. So, while the distance variable is insignificant, this may speak to the strength of the producer network, where the changes in efficient production practices are not limited to pockets of producers but are rapidly and widely disseminated.

The last area of focus is on each individual flock factors which include the flock number, the harvest month, and the harvest year. For the flock number, after the first flock, the comparative efficiency decreases by 0.0194 before beginning to increase to where it is no different than flock 1 by flock 4. From there, there is a little bit of an up and down cycle before reaching flock 8. From flock 8 through flock 11, the comparative efficiency continues to rise until it reaches 0.0695 higher than flock 1. It is likely that for the first flock, or maybe even the first two flocks, the farmers are getting a lot of guidance from the flock technicians, but by the third flock, they might be on their own taking more personal ownership. Without intensive oversight by the flock technicians' experience or the complacency of two successful flocks, production might dip, but it begins to rise again after some cycling. Business cycles are apparent in any industry. These results show that there are some fluctuations in production efficiency as this industry is developing.

All coefficients on harvest year are significant except for 2019. 2018 was selected as the base year as it was the first year that all harvests continued for the full year. 2019 might have no noticeable effect from 2017 since they similarly will be made up of a large number of first flocks by farmers with 2017 being the introductory year and 2019 being the most recent full year with the most data points which include lots of new farmers. No definitive conclusion can be drawn, to explain these annual effects, however there may be wider Rwandan political or environmental factors that may contribute to these results. What it does indicate is that there were specific annual effects.

For harvest month, there initially seems to be no reason that some months are significantly better than other months, but it was thought to be possibly connected to Rwanda's rainy seasons. March to May is the largest rainy season, October to December being a more minor rainy season, and the rest of the year is relatively dry (World Climate Guide, 2020). However, these weather conditions did not fit the pattern presented. This means that the monthly change in estimated comparative efficiency is likely due to some unknown source such as temperature or other factor. Another possible explanation could simply be lack of data points as this data collection period only covers three years. Since these factors cannot be tracked at this time, only blind assumptions can be made as to what they might be. That being said, the data presented seems to show some relationship between month and comparative efficiency with July to October having the largest negative effects and December to March having the most positive effects, so flocks could benefit from being raised during times of the year where their harvest would not coincide with the months of July to October.

Conclusion

In this paper, the TI program's poultry operations in Rwanda were analyzed to track the progress of farmers through the program and the factors that contribute to any positive or negative progress in the program. The goal of the paper was to observe how farmer characteristics, farm characteristics, and flock characteristics affect each farmer's efficiency when compared to their peers in the program. A DEA was completed at the flock and cohort level to understand overall trends. A DEA over the entire dataset was also completed for the purpose of a truncated, bootstrapped standard error regression which included the comparative efficiency score as the dependent variable and all characteristics that relate to the flocks as the independent variable. From this two-stage analysis, it can be concluded that there are variables of note that significantly affect the comparative efficiency of each flock. The ones that significantly affect comparative efficiency include farmer characteristics: gender, age, and family size; farm characteristics: elevation; and flock characteristics: flock number, month, and year. An unexpected characteristic that did not significantly affect comparative efficiency was distance from another farmer, but this might be explained by the relatively close distance all farmers find themselves to one another or the work of the flock technicians.

Overall, the number of flocks a farmer has raised and what month that farmer raises them in is the most controllable aspects that can improve the comparative efficiency of a farm. Improvement comes with experience, according to this model, but also, it appears to be beneficial to aim harvest of a flocks away from the months of July to October. With time, a farmer might be able to adjust the number of chickens he or she raises at any time of the year to take advantage of the seasonal differences in comparative efficiency.

The controllable aspects that those picking farmers for the program can focus on includes the gender, age, and family size of a farmer. Younger female farmers that have smaller families appear to perform better. The exact reasoning that this is the case is not yet clear, especially considering that older farmers with larger families perform worse. Time available might play into this. Since raising broilers is additional income for the farmers, as farmers age and grow in family size, they might be less willing to devote time to broilers since it might take away from time with their full-time jobs or families.

The less controllable aspects that affect comparative efficiency include elevation and yearly patterns. Some years do significantly worse or better than others. While this may be connected to rainfall or temperature, this cannot be controlled except by management tactics that account for the yearly weather. Elevation could be selected in the process that decides who joins the program, but as Rwanda is a mountainous country, it would severely limit possible participants, and would shrink the availability of the chicken products throughout the country which is opposite of TI’s goals. However, placing a limit on elevation of farms could accomplish this task and decrease the risk of lower production at higher elevations.

While there are some solid inferences that can be made from the two-stage analysis carried out, more information will always be helpful in deciding what plays a role in the comparative efficiency of Rwandan, small-scale poultry farmers. Possible influential variables include how much time a farmer spends with the chickens each day and how much time other members of the family spend with them as constant husbandry could improve efficiency, a mortality report that shows at what age lost birds are dying as the older a broiler is when it dies, the larger the impact it will have on the comparative efficiency, and how often each farmer accepts additional help from the flock technicians as expert assistance could play a large role in the knowledge each farmer has when it comes to chicken husbandry.

Possible future analysis includes comparing the input to output ratio of the Rwandan, small-scale farmers next to that of large-scale farmer in the US. While the production systems are different, the genetics used on the chicken farms in Rwanda and the US are the same which means that the needs of the chickens would be similar. With knowledge about how a US farmer produces efficiently, a Rwandan farmer might be able to adjust their management practices to better mirror that of which the chickens were bred to be raised in. This might include adjustment to enclosures, feed ration changes, or air and water quality differences between the chickens in Rwanda and the US.

CHAPTER 2: ANALYSIS OF CAMELINA MEAL AS AN ALTERNATIVE POULTRY FEED SOURCE

ABSTRACT CHAPTER 2

The main source of protein for commercial broilers is obtained from soybean meal. With a high protein percentage and low anti-nutrient properties, soybean meal is a complete, low-cost source of protein meal. However, solely relying on one type of protein meal leaves broiler producers open to price volatility. To combat this, it is beneficial to have an alternative protein meal source available to lower the overall feed cost or reduce price volatility risk. Camelina meal offers a way to supplement the protein meal in broiler feed to solve this problem. Camelina meal is an oilseed crop that can be used for biofuel production. After the oil is extracted, however, with present anti-nutrient problems that exist with camelina meal, a challenge is posed when it comes to the growth rate of the broilers, so camelina meal can only be used in broiler finisher feed. To identify the demand of camelina meal for broiler finisher feed, a linear programming model was constructed that determines how much camelina meal would be selected for multiple price points in relation to soybean meal price. To take into account the distribution of protein around both camelina meal and soybean meal, the stochastic LP model will be estimated at 5000 iterations per price point with each iteration randomly selecting from the distributions of camelina meal and soybean meal. The results show that the average amount of camelina meal continues increasing until the price of camelina meal is 60% relative to the price of soybean meal with the maximum amount of camelina meal selected in the best-case-scenario also being reached at this price level. These results prove that there is a theoretical market for camelina meal within the broiler market as an alternative feed stock in broiler finisher feed. The optimal price would best be set at the level that allows for the maximum sale of camelina meal from the camelina oil refinery to the feed producers. This would create a dependable market for the meal byproduct that is produced by the oil refinery. Through this additional revenue, camelina oil refineries can

offer farmers a higher price for their camelina which increases the incentive for farmers to switch their production to camelina over the traditional crops that they currently grow and broiler producers are better protected from price volatility of soybean meal.

Introduction

Poultry is one of the lowest-cost animal proteins to produce which is in part related to access to affordable feed sources such as domestically produced soybeans. US poultry makes up 51% of all soybean consumption by livestock with broiler and turkey production alone accounting for 44% of all US soybean consumed by livestock (Waldroup & Smith, 2018). Soybeans have been used increasingly more for their protein content as consumer preferences begin to show a negative reaction to the use of animal proteins in poultry feed (Waldroup & Smith, 2018). However, the low cost for soybeans can always change depending on market forces, so it would be beneficial to farmers to lower the price risk of a highly demanded input. In 2012 US crop prices rose due to a countrywide drought that effected the commodity prices of all crops (Smith, 2012). This sent soybeans to over $17 a bushel from just over $13 a bushel for the same time the year in 2011. Substantial increases in prices of inputs can lead to impacts to the poultry industry such as decreased farmer profitability, increased prices to consumers, or changes in demand for poultry products. One way to mitigate the risk of input prices and avoid price and demand changes is to diversify the feed inputs in poultry feed.

There are a wide variety of oilseed crops grown in the US including soybeans, cottonseed, sunflower seed, canola, rapeseed, and peanuts. These make up 90% of all oilseed grown in the US (USDA, 2019). While soybeans currently account for more than half of US biodiesel production by volume, only 30% of US soybeans went to biodiesel production in 2018 with the other 70% either being exported or going into livestock feed or for human consumption (US Energy Information Administration, 2019). Although soybeans and other widely used crops can represent a larger percentage of crops in biodiesel production, there is a search for crops that can provide low-cost oil due to low demand for the products. Camelina and other oilseed crops are being studied as a possible alternative for biodiesel and aviation fuel production. This chapter will focus on camelina meal's ability to partly substitute soybean meal in broiler feed and the price at which broiler producers would begin to attempt substitution.

