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A Comparative Analysis of Feed and Environmental Factors on Broiler Growth in the United States

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A Comparative Analysis of Feed and Environmental Factors on Broiler Growth in the United States

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Abstract

Broiler production in the United States has become an important industry within the last half century. As the demand for poultry continues to increase and the concern of climate change also increases, it will become an important part of the industry to become more sustainable.

This study uses a feed optimization model, a broiler growth model, and a life cycle assessment (LCA) to determine how feed ingredients and the barn environment can affect the broiler's growth and production emissions. A multi-criteria ration optimization model is used to produce feeds based on carbon footprint and cost. A growth model is used to simulate a broiler's growth in different barn conditions and with different types of feeds. The models require additional work and the study did not produce that would be alter broiler production considerably.

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List of Abbreviations

AP	Acidification Potential
AR	Arkansas
CH_4	Methane
CO_2-eq	Carbon dioxide equivalent
CP	Crude Protein
CW	Carcass weight
DE	Digestible energy
DM	Dry matter
ECO	Ecotoxicity
EF	Emission Factor
EP	Eutrophication Potential
FCR	Feed conversion ratio
FEU	Fossil Fuel Depletion
GA	Georgia
GHG	Greenhouse gas
GWP	Global Warming Potential
K	Potassium
KPI	Key Performance Indicator
LCA	Life cycle assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LW	Live weight
m^2a	land occupation unit (square meter years)
ME	Metabolized energy
N	Nitrogen
N-EX	Nitrogen excreted
NC	North Carolina
NH_3	Ammonia
N_2O	Nitrous oxide
N-Vol	Volatilized nitrogen
P	Phosphorous
RH	Relative Humidity
TAM	Typical average animal mass
US	United States

I. Introduction

A. Background

Broiler production has become an important agricultural business in the United States (US). In the 1940's, the business began to grow following the USDA launch of quality assurance, the vertical integration of feed mills, hatcheries, farms and processors, and the emergence of refrigeration systems in the average American home. In 1985, Americans began consuming more chicken meat than pork and by 1992 chicken consumption eclipsed beef consumption (NCC). As of 2016, US produced 20.7 percent of the world's broiler meet (18,690 thousand metric tons). Of that amount, 83.7 percent of the meat was consumed domestically. The remaining 3,128 thousand metric tons of meat was exported (27.5 percent). Only Brazil exports more broiler meat than the US with 4,385 thousand metric tons (38.56 percent) (USDA, 2017). Today's broiler industry provides nutritious, high quality, and affordable chicken meat to both domestic and international consumers. To meet these growing demands, producers must continue to improve their production process. The products are continually improved by conducting research to analyze what effects broiler growth and how production can be improved. Recently, advancements have been made to improve barn ventilation and temperature controls, genetic selection programs, and bird pharmaceuticals. This research aims to provide a useful source for producers to determine how feed and environmental factors effect broiler growth and the production process.