Literature Review

Benefits of soybean meal

Currently soybean meal is used in 63% of all livestock feed worldwide as the protein source in feed (Cromwell, 1999). In the US, poultry makes up 53% of the soybean meal use in livestock (Cromwell, 1999). The reason for this is the high level of digestibility, high source of protein, and good mix of amino acids that make up that protein (Cromwell, 1999). Since soybean also makes up for about 26% of the crops grown in the US by crop-land mass, it is also typically wide-spread and a cheap source of protein meal for poultry feed (Cromwell, 1999). The poultry industry used 15 million tons of soybeans in 2018, (United Soybean Board, 2018). Soybeans do contain some anti-nutrient compounds, mainly being a compound called a trypsin inhibitor which stops enzymes from functioning correctly; however, most of these are destroyed in the heating process that removes the oil from the meal (Poultry Hub, 2020b). Soybeans have been widely grown and have been a low cost feed over the past decades which will make replacement in the market a difficult task that will have to be accomplished with proven equivalence in available protein content, palpability, and price.

In the US, the poultry industry has developed into a well-developed, vertically integrated industry with all necessities for production held by the company including breeding flocks, hatcheries, feed mills, broiler flocks, and processing facilities (Parham, 2011). The only assets not held by the company are the barns in which the birds are grown. These barns are often held by the farmer who is contracted out to grow the birds, and the feed sources, which are purchased by the company and milled into the feed needed. In 2010, one-hundred percent of commercial broilers were fed by commercial feeds supplied by the integrators, which indicates that feed stock decisions are made by the integrator rather than the farmer (Parham, 2011). This vertical integration from egg to table gives a low cost product that can prove to be an inexpensive source of protein in the US which has caused production to increase to 43.4 billion pounds in 2019 with an average growth rate in the industry of 1.5 to 3 percent every year (NCC, 2020).

Broiler feed and its components

The following paragraph of literature references Poultry Hub which is an extension output of New England University in Australia. It stores and reports independent data that is inclusive of all aspects of broiler feed and rations needed in this analysis. Broiler feed is made up of several components including cereal grains, protein meals, fats and meals, minerals, and vitamins. The goal of a poultry feed mixture is to provide a highly palpable feed that is voluntarily eaten by the broiler while also being low-cost and free of anti-nutrient factors (Poultry Hub, 2020b). In the US, the most popular cereal grain is overwhelmingly corn; the cereal grain is there mainly for the energy requirements of the bird rather than the nutrients needed for growing or maintaining as cereal grains like corn have high levels of starch that supply the broiler with all its needed energy (Poultry Hub, 2020b). Protein meals, mainly soybeans in the US, make up 20%-30% of a broilers feed ration to provide the protein necessary for muscle growth in the broiler (Poultry Hub, 2020b). Soybean is popular because of its high protein content (48%) and its anti-nutrient factor can be mostly eliminated through heat treatment. Although being used less in the poultry industry today due to outside pressures, another means of protein addition to broiler feed is through animal byproducts that are high in protein. Byproduct, or not used for human consumption, accounts for 50 percent of ruminant's and 30 percent of poultry's live-weight, and the rest of the animal is rendered and then repurposed for things including broiler feed additives (Poultry Hub, 2020b). Aside from protein, animal byproduct additives also are good sources of essential amino acids, energy, and minerals that are hard to find readily available in plant substitutes (Poultry Hub, 2020b). Also added to broiler feed regularly are fats and oils. Fats including lard and tallow, and vegetable oils including soybean oil and cottonseed oil are good, dense sources of energy and some amino acids and minerals that are easily eaten and digested by broilers (Poultry Hub, 2020b). Finally, amino acids, minerals, and both fat and water soluble vitamins are added to broiler feeds to round out their nutritional needs so that they have a complete diet that promotes steady, healthy growth; these help with things like bone growth and enzyme activation as well as essential bodily functions (Poultry Hub, 2020b). Some of the vitamins and minerals that broilers require are found in the feed ingredients, but the requirements are met from these additives (Poultry Hub, 2020b). The levels of each of these components can vary based on age. There is typically a starter feed, grower feed, and a finisher feed for broilers, and there is variation within even these two divisions (Poultry Hub, 2020a). The started and grower feed will be used through about the first five weeks of a broiler's life, and the finisher feed will be used through the last weeks the broiler is growing, 6 to 8 weeks.

Alternative feed sources

There are several different alternative crops that can be used for biofuel sourcing including camelina, pennycress, and carinata. After the oil is extracted for the production of biofuel, the co-products, which is often called meal, has the possibility to be used as a protein alternative in broiler feed. For this paper, camelina meal (a by-product of biorefinement of camelina) is analyzed at as a replacement for soybean dry matter based on its protein content of 35% to 40% which is higher than pennycress seed oil (27%) and carinata meal (28%) (Hojilla-Evangelista et al., 2013; PFG Biofuels, 2020). While any of these biofuel sources could potentially be used in poultry feedstocks, starting with camelina will provide a baseline feasibility and if substituting camelina for soybean in poultry feed is shown to be feasible and cost effective, pennycress and carinata can be similarly evaluated in future work.

Camelina in feedstocks

Camelina is an oilseed crop that is studied as a possible alternative to traditional oil-based fuels. It has a unique composition that make it useful for the production of biofuel such as jet fuel (Berti et al., 2016). Camelina exists in both a winter and spring variety with the winter variety being cold hardy, and it has the ability to adapt in a wide range of climates meaning it could be an ideal crop to be used across the US as a rotational crop replacing some of the market currently dominated by cereal grains, corn, and soybeans (Berti et al., 2016). Camelina plants require input few applications of fertilizers, pesticides, or herbicides, and do not require irrigation (Cherian, 2012). Since the oil content is 38.9% in camelina seed, it will produce 778 pounds of oil per ton of oilseed which could be used for biofuel production, (Cherian, 2012). Rahman (2018) suggests that there is a breakeven level for the production of camelina that will make it available for biofuel production. Assuming a constant oil rate, seeding rate, yield, and price, there is a net return of $128 to $139 per acre depending on the region (Rahman, 2018). Aside from the high oil content itself, camelina meal has a high level of unsaturated fatty acids, but its fatty acid makeup possibly needs to be better refined to make it more efficient for biofuel uses (Sainger et al., 2017). Even so, camelina seed looks promising as a biofuel alternative.

Given the ability for camelina to be grown over most of the US, including areas of broiler production, camelina may be beneficial to use in poultry feed as an alternative sourced protein in broiler feed. If this leftover dry matter that tends to have high protein content can be used as poultry feed source, then biofuel production would be further incentivized by the additional revenue stream from the biofuel by-products.

After the cold-press process that removes the oil from camelina, the remaining dry matter contains 35% to 40% crude protein compared to 43% to 55% crude protein in soybean meal (Cherian, 2012; Feedipedia, 2020b). Although it has a lower crude protein content than the preferred soybeans, a larger mass or mix with soybeans could meet protein needs for animal protein. There is already some evidence of camelina being beneficial as a livestock feed. The combination of omega 3 fatty acids as well as the energy provided by the calories and protein present has contributed to healthy weight gain in cattle (Koeleman, 2016).

When fed to broiler chickens there have been mixed results. Aziza, Quezada, and Cherian (2010) report that there is no difference in performance at the 2.5%, 5%, and 10% level in the feed ration. While there was no significant decrease in final weight, there was a decrease in feed conversion ratio and there was a decrease in consumption in the starter phase (Aziza et al., 2010). However, Ryhanen et al. (2007) states that there are some decreases in performance at the 5%-10% level in the feed ration. Starting at the 5% level in the feed ration there is a decline in peak growth from 15 to 37 days of age especially among the male broilers (Ryhänen et al., 2007). Final combined body weights were from 7% to 10% lower on the camelina ration than broilers that were fed with traditional broiler diets (Ryhänen et al., 2007). This leads to the possibility that camelina meal might only be possible as a substitute in finisher feed. This should not affect the viability in broiler rations as camelina meal is being looked at as a lower protein percentage substitute rather than a complete replacement of soybean meal.

Limitations of camelina in feedstocks

The problem with camelina meal as a livestock feed is that it contains glucosinolates (Helsel, 2019). Glucosinolates are a sulfur-containing compound produced in small quantities by some plants, and can have negative effects on livestock (Tripathi & As, 2017). In poultry, depending on the amount consumed, glucosinolates can cause a decrease in the ability to absorb amino acids (Tripathi & As, 2017). This is the likely reason behind the decreased growth rate in the feed trials previously mentioned. However, poultry can consume more glucosinolates in their diet than most other livestock species (Tripathi & As, 2017). Also, there are many cases where camelina has been used as a supplement in livestock feed indicating that there could be some uses for camelina in broiler feed (Cherian, 2012). Some of the other compounds present in camelina meal are non-starch polysaccharides, which also affect feed consumption and growth performance like glucosinolates, and phenolic compounds and tannins are present in camelina meal which affect digestibility and absorption of energy and protein (Cherian, 2012). Use of camelina meal in broiler feed will likely be limited unless a low-cost, effective way of overcoming these anti-nutritional effects is discovered and used in the feed ration.

There is a misconception that chickens will eat the amount of feed that is needed to reach the nutrition levels their bodies require (Scott et al., 1982). However, there is little evidence to support this claim, and in fact there is evidence in contradict this. There seems to be a direct correlation between the overall protein percentage in poultry diet and the rate of growth in chickens (Fisher & Wilson, 1974). This means that there could be some problems when it comes to implementing a feed budget that has a higher percentage of crude protein compared to the other nutritional requirements. These problems would only be able to be noticed in practice rather than theory, however, and based on the evidence provided by Aziza et al (2010), these problems might only show themselves if camelina meal is used in the starter phase of broiler production. If only used in finisher feed, the potential drawback of using camelina meal would be in the feed conversion ratio which is suspected to be higher as more feed would have to be used to reach the requirements. The cost would not be affected if camelina meal is actually used or there would be no incentive for poultry companies to substitute soybeans with camelina. In fact, the worsening feed conversion ratio explained by Aziza et al (2010) might actually describe the ability for a broiler to eat more based on its own nutrition requirements.

Conceptual Framework

This analysis aims to determine the price difference between soybean meal and camelina meal that might lead to the use of camelina meal over soybean meal and at what quantities. This price difference will be the point where the use of camelina meal will cost less in inputs than soybean meal. The reason that a farmer would want to lower their cost is motivated by profit maximization. To maximize profit, producers will look to the feed that produces the least cost per unit of meat production, called the least cost feed model (Pesti et al., 1985). This means finding the lowest cost materials in feed subject to the necessary nutrition to raise a set number of chickens and the volume that those chickens can eat in a certain time (Pesti et al., 1985). This least cost feed ration can be shown in equation 2.1 as:

(2.1) $$Min\ C = P_i \times Q_i + P_{of} OF + K$$

$$S.T.\ \alpha_i Q_i > A_i$$

$$\sum_{i=1}^{N} Q_i + F = 1000kg$$

where P_i is the price of ingredient *i*, Q_i is the quantity of ingredient *i*, Po_f are the prices for other ingredients, *OF* represents all other feedstock ingredient quantities, *K* is a constant for all other costs such as transportation or milling, α is the protein content of ingredient *i* and is stochastic over a distribution, and *A* is the kilograms of protein content required by meal in the mix by the i^{th} protein source- camelina and soybean meals. For the purposes of this analysis, the only variable changing will be the meal source of protein, and all other ingredients and their nutritional contribution are fixed in price and proportion.

Given that each feed ration has limiting protein contents depending on the amount in the feed source (α in Equation 2.1), to compare across feed rations the number of birds serviced by each 1,000 kg ration is calculated. The calculation of the number of birds satisfied with the feed ration is represented in Equation 2.2:

(2.2) $$\frac{\sum_{i=1}^{2} \alpha_i Q_i}{B_\alpha} = H$$

where α_i and Qi are previously defined, B_α is the amount of protein required by a single chicken, and H is the number of chickens that the meal will support. With these two equations, the percentage of the meal that must be camelina meal can be calculated in the first equation. In the second equation, the protein content present in the feed budget from the first equation is divided by the total protein required by one chicken to calculate how many chickens can be raised off that feed. H can be set constant in order to find the level of Q_i to meet the nutritional requirements at the least cost.

The hypothesis of this paper is that camelina meal can fit into the low-cost feed budget at the nutrient level required for the chickens to consume the feed ration in great enough volume to reach the nutrient level necessary. An optimal solution will be found where the minimum protein requirements of the feed are met. From there, the low-cost side of the equation will be calculated by determining the necessary difference in price between camelina meal and soybean meal.

Methodology

Determining the quantity of camelina meal that can replace soybean meal in a broiler finisher ration is the goal of this analysis. The objective is to estimate a minimum cost, linear production model that will determine what quantity of camelina minimizes feed cost in a mix between camelina meal and soybean meal subject to necessary constraints. From there, it is necessary to understand how much camelina meal is optimal to use at various price points. This objective is accomplished by using a linear programming model that stochastically determines protein percentages from a pert distribution around both soybean meal and camelina meal with varied camelina price discounts to soybean meal. By examining the quantities used at each price point, conclusions can be drawn about how the optimal price of camelina meal relative to soybean meal price.

Minimum cost model

The objective will be accomplished first through a linear programming model that finds the optimal quantity of camelina and soybean meal. The amount of meal that is required in a mix is fixed in order to maintain the quality of the feed. The goal of this model will be to keep the minimum protein that is required from the meal in a mix while minimizing the total cost by mixing camelina meal and soybean meal with the assumption that camelina meal cost will be less than that of soybean meal. It is also important to note that the protein percentage of both camelina meal and soybean meal are drawn from a distribution which can be found in Table 2.1. Although a minimum, maximum, most likely, and standard deviation exists for both camelina meal and soybean meal, the shape of the distribution is unknown, so a pert distribution will be used to estimate the distribution around the protein content of both meals. The minimum cost of the equation is represented by the quantity of the blended meal times the price of the blended meal plus the penalty of a soft constraint that is used to add soybean meal in case the protein does not meet the minimum level which is 88.2kg in a 1000kg mix. The equation that determines whether or not to add an additional quantity of soybean meal depends on whether the protein in the meal blend meets the minimum requirement. This if equation depends on the quantity of protein in the blend which is the sum of the quantity of protein in the camelina meal and the soybean meal. The quantity of each meal's protein is the product of the quantity of that meal in the mix and its protein percentage. The total protein percentage is determined by the total meal in the mix divided by the total quantity of protein in the blend. The quantity of meal in the blend must be 200kg for a 1000kg mix. The price of each meal, quantity and price of the blend, and the protein of each meal must be greater than or equal to 0. This minimum cost equation can be expressed as equation 2.3:

(2.3)

$$Min\ C\ = Q_b * P_b + \varphi$$

$$where \begin{cases} \varphi = ((88.2 - R_b)/W_s) * P_s\ , R_b < 88.2 \\ \varphi = 0\ , R_b \geq 88.2 \end{cases}$$

$$S.T.:\ R_b = R_s + R_c$$

$$R_i = Q_i * W_i$$

$$Q_b, P_b \geq 0$$

$$W_i \geq 0$$

$$R_b \geq 88.2$$

$$Q_b = 200$$

where Q is the quantity and P is the price of the blend denoted by b. The quantity will be referred to in kilograms. W_i is a reference to the percentage of protein in the meal, and i can refer to soybeans, s, or camelina, c. W_i is on a distribution for both camelina meal and soybean meal which is denoted by F_i. φ represents a penalty for the soft constraint on kilograms of protein in the blend, R_b, which must be at least 88.2 kilograms. If the protein does not meet the minimum requirements, additional kilograms of soybean meal are added to the mix to bring it up to the minimum protein required. The soft constraint allows for flexibility in optimization in the @Risk software such that a solution can be found. R_i is the total protein, in kilograms, of soybean meal or camelina meal in the mix. This optimization is subject to constraints. These include non-negativity constraints on quantities, prices and blend protein amounts, assumptions on protein amount as described, and the maximum quantity of the blend. The total quantity of the optimized blend is fixed to 200 kilograms out of a 1000-kilogram ratio as a broiler finisher ration consists of 20% dry meal on average. This fixed quantity is due to the decrease in pelletization of the feed when excess dry matter is added. Poultry are known not to eat as much feed when it is not in pellet form. This also is the reasoning why the φ equation only selects for soybean meal and no camelina meal. As soybean meal has the higher protein content, the content of the meal will reach the minimum level quicker with soybean meal so that the integrity of the feed pellet is more likely to be sustained. The goal is that little to no extra soybean meal is added by the model bringing the total meal quantity over 200kg. The model should keep φ minimized since it represents an additional cost.

In addition to the previous constraints there are additional constraints to account for the nutritional nature of camelina meal. As discussed earlier in the literature review, negative returns begin in broiler production when camelina meal reaches 10% of the ration due to the anti-nutrient factors that are not denatured in the heat process. For this reason, it is necessary to limit the amount of camelina meal in the 1000-kilogram ration to 100 kilograms.

(2.4)

$$Q_c \leq 100$$

The price of the blend, P_b, is determined by the percentage of soybean meal of the 200 kilograms times its price, plus the percentage of camelina meal of the 200 kilograms times its price which can be expressed as

(2.5)

$$P_b = P_s * V_s + P_c * V_c$$

where P_s and P_c are the price of soybeans and camelina, and V_s and V_c are the percentage of the 200-kilogram meal mix made up of soybean meal and camelina meal respectively. The formula for the constraint on V_i (where i is soybean meal or camelina meal) is expressed as

(2.6)

$$V_i = {}^{Q_i}/_{Q_b}.$$

$$V_s + V_c = 1$$

so that the percentage of each type of meal in the blend is the quantity of that meal in the blend divided by the total quantity of the blend needed. The sum of this percentage for soybean meal and camelina meal must equal 100%. In order to obtain results of the model possibly increasing camelina meal, the price of camelina meal, P_c, will be decreased to see how the model changes quantities of camelina meal for each price. P_c will start at 99% of the price of soybean meal. The price of soybean meal will be gathered from the average price from the Chicago Mercantile Exchange (CME) over the past five years. P_c will then be decreased to 90% of the price of soybean meal and decreased in increments of ten percent.