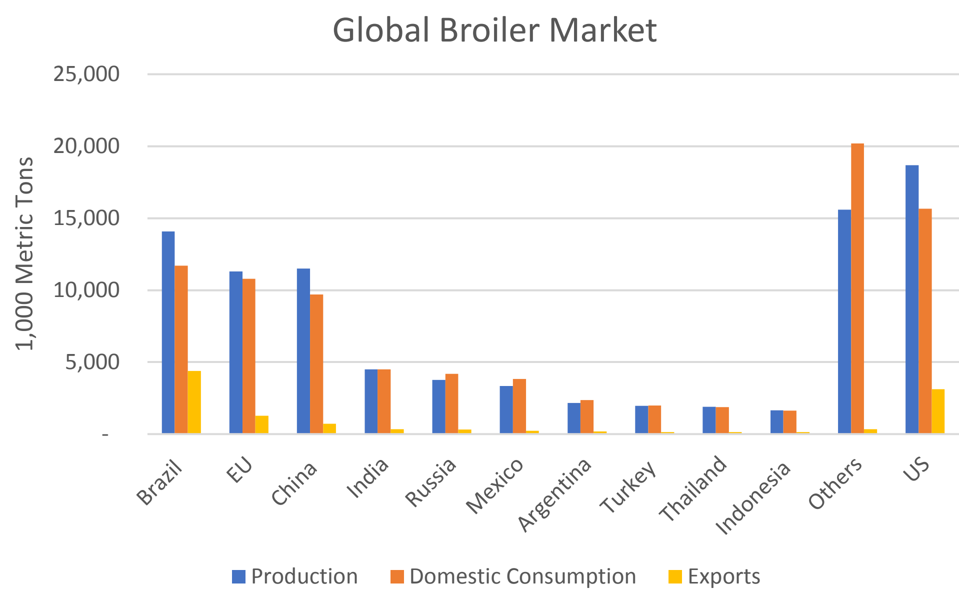


Figure 1. World broiler production, domestic consumption, and exports presented by country in 2016 (USDA, 2017).

The atmosphere contains greenhouse gasses (GHG) that trap heat and keep the planet warm enough to support life. Over the past two hundred years, the Earth's surface temperature has increased by an estimated 0.85°C (Stocker, 2013). Although the increase may appear small, the change has an impact on the world's climate and weather. The Intergovernmental Panel on Climate Change concluded in 2013, "That it is almost certain (95% confidence interval) that human influence on climate caused more than half of the observed increase in global average surface temperature from 1951 to 2010 (IPCC, 2013)." As a result of international research and the conclusions made by this panel, there has been an increased interest in developing new technologies and adapting current technologies to reduce environmental impacts in industry.

One method used to improve production methods and identify environmental impacts is life cycle assessment (LCA). LCA is a quantitative method that is used to assess the potential environmental impacts related to a process or product over the course of its life. LCA can be used in conjunction with other models to predict the behavior of a variety of production cycles, including agricultural ones. For this study, a feed optimization model and broiler growth model were used to examine broiler growth and the production process's impacts on the environment. The first model is a multi-parameter feed optimization model (Burek, 2017), which will be used to determine the optimal feed given a set of nutrition parameters required for broiler growth. These values include key parameter indicators for the feed ingredients, the nutrients contained in each feed ingredient, the minimum and maximum amount of each ingredient, and the minimum of each nutrient required for broiler growth. The model and the required parameters are discussed further in the methods section of this report.

The broiler growth model is used to determine how feed and environmental conditions affect broiler growth This model is a growth model adapted from the INAVI model (Méda, 2015), which is used to simulate broiler growth as a function of nutritional and environmental parameters. The animal is simplified to an energy balance, which examines the relationship between feed intake and the outputs of the bird. Metabolizable energy intake (MEI) is the amount of energy available from the feed consumption. This energy is used for physical activity, body maintenance, bird growth, and heat. The amount of energy used by each of these is estimated mathematically based on experiments outlined in the book, *Nutritional Modelling for Pigs and Poultry* (Méda, 2015). The results from the multi-criteria feed optimization model are used to for the feed variable inputs, which include ME, crude protein (CP), potassium content, and phosphorus content. The model also simulates the effect of the barn's environment, such as temperature, humidity, and airspeed, on the broiler's growth. These inputs were developed from various industry standards.

This study aims to use LCA, along with the multi-criteria ration optimization and growth models, to determine the best conditions for broiler growth. The report will examine a variety of factors that will affect the growth of the bird, as well as the impact of the broiler's production process on the environment.

B. Scope of the Thesis

The goal of this study is to determine the conditions that provide the largest broiler, with the smallest environmental impact, using a multi-model approach. The study creates optimized rations based on carbon footprint and cost, uses the rations and environmental factors to predict the broiler's growth, and asses the environmental impacts associated with the production of the broiler using LCA.

C. Outline of the Report

This report contains five sections, including this introduction section. Section two contains the literature review conducted on relevant reference materials, such as other LCA's and broiler studies. The literature review was used to develop the model scenarios, create the broiler LCA, and to compare this study's results. The next section of the report contains the methods used for the analysis. The methods section provides an overview of scenario development, model inputs, and other material required for the study. Section 4 contains the discussion of the results for the two models and LCA. The final conclusions and further recommendations can be found in section 5. The appendices of this report contain relevant data tables and graphs.

II. Literature Review

A literature review was conducted for material related to the factors that affect broiler growth and recent LCA studies conducted on broiler production processes. Broiler growth is affected by both the feed it consumes and the environment of the barn it grows in. First, a review of other broiler growth studies and LCA's was conducted to determine what aspects of feed can increase or decrease the bird's growth rate. Animal feeds typically come in two different forms, mash and pellet. A mashed feed is finely ground and mixed to prevent the birds from separating the different ingredients. Pellet feeds are mechanically pressed mash into dry pellets. Many studies have been conducted to determine how the feed form and the particle size affect the broiler's growth. Through a variety of studies (Nir, 1995; Engberg, 2002; Svihus, 2004; Amerah, 2007; Zang, 2012; Ly, 2015), it has been determined that feed particle size has little effect on a broiler's growth performance and that pelleted diets typically show improved growth in broilers. Therefore, particle size will not be included in this analysis.

The amount of metabolizable energy and crude protein can also have a strong relationship with the broiler's body weight. A study was completed to assess dietary crude protein (CP) and metabolizable energy (ME) concentrations for optimum growth performance of French New Guinea broilers (Nahashon, 2005). It was observed that as the broiler ages, it requires less metabolizable energy and more crude protein to promote growth. Another study (Leeson, 1996) was conducted to record the broiler's response to diet energy. For birds that consumed the diets ad libitum, it was observed that the bird had a good ability normalize its energy intake. For diets manually controlled, it was observed that a decrease in metabolizable energy or increase in protein intake can lead to more carcass fat in the birds.

The broiler's feed is not the only factor that effects the growth of the broiler. The temperature and humidity of the barn also effects the broiler production. Most of the basic studies involving temperature and humidity's influence on broiler growth were conducted about 30 years ago. In many studies, heat stress was observed to cause decreases in the broiler's growth (Dale and Fuller, 1980; Dokoh, 1989; May and Lott, 1992; Hacina, 1996; Abu-Dieyeh, 2006).

The high temperatures caused physiological changes in the birds, such as a lower metabolic rate. This causes a decrease in feed consumption (Pyne, 1966) and poor digestion (Har, 2000; Bonnet, 1997).

Reviewing past life cycle assessments is important to compare the results of this study. Many LCA's have been conducted, but many of them were not conducted for broiler production industry or for broiler production outside of the United States. One study was conducted to determine the environmental burdens of 3 broiler systems in the United Kingdom (UK). The three modelled broiler systems were standard indoor, free range and organic. The standard indoor system had the highest GWP (1.11kg CO_2e), pesticide use, and acidification potential (4.5 kg SO_2e). The environmental burden for the soybean meal contributed most to the GWP for the standard and free range diets (Leinonen, 2012). A global assessment of greenhouse gas emissions from pig and chicken supply chains was conducted by MacLeod in 2013 (MacLeod, 2013). The cradle to retail study produced results as a kg of CO_2eq of kg CW or kg of CO_2eq of protein. For poultry, feed production makes up 57 percent of the emissions. The next highest category of emission was manure storage and processing with 11 percent. The average emission intensity was 5.4 kg CO2e per kg CW. The authors recommend a reduction of land use change, increased efficiency of crop production, and improving the efficiency of energy use on the farm to decrease GHG emissions.