Interpreting output

To select multiple protein percentages for camelina meal and soybean meal along their distributions, 5000 iterations will be estimated at every price point for camelina meal. An average will be taken for the iterations of each price point for the quantity of camelina that is used. It is hypothesized that as the price for camelina meal decreases in relation to soybean meal price, the model will select more camelina meal until it reaches its maximum at 100kg. However, as camelina meal reaches 100kg, more excess soybean meal will be used.

Data

The data collected for this analysis comes from several sources. Table 2.1 summarizes the protein distribution around camelina and soybean meals. This table shows that camelina meal has a mean of 35.7% protein with a minimum of 31.3% and a maximum of 41.1% (Feedipedia, 2020a). In comparison, soybean meal has an average of 49.5% protein with a minimum of 44.1% and a maximum of 54.9% (Feedipedia, 2020b). While the standard deviation is given for each protein distribution, the shape of the distribution is unknown. A pert distribution will be used and is discussed further in the methodology.

A broiler finisher feed is used in this analysis considering that broilers can be negatively affected by camelina in their diet before the finisher phase. A finisher feed is used at the end of the grow out phase for approximately the two weeks leading up to slaughter. Based off of the requirements of broiler finisher feed, 20% of the ration will be comprised of soybean meal (Esmail, 2016). Therefore, broilers require 88.2kg of protein from the meal source in their finisher feed on average.

As for the price of soybean meal which is used to calculate both the relative price of camelina meal and the total price of the blend in the linear programming model, the price used was the five-year average from January 2015 to December 2020 for soybean meal based off of the Chicago Mercantile Exchange (CME) futures prices for soybean meal. The mean price is $319.57 per metric ton or $0.32 per kilogram. While the true soybean price does fluctuate in the time frame, this study is focused on the relative price difference between soybean and camelina meal prices rather than the actual cost of soybean meal.

Results

To model the optimal quantity of camelina meal, camelina meal price was varied in 10 percentage point increments starting at 30% of soybean meal price all the way up to 90% of soybean meal price. An estimation of camelina meal price at 99% of soybean meal price was also included to show the model's sensitivity to marginal price differences. The model was estimated with 5,000 iterations at each price point to understand the distribution of optimal outcomes as they relate to the distribution of protein around camelina meal and soybean meal. For each iteration, the prices of camelina meal and soybean meal remain constant, but the protein content varies based on a random selection by the model from the distribution around protein for boy meals. Results are presented in Table 2.2 and Table 2.3, showing the mean and the best-case outcomes for camelina meal selected.

Mean optimal camelina meal results

Figure 2.1 shows the plot of the mean camelina meal quantity for the various camelina meal price points. This figure shows that as the relative price of camelina meal to soybean meal decreases, the mean quantity of camelina meal the model selects increases. From the means for all iterations in Table 2.2, the price of the blend decreases as the price of camelina meal decreases. The quantity of camelina meal used increases as its relative price to soybean meal decreases. It is useful to potential camelina producers and alternative fuels industries to see the quantity of camelina meal used rise even though it leads to a higher likelihood that additional soybean meal would need to be used. The additional soybean meal accounts for the differences in protein distributions for camelina meal, which is lower, and soybean meal. The mean use of camelina meal among the models maxes out when camelina meal price is 60% of the soybean meal price. From there, the quantity changes in small increments, mostly decreasing, that is likely explained by the random selection of protein distributions provided by the model. These random selections can result in similar, but different, optimal feed rations even within the exact same model definition. When the price of camelina meal relative to soybean meal is at 60%, the quantity of camelina meal selected by the model maximizes, so as price decreases from the relative point of 60%, there is no significant change in quantity.

However, despite the uptake of camelina meal, at the camelina meal price level that is 60% of soybean meal price there is a larger amount of additional soybean meal needed on average. From relative prices of 99% down to 70%, there is less than 1kg additional soybean meal needed for the 200kg of meal needed in the finisher feed ration, but at and below 60% which reflects a greater discount to soybean meal prices, the amount of additional soybean meal needed ranges from about 3.5kg to 6.9kg needed. As mentioned previously, reduced pelletization of the ration becomes a problem with the feed whenever the dry matter begins to exceed the rations wet matter ratios. This means that in terms of feed ration mixing, it is preferable to have little to no additional soybean meal in the blend. From these results which uses the most camelina without negative effects, optimal usage would be at 74.23 kg in a 1,000kg finisher feed ration. In terms of optimal price, this would mean that to drive the highest level of usage on average without sacrificing pelletization, prices would need to be at least 70% of the soybean meal price, or at a 30% discount

Best iteration / optimal results

In the stochastic model, the optimal solution changes with each iteration. For each price point, the iteration with the lowest price of the total blend was recorded as a "best-case-scenario" option (Table 2.3). Figure 2.2 shows the plot of the camelina meal quantity for the best iteration at every camelina meal price point. For all price points analyzed, the most expensive blend is made up of 200kg of soybean meal and no camelina meal which means that when camelina meal can be included without dropping below the minimum protein requirements, it will always result in a lower price than 100% soybean meal. The lowest price for the total blend found will follow. For a camelina meal price 99% of the soybean meal price, the best iteration has a quantity of 65.76kg of camelina meal for the 1000kg of feed. For a camelina meal price of 90% of soybean meal price, the best iteration has a quantity of 72.43kg of camelina meal for the 1000kg of feed. For a camelina meal price of 80% of soybean meal price, the best iteration has a quantity of 70.62kg of camelina meal for the 1000kg of feed. For a camelina meal price of 70% of soybean meal price, the best iteration has a quantity of 79.26kg of camelina meal for the 1000kg of feed.

Similar to the analysis at the means, the best iteration maxes out in relation to the quantity of camelina meal when the price of camelina meal gets down to 60% of the price of soybean meal. At 60% and lower relative price to soybean meal, the quantity of camelina meal in the best trial is 100kg. The best trial is defined by the lowest price of the meal mix. At that price point of 60%, the best trial then includes an additional quantity of soybean meal necessary, whereas above 60%, none is required by the model.

Application of results in Tennessee

These results have shown the potential use of camelina meal in a broiler finisher ration. The real-world effects of this would be driven by the relative demand by the broiler industry, production of camelina, proximity to biorefineries, and a system to transport products between the enterprises. To illustrate the potential use, an estimated demand for a moderate broiler producing state, Tennessee, is calculated. In 2017, Tennessee produced 30.5 million meat-type chickens (NASS, 2017). To calculate the amount of camelina meal these broilers could have demanded it is necessary to remember that only during the finishing phases, about 6 to 7 weeks old, is it possible to use camelina meal in the feed ration without negative effects on growth. In finisher feed, broilers have about 20% soybean meal on average (Esmail, 2016). With only 10% of the broiler finisher feed allowed to be camelina meal, this leaves open 100kg per 1000kg of feed. While eating finisher feed, broilers will eat an average for males of 0.21kg per broiler every day during week 6 and 0.227kg per broiler every day during week 7 (Opeyemi, 2019). Females eat an average of 0.192kg per broiler every day during week 6 and 0.211kg per broiler every day during week 7 (Opeyemi, 2019). The average of these is 0.42kg per broiler every day or 2.94kg per week. Using the 2017 numbers for broilers, it can be assumed that 89.67 million kg of finisher feed were consumed by broilers in Tennessee. Given that 20% of that finisher feed would have been soybean meal, it can be assumed that 17.93 million kilograms of that would have been soybean meal. Using the presented results for the demand of camelina meal as a replacement for soybean meal, a demand calculation can then be estimated.

When the price of camelina meal is 99% to 80% of the price of soybean meal, camelina meal demand averages range from 62.53kg to 68.38kg of the 200kg of dry meal in a 1000kg feed ration or 31.3% to 34.2% of the dry meal necessary. Based off the quantity of soybean meal demanded for broiler finisher feed, there would be a demand of 5.61 million kg to 6.13 million kg for broiler finisher feed in Tennessee. This would create gross sales of $19.81 million to $19.69 million per year.

When the price of camelina meal is 70% of the price of soybean meal, camelina meal demand averages 74.23kg of the 200kg of dry meal necessary in a 1000kg feed ration or 37.1% of the dry meal necessary. This amounts to a demand for camelina meal of 6.65 million kg for broiler finisher feed in Tennessee. This would create a gross sale of $16.63 million.

Finally, where the price of camelina meal is 30% to 60% of the price of soybean meal, camelina meal demand averages from 83.71 million kg to 86.34 million kg of the 200kg of dry meal necessary in a 1000kg feed ration or 41.9% to 43.2% of the dry meal necessary. This would create gross sales of $8.21 million to $16.57 million. The best price point would depend heavily on what quantity and quality of camelina meal is produced each year that is in close enough proximity to the feed mill to be purchased in used in the feed ration.

Conclusion

Camelina has been shown to have potential substitutability, at least in theory, for soybean meal in broiler finisher rations if the camelina meal is priced at a discount to soybean meal. There is an increasing quantity of camelina meal selected as the price lowers with respect to soybean meal prices. However, the quantity demanded does not change much once camelina meal is priced at 60% to 70% of soybean meal prices. Based off the quantity of camelina meal that is produced in close enough proximity to chicken feed mills in Tennessee and the amount of broiler finisher feed produced by those mills, this information could be used to give a camelina refinery a price point for their camelina meal byproduct.

Based on the mean results, it can be inferred that both camelina oil refineries looking to sell the meal byproduct and broiler producers can benefit from camelina meal supplementing broiler finisher feed. The oil refinery can determine their price point based off the quantity of meal they need to sell by using these results and the quantity of finisher meal broiler producers' demand. Camelina oil refineries benefit by selling what would otherwise be a discarded byproduct. Broiler producers would benefit by a decrease in feed cost without sacrificing broiler weight.

These results could lead to an increased incentive for growing camelina because there would be an increased profitability from the seed itself. With refineries able to sell the meal byproduct in addition to the extracted oil for biofuel, they could offer farmers a higher price. With higher buying price, farmers would begin turning away from traditional crops for a higher profit crop in this new market, or farmers will begin to adopt camelina as a cover crop. However, there are still feasibility issues when it comes to whether the price would be high enough for the farmers. With no camelina oil refineries or commercial biofuel markets creating biofuel from camelina oil currently in the state of Tennessee, it is unknown if the price the refinery would get from the oil supplemented with the sale of the meal would allow the refinery to offer farmers enough for camelina to incentivize them to grow camelina rather than their normal crops. It is also unknown if camelina meal would be feasible in broiler feed. The texture of broiler feed must be pellet shaped for broilers to eat it. If camelina meal does not allow pelletization, then it would not be useful for broiler feed. Broiler producers also might be wary to use camelina meal because of its negative affect on broiler growth. With a possible decrease in weight for finished broilers, any saved costs might be quickly lost with smaller broilers being produced.

If feasible, the broiler industry could save on feed cost as well as decrease the risk that price volatility from the soybean market presents to broiler feed cost. By having camelina meal as an option, broiler feed mills would not be totally dependent on the current price of soybeans as more camelina meal can be introduced into broiler finisher feed as the price of soybean meal rises.

Further studies could look at the palpability and pelletization of camelina meal in broilers, and whether the antinutrient properties in camelina meal has a negative impact on the size of the finished broilers. Further research also needs to be done to determine how much farmers need to receive for camelina to begin growing it, and how much refineries need to receive from camelina meal in order to provide that price to farmers. Based on these prices, the cost of feasibility of introducing camelina meal into broiler feed can be realized as feasible or infeasible. Another way this analysis can offer solutions to lowering the cost of broiler feed and giving additional revenue to biofuel producers will be to apply this model to other biofuel seeds to identify profitability.

REFERENCES

Alexandratos, N. (2012). *World Agriculture towards 2030/2050: The 2012 revision*. 154.

Aziza, A., Quezada, N., & Cherian, G. (2010). Feeding Camelina sativa meal to meat-type chickens: Effect on production performance and tissue fatty acid composition. *Poultry Science Association J. Appl. Poult. Res, 19*, 157–168. https://doi.org/10.3382/japr.2009-00100

Berti, M., Gesch, R., Eynck, C., Anderson, J., & Cermak, S. (2016). Camelina uses, genetics, genomics, production, and management. *Industrial Crops and Products*, *94*, 690–710. https://doi.org/10.1016/j.indcrop.2016.09.034

Cherian, G. (2012). *Camelina sativa in poultry diets: Opportunities and challenges*. 47.

Chief, E. in. (2019, March 31). 19 Advantages and Disadvantages of Poultry Farming. *ConnectUS*. https://connectusfund.org/6-advantages-and-disadvantages-of-poultry-farming

Cooper, W. W., Seiford, L. M., & Zhu, J. (2004). Data Envelopment Analysis. In W. W. Cooper, L. M. Seiford, & J. Zhu (Eds.), *Handbook on Data Envelopment Analysis* (pp. 1–39). Springer US. https://doi.org/10.1007/1-4020-7798-X_1

Cromwell, G. L. (1999). *Soybean Meal—The "Gold Standard."* 3.

Demment, M. W., Young, M. M., & Sensenig, R. L. (2003). Providing micronutrients through food-based solutions: A key to human and national development. *The Journal of Nutrition*, *133*(11 Suppl 2), 3879S-3885S. https://doi.org/10.1093/jn/133.11.3879S

Esmail, S. (2016, November 9). *Understanding protein requirements*. PoultryWorld. https://www.poultryworld.net/Nutrition/Articles/2016/11/Understanding-protein-requirements-2914798W/

Fasina, F. O., Ali, A. M., Yilma, J. M., Thieme, O., & Ankers, P. (2012). The cost–benefit of biosecurity measures on infectious diseases in the Egyptian household poultry. *Preventive Veterinary Medicine*, *103*(2), 178–191. https://doi.org/10.1016/j.prevetmed.2011.09.016

Feedipedia. (2020a). *Camelina (Camelina sativa) seeds and oil meal | Feedipedia*. https://www.feedipedia.org/node/4254

Feedipedia. (2020b). *Soybean meal | Feedipedia*. https://www.feedipedia.org/node/674

Fisher, C., & Wilson, B. J. (1974). Response to dietary energy concentration by growing chickens. *Energy Requirements of Poultry*, 151–184.

Gill, T. (2018). *Feed the Future Tworore Inkoko, Twunguke ANNUAL WORK PLAN* (The United States Agency for International Development Rwanda). University of Tennessee Institute of Agriculture.

Gill, T., Urban, E., Ader, D., & Nisengwe, R. & G. (2020). Piloting a Commercial Broiler Production Model for Smallholders in Rwanda. *African Journal of Food, Agriculture, Nutrition and Development*, *20*(2), 15660–15676.

Helsel, Z. R. (2019, April 3). *Camelina for Biofuel Production – Farm Energy*. https://farm-energy.extension.org/camelina-for-biofuel-production/

Hojilla-Evangelista, M. P., Evangelista, R. L., Isbell, T. A., & Selling, G. W. (2013). Effects of cold-pressing and seed cooking on functional properties of protein in pennycress (Thlaspi arvense L.) seed and press cakes. *Industrial Crops and Products*, *45*, 223–229. https://doi.org/10.1016/j.indcrop.2012.12.026

Ji, Y., & Lee, C. (2009). *Data Envelopment Analysis in Stata*. 13.

Koeleman, E. (2016, May 2). *How much soybean meal is consumed in the US?* AllAboutFeed. https://www.allaboutfeed.net/Raw-Materials/Articles/2016/5/How-much-soybean-meal-is-consumed-in-the-US-2797285W/

Mack, S., Hoffmann, D., & Otte, J. (2005). The contribution of poultry to rural development. *World's Poultry Science Journal*, *61*(1), 7–14. https://doi.org/10.1079/WPS200436

Mbuza, F., Denis, M., Janvier, M., & Xavier, R. (2016). Characterization of low cost village Poultry production in Rwanda. *International Journal of Livestock Production*, *7*(9), 76–82. https://doi.org/10.5897/IJLP2016.0300

Murphy, S. P., & Allen, L. H. (2003). Nutritional Importance of Animal Source Foods. *The Journal of Nutrition*, *133*(11), 3932S-3935S. https://doi.org/10.1093/jn/133.11.3932S

NASS. (2017). *2017 Census of Agriculture State Profile—Tennessee*. Nass.Usda.Gov. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/County_Profiles/Tennessee/cp99047.pdf

NCC. (2020). U.S. Broiler Production. *The National Chicken Council*. https://www.nationalchickencouncil.org/about-the-industry/statistics/u-s-broiler-production/

Nicholson, W., & Snyder, C. M. (2012). *Microeconomic Theory: Basic Principles and Extensions*. Cengage Learning. https://books.google.com/books?id=ZGNxrLRYLF4C

Opeyemi. (2019, May 28). Expected Broiler Weight Per Week And How to Get It! *Guidefreak*. https://guidefreak.com/broiler-weight-per-week/

Parham, D. D. (2011). *Structure of the U.S. Poultry Industry, 2010*.

Pesti, G. M., Miller, B. R., & Carey, C. A. (1985). Proportionality Among Nutrients in Least Cost Feed Formulation. *Poultry Science*, *64*(5), 824–831. https://doi.org/10.3382/ps.0640824

Peters, C. J., Picardy, J. A., Darrouzet-Nardi, A., & Griffin, T. S. (2014). Feed conversions, ration compositions, and land use efficiencies of major livestock products in U.S. agricultural systems. *Agricultural Systems*, *130*, 35–43. https://doi.org/10.1016/j.agsy.2014.06.005

PFG Biofuels. (2020). *PGF Biofuels—Carinata Oilseed Production*. http://pgfbiofuels.com/carinata/

Pillman, S. (2018, May 28). Altitude To Oxygen Chart—Oxygen Levels At High Altitudes—Hypoxico. *Hypoxico.Com - The Leaders In Altitude Training, Altitude Tents*. https://hypoxico.com/altitude-to-oxygen-chart/

Poultry Hub. (2020a). Commercial Broiler Production. *Poultry Hub*. https://www.poultryhub.org/family-poultry-training-course/trainees-manual-2/commercial-broiler-production/

Poultry Hub. (2020b). Feed Ingredients. *Poultry Hub*. http://www.poultryhub.org/nutrition/feed-ingredients/

Rahman, U. (2018). *Potential of Biomass in Developing Renewable Energy: Wood Pellet Trade from US and Development of Aviation Fuel from Oilseed Crops*. 94.