Nathan Pelletier conducted an LCA to predict the environmental impacts of the material and energy inputs and emissions along the broiler supply chain in the United States. The cradle-to-farmgate LCA had a functional unit of one live ton of broiler poultry. The assessment showed that feed accounted for 82 percent of the greenhouse gas emissions, 96 percent of the acidifying emissions, and 97 percent of the eutrophying emissions. The feed ingredient that contributed most in all the impact categories was corn. Corn contributed to 70 percent of the feed by mass and 41 percent of the impact categories. Soybean meal was the second largest contributor with 20 percent of feed by mass and 12 percent of the impact categories. Poultry meal and poultry fat were the third largest contributor with 7.5 percent of the feed by mass and 41 percent of the impact categories. Even though the poultry meal and fats are used in small quantities they have an unbalanced amount of the environmental burden (Pelletier, 2008). A retrospective conducted at the University of Arkansas compares United States poultry production in 1960 and 2010. The broiler production process produced 1280 kg CO_2 eq/1000 kg LW, 45.75 kg SO_2 eq/1000 kg LW, and 21.00 kg N eq/1000 kg LW. The broiler feed contributes the most to GWP and eutrophication in both scenarios. The GWP for 1960 and 2010 are 75 percent and 66 percent respectively. The broiler barn contributes the most to the acidification potential with 69 percent in 2010 and 60 percent in 1960 (Putman, 2017). The broiler bar consists of the utilities (electricity, heating fuel, water) and wood shavings for liter.

I Methods

A. Multi-Criteria Ration Optimization Model

A ration optimization model developed at the University of Arkansas optimizes pork diets based on cost, carbon footprint, water footprint, and land footprint (Burek, 2017). The tool uses two separate Matlab scripts to estimate the optimum ration based on specified key performance indicators (KPI's). The two scripts are designed to complete a least-squares regression analysis and Pareto multi-objective optimization for the defined parameters. These parameters include the cost and carbon footprint of each feed ingredient, the lower nutrient limits for each ingredient, the amino acids and nutrients provided by each ingredient, as well as the minimum and maximum amount of each ingredient in the feed. The scripts were modified for a three-phase broiler diet (starter, grower, finisher) to provide a variety of diets based on carbon footprint and cost. These diets will be compared to rations provided by the Commercial Poultry Nutrition textbook (Leeson and Summers, 2009).

Prior to the use of the optimization model, the feed ingredient and nutrient data for poultry feeds must be collected to constrain the outcomes to required limits. The user has to provide the ingredients of the ration, as well as the minimum and maximum percentage of each ingredient. The amount of metabolizable energy, calcium, phosphorous, amino acids, and trace nutrients are provided for each ingredient based on database values (NRC, 2015). The key performance indicators (KPIs) such as cost, carbon footprint (kg CO_2/100 kg dry feed), water footprint (m^3/kg dry feed), and land footprint (m^2a/kg dry feed), must also be provided. For this study, those values were collected from the National Research Council (NRC, 2015). The lower nutrient limits, or nutrient minimums, are used to ensure the bird receives the minimum amount of nutrients for bird's body to maintain itself and for physical activity. The amount of each nutrient within the feed must be calculated for metabolizable energy, calcium, phosphorus, amino acids, and trace nutrients. A variety of lower nutrient limits were collected for this study from (Leeson and Summers, 2009; Cobb 2012; Ross, 2014; Hubbard, 2016).

Following the collection of the necessary ingredient and nutrient data, the program can be run. The first script completes a least-squares regression analysis for each of the desired KPI's. The script formulates diets for a single objective linear model by varying the ration's ingredients based on the provided minimums and maximums. It formulates diets for each of the single objectives, or KPI's and minimizes the squared errors. For this study, only cost and carbon footprint were used. The next step is to run the Pareto multi-objective optimization. This optimization changes the ration results by increasing at least one of the KPI's. The final set of solutions includes various ration formulations. Each of these solutions is based on various trade-offs between the optimality criteria.

i. Scenario Selection

In this study, the type of feed ingredients in the ration will remain constant. Therefore, the cost per kg, carbon footprint, and nutritional content of each feed ingredient will remain the same in the ration optimization model. However, the lower nutrient limits and maximum feed ingredient for each scenario will change. Seven scenarios were developed: four scenarios were produced based on literature sources (4-7) and three scenarios were experimental (1-3). Feed 4 contains data from the Commercial Poultry Nutrition textbook. The textbook proposes different types of feeds based on the desired amount of nutrients and feed ingredients. For this study, the high nutrient broiler ration containing corn and meat meal. Other rations presented by the textbook feature wheat and sorghum based rations. The corn based ration was selected sorghum is less available and wheat is more expensive than corn. Feeds 5- 7 are based on the Hubbard, Cobb, and Ross production manuals respectively (Hubbard, 2016; Ross, 2014; Cobb, 2012). The remaining three scenarios (1-3) are theoretical feeds developed based on the results of feed 4-7.