Ryhänen, E.-L., Perttilä, S., Tupasela, T., Valaja, J., Eriksson, C., & Larkka, K. (2007). Effect of Camelina sativa expeller cake on performance and meat quality of broilers. *Journal of the Science of Food and Agriculture*, *87*(8), 1489–1494. https://doi.org/10.1002/jsfa.2864

Sainger, M., Jaiwal, A., Sainger, P. A., Chaudhary, D., Jaiwal, R., & Jaiwal, P. K. (2017). Advances in genetic improvement of Camelina sativa for biofuel and industrial bio-products. *Renewable and Sustainable Energy Reviews*, *68*, 623–637. https://doi.org/10.1016/j.rser.2016.10.023

Sans, P., & Combris, P. (2015). World meat consumption patterns: An overview of the last fifty years (1961–2011). *Meat Science*, *109*, 106–111. https://doi.org/10.1016/j.meatsci.2015.05.012

Scott, M. L., Nesheim, M. C., & Young, R. J. (1982). Nutrition of chicken-3 rd Edn.(Ed.) Scott. *ML and Associates, Ithaca, NY*, 424–425.

Simar, L., & Wilson, P. W. (2011). Two-stage DEA: Caveat emptor. *Journal of Productivity Analysis*, *36*(2), 205. https://doi.org/10.1007/s11123-011-0230-6

Smith, A. (2012, August 9). *U.S. drought drives up food prices worldwide*. CNNMoney. https://money.cnn.com/2012/08/09/news/economy/food-prices-index/index.htm

Sonaiya, B. (1990). *Toward Sustainable Poultry Production in Africa*. http://www.fao.org/3/t0582e/T0582E26.htm

StataCorp, L. P. (2005). *Stata Base Reference Manual*. Stata.

Statista. (2019). *Broiler meat production worldwide, 2012-2019*. Statista. https://www.statista.com/statistics/237637/production-of-poultry-meat-worldwide-since-1990/

Tohidi, G., & Razavyan, S. (2013). A circular global profit Malmquist productivity index in data envelopment analysis. *Applied Mathematical Modelling*, *37*(1), 216–227. https://doi.org/10.1016/j.apm.2012.02.026

Tripathi, M. K., & As, M. (2017). Prospects and Problems of Dietary Glucosinolates in Animal Feeding. *Advances in Dairy Research*, *05*(03). https://doi.org/10.4172/2329-888X.1000180

United Soybean Board. (2018). *2018 Soybean Meal Demand Assessment*.

US Energy Information Administration. (2019, July 5). *Soybean oil comprises a larger share of domestic biodiesel production—Today in Energy—U.S. Energy Information*

Administration (EIA) [Government]. EIA. https://www.eia.gov/todayinenergy/detail.php?id=39372

USDA. (2019, August 20). *USDA ERS - Oil Crops Sector at a Glance* [Government]. USDA ERS. https://www.ers.usda.gov/topics/crops/soybeans-oil-crops/oil-crops-sector-at-a-glance/

Waldroup, P. W., & Smith, K. (2018). *Soybean Use—Poultry*.

World Climate Guide. (2020). *Rwanda climate: Average weather, temperature, precipitation, best time*. Climates To Travel. https://www.climatestotravel.com/climate/rwanda

APPENDIX

Table 1.1: Summary Statistics of Poultry Inputs and Outputs per Rwandan TI Farmer Flock

Variable Name	Observations	Mean	Min	Max
Feed Quantity (Kg)	2,202	599.78	200	1100
Charcoal Usage (bags)	2,202	2.31	0	5
Sale Age (days)	2,202	51.52	14	414
Livability	2,202	89.54%	43%	100%
Whole Flock Live Weight	2,202	264.61	76.53	432.68

*The inverted feed conversion ratio is calculated as 1 divided by the feed conversion ratio

Table 1.2: Summary Statistics of Regressors on Comparative Efficiency Scores

	Variable Name	Obs.	Mean	Min	Max
Farmer Characteristics	**Male**	1,071	0.49	0	1
	Female	1,131	0.51	0	1
	Farmer Age	2,202	39.30	18	76
	Family Size	2,202	4.18	0	11
Farm Characteristics	**Elevation (Km)**	2,202	2.10	1.692	2.532
	Distance from Another Farmer (Km)	2,202	0.08	0	3.197
Flock Characteristics	**Flock Number**	2,202			
	1	472	0.21	0	1
	2	397	0.18	0	1
	3	365	0.17	0	1
	4	312	0.14	0	1
	5	231	0.10	0	1
	6	148	0.07	0	1
	7	120	0.05	0	1
	8	76	0.03	0	1
	9	56	0.03	0	1
	10	23	0.01	0	1
	11	2	0.00	0	1
	Harvest Month	2,202			
	January	178	0.08	0	1
	February	198	0.09	0	1
	March	158	0.07	0	1
	April	229	0.10	0	1
	May	135	0.06	0	1
	June	130	0.06	0	1
	July	167	0.08	0	1
	August	136	0.06	0	1
	September	112	0.05	0	1
	October	267	0.12	0	1
	November	246	0.11	0	1
	December	246	0.11	0	1
	Harvest Year	2,202			
	2017	72	0.03	0	1
	2018	459	0.21	0	1
	2019	1,217	0.55	0	1
	2020	454	0.21	0	1

Table 1.3: Regression Output of Farmer Characteristics, Farm Characteristics, and Flock Characteristics on Comparative Efficiency Scores of Rwanda Small-Scale Chicken Farms

Variable	Parameter	Bootstrap Standard Error	P-Value
Male	-0.0065	0.0034	*
Farmer Age	-0.0008	0.0003	**
Farmer Age*Family Size	0.0002	0.0001	**
Family Size	-0.0176	0.0027	***
Family Size^2	0.0012	0.0003	***
Elevation (Km)	-0.1012	0.0086	***
Distance from Another Farmer (Km)	0.0142	0.0109	
Flock Number 2	-0.0194	0.0070	**
Flock Number 3	-0.0270	0.0075	***
Flock Number 4	-0.0066	0.0072	
Flock Number 5	0.0132	0.0078	*
Flock Number 6	-0.0136	0.0081	*
Flock Number 7	0.0013	0.0108	
Flock Number 8	0.0322	0.0110	**
Flock Number 9	0.0353	0.0124	**
Flock Number 10	0.0503	0.0188	**
Flock Number 11	0.0695	0.0388	*
Harvest Month			
February	-0.0054	0.0068	
March	0.0224	0.0077	**
April	-0.0079	0.0087	
May	-0.0155	0.0090	*
June	-0.0145	0.0104	
July	-0.0235	0.0088	**
August	-0.0161	0.0095	*
September	-0.0520	0.0083	***
October	-0.0640	0.0095	***
November	-0.0186	0.0086	**
December	0.0179	0.0078	**
Harvest Year			
2017	0.0318	0.0154	**
2019	0.0066	0.0060	
2020	0.0443	0.0085	***

Note: ***p <0.01; **p<0.05; *p<0.10

Table 2.1: Protein Composition of Camelina and Soybean Meals

	Crude Protein %			
	Mean	St. Dev.	Min	Max
Camelina Meal	0.357	0.025	0.313	0.411
Soybean Meal	0.495	0.017	0.441	0.549

Source: (Feedipedia, 2020a, 2020b)

Table 2.2: Mean Results from Linear Programming Model of 5000 Iterations for Camelina Meal Usage in Broiler Finisher Feed

Key Output Variables	Unit	Mean Model Output							
Percentage of Soybean Meal Price	%	99%	90%	80%	70%	60%	50%	40%	30%
Price of Blend Meal	USD	63.71	61.73	59.70	56.80	52.88	50.13	47.86	44.98
Price for Additional Soybean Meal[1]	USD	0.25	0.21	0.29	0.09	1.13	2.20	1.80	0.33
Total Price of Meal	USD	63.96	61.94	60.00	56.89	54.00	52.33	49.67	45.32
Camelina Meal Quantity	KG	62.53	68.38	65.85	74.23	86.34	86.27	83.71	84.63
Soybean Meal Quantity	KG	137.47	131.62	134.15	125.77	113.66	113.73	116.29	115.37
Additional Soybean Meal Quanity[1]	KG	0.77	0.65	0.91	0.29	3.53	6.87	5.65	1.05
Total Soybean Meal Quantity	KG	200.77	200.65	200.91	200.29	203.53	206.87	205.65	201.05
Missing Protein	KG	0.00	0.00	0.00	0.00	0.35	2.38	1.55	0.00
Protein Quantity	KG	88.55	88.74	89.07	88.97	87.85	85.82	86.65	89.51
Blend Price	USD/KG	0.32	0.31	0.30	0.28	0.26	0.25	0.24	0.22
Camelina Protein %	%	37%	36%	32%	35%	36%	36%	36%	37%
Soybean Protein %	%	48%	49%	51%	50%	50%	48%	48%	50%
Blend Protein %	%	44%	44%	45%	44%	44%	43%	43%	45%

[1] The additional kgs of soybean meal represent the penalty for the soft constraint to help bring protein to necessary levels.

Table 2.3: Best Iteration Results from Linear Programming Model of 5000 Iterations for Camelina Meal Usage in Broiler Finisher Feed

Key Output Variables	Unit	Best Trial Model Output							
Percentage of Soybean Meal Price	%	99%	90%	80%	70%	60%	50%	40%	30%
Price of Blend Meal	USD	63.70	61.60	59.40	56.31	51.13	47.94	44.74	41.54
Price for Additional Soybean Meal[1]	USD	0.00	0.00	0.00	0.00	1.44	2.68	2.32	0.48
Total Price of Meal	USD	63.70	61.60	59.40	56.31	52.57	50.61	47.05	42.02
Camelina Meal Quantity	KG	65.76	72.43	70.62	79.26	100.00	100.00	100.00	100.00
Soybean Meal Quantity	KG	134.24	127.57	129.38	120.74	100.00	100.00	100.00	100.00
Additional Soybean Meal Quanity[1]	KG	0.00	0.00	0.00	0.00	4.51	8.37	7.25	1.50
Total Soybean Meal Quantity	KG	200.00	200.00	200.00	200.00	204.51	208.37	207.25	201.50
Missing Protein	KG	0.00	0.00	0.00	0.00	2.25	4.02	3.50	0.75
Protein Quantity	KG	88.20	88.20	88.20	88.20	85.95	84.18	84.70	87.45
Blend Price	USD/KG	0.32	0.31	0.30	0.28	0.26	0.24	0.22	0.21
Camelina Protein %	%	37%	36%	32%	35%	36%	36%	36%	37%
Soybean Protein %	%	48%	49%	51%	50%	50%	48%	48%	50%
Blend Protein %	%	44%	44%	44%	44%	43%	42%	42%	44%

[1] The additional kgs of soybean meal represent the penalty for the soft constraint to help bring protein to necessary levels.

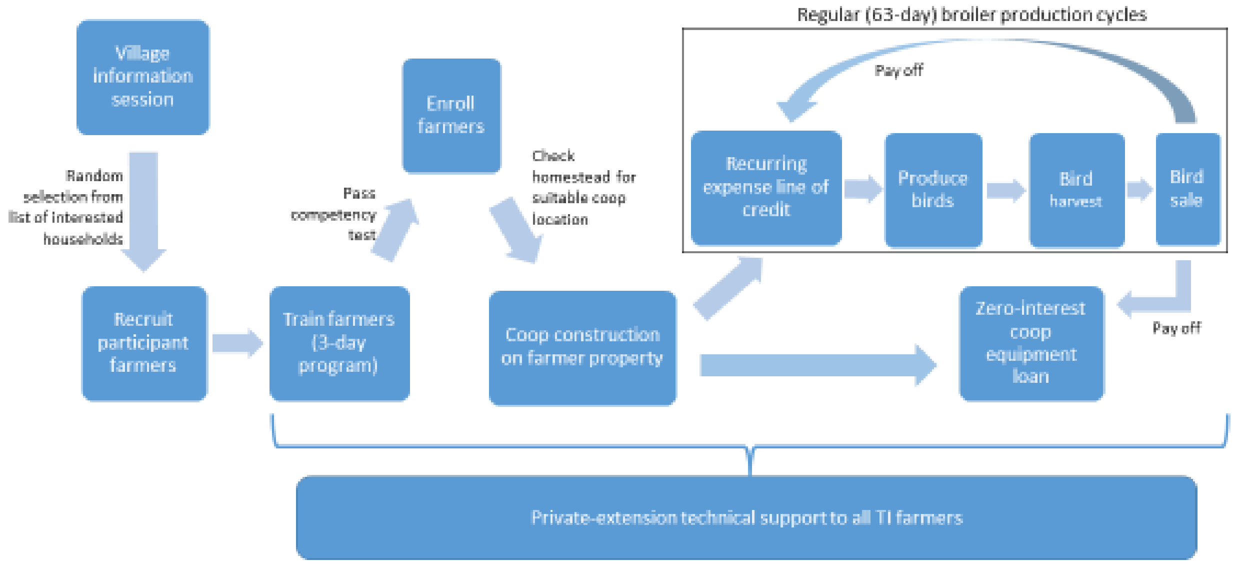

Figure 1.1: Tworore Inkoko, Twunguke Smallholder Broiler Production Model (Gill et al., 2020)

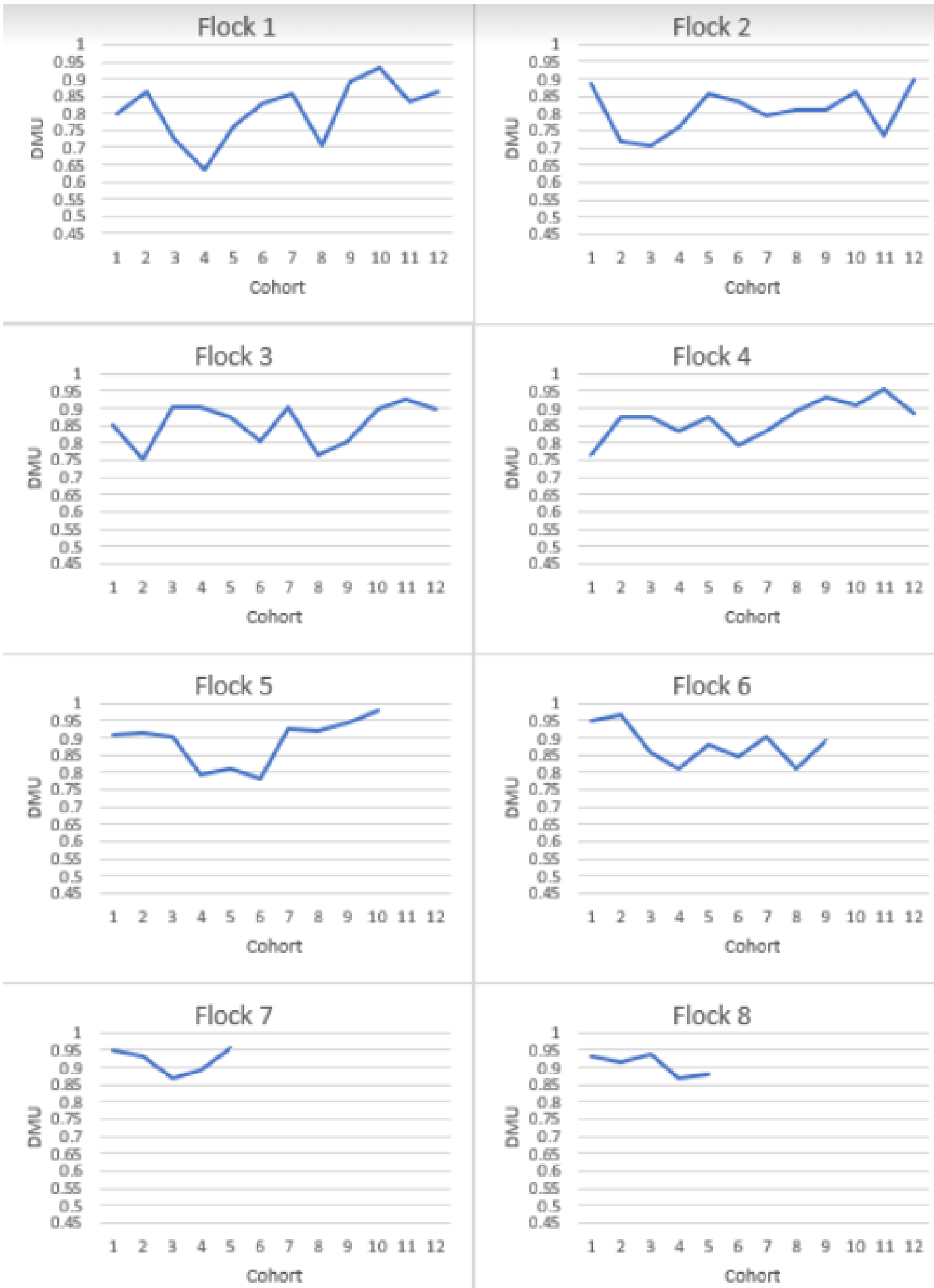

Figure 1.2: Comparative Efficiency Averages from Data Envelopment Analyses Estimated with Flocks Held Constant for Rwandan Small-Scale Broiler Production 2017-2020
NOTE: Due to data envelopment analyses estimation methods, graphs cannot be compared among one another by values, only by patterns.

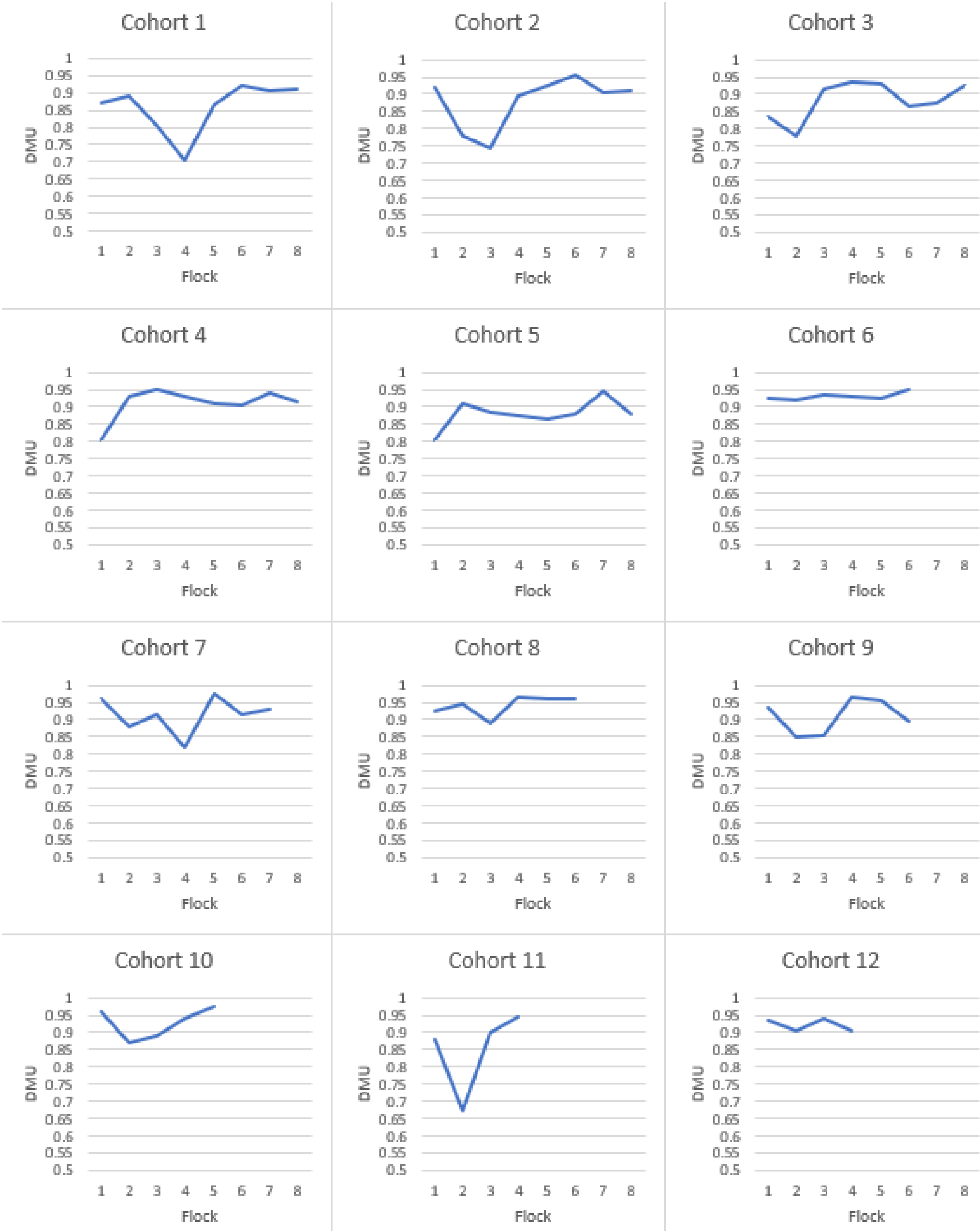

Figure 1.3: Comparative Efficiency Averages from Data Envelopment Analyses Estimated with Cohorts Held Constant for Rwandan Small-Scale Broiler Production 2017-2020
NOTE: Due to data envelopment analyses estimation methods, graphs cannot be compared among one another by values, only by patterns.

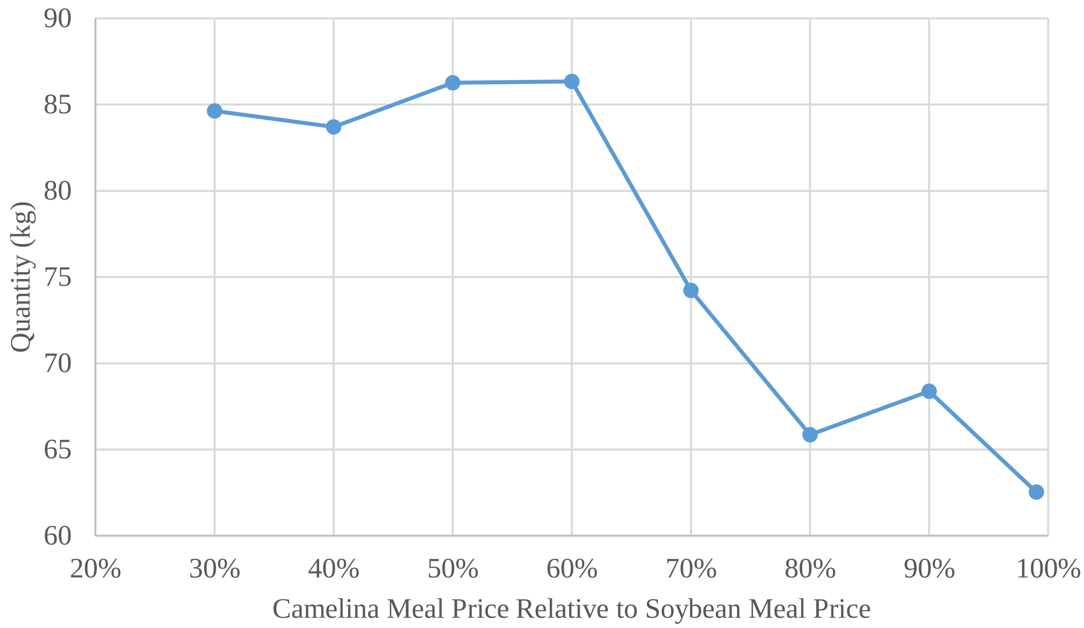

Figure 2.1: Mean Optimal use of Camelina Meal at Relative Price Points to Soybean Meal in a 1,000 KG Broiler Finisher Diet

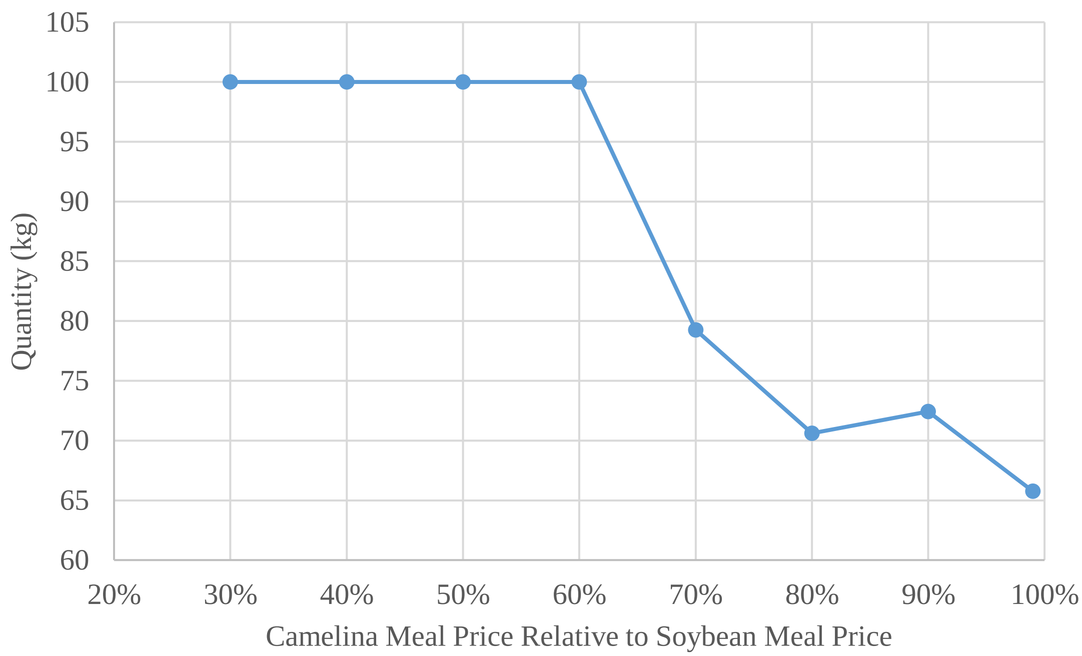

Figure 2.2: Best Iteration of Camelina Meal use at Relative Price Points to Soybean Meal in a 1,000 KG Broiler Finisher Diet

VITA

Ty Madison Wolaver is from Fayetteville, TN and graduated from Lincoln County High School in 2015. He graduated *cum laude* from The University of Tennessee in 2019 with a Bachelor of Science in Agricultural and Resource Economics with a major in Food and Agricultural Business, a concentration in Finance and Risk Management, and a minor in Business Management. He interned with the Country Music Association in the summer of 2016 and for Perdue Farms as a plant intern in the summer of 2017 and a flock advisor intern in the summer of 2018. Upon completion of his master's thesis, he will begin working with The University of Tennessee Extension as a Farm Area Specialist in East Tennessee providing farmers with assistance with their financial well-being and farm management.