Table 1. Feed scenario numbers and the literature source they were developed from.

Feed Scenario	Source
1	Experimental
2	Experimental
3	Experimental
4	CPN, 2008
5	Hubbard, 2016
6	Cobb, 2012
7	Ross, 2014

B. INAVI Based Broiler Growth Model

As discussed in the introduction, a growth model was developed to simulate a broiler's growth as a function of nutritional and environmental parameters. These parameters include environmental variables, such as temperature, humidity, and airspeed, and feed variables, including ME, CP, phosphorous (P), and potassium contents (K). The Excel ® based model contains calculations outlined in Nutritional Modelling for Pigs and Poultry (Meda 2015). The author discusses how the growth model will simulate the amount of feed required and the amount of ME available for growth.

The amount of ME available for growth (MEdc) is determined by subtracting the ME required for maintenance requirements (MEm) and the bird's physical activity (EPA). MEm is calculated using equation 1, where IM is index of maintenance and BW is the bird's body weight.

$$MEm = IM \ x \ BW^{0.75} \qquad \text{(EQ.1)}$$

The physical activity of the bird (EPA) is dependent on the bird's activity level (PAL), the energy consumption per gram of body weight (AU), and the bird's body weight.

$$EPA = PAL\ x\ AU\ x\ BW \qquad \text{(EQ.2)}$$

PAL, or the percentage of time the bird is active, is estimated by subtracting an activity factor (AF) from the initial PAL. The authors presented a fixed value of 1.5 kcal per percent PAL per gram of body weight based on experimental data. Once MEdc is estimated, the amount of energy deposited in the broiler's tissues (NED) can be determined. The amount of energy is associated with the efficiency of the deposition (Ed), which was be estimated to be approximately 0.60 based on experimental observations.

$$NED = MEdc\ x\ Ed \qquad \text{(EQ.3)}$$

The weight gain of the bird can be estimated as the ratio of lipid and protein energy deposited to the total energy deposited in the tissue. The total body weight can then be calculated by adding the bird's gains to the initial body weight.

$$Gain = NED/Ved \qquad \text{(EQ.4)}$$

VED is dependent on the bird's body weight and after experimental observation, it was noted that the relationship was not linear. Based on a linear regress completed by Meda, using the data presented in Gous et al. (1999), the relationship found to be represented by equation 5.

$$VED = 1.56 + 0.63\ X\ BW^{0.6} \qquad \text{(EQ.5)}$$

To account of genetic variations in fattening and protein deposition a genetic factor (Feg) was created to modify VED based on different body compositions.

Using the Cobb broiler management guide (Cobb, 2012), reference data was collected at the reference conditions. This data was used to fit the experimental data by using the Excel ® solver function to minimize the difference between calculated final body weight and observed final body weight at the reference conditions. The calibration parameters that were adjusted were IM, AF, and Feg.

Another parameter briefly mentioned in the text book is prehensibility. Prehensibility is used to demonstrate the feed's ease of intake and is dependent on the first limiting essential amino acid. For this study, the percent of the first limiting essential amino acid remain constant for all scenarios and phases of growth.

The textbook also discusses environmental parameters that can affect the broiler's growth. The main parameter is thermolysis capacity. Thermolysis capacity is the dispersion of bird's body heat. It is calculated by finding the difference in MEI and Ved, or the heat produced by the bird (HP). The thermolysis capacity can then be determined using equation 6.

$$Thermolysis\ Capacity = HP/BW^{0.75} \qquad \text{(EQ. 6)}$$

The thermolysis capacity is used to determine the thermostat, or the thermal balance of the bird regarding the standard. The thermostat is applied to make correction to the MEI based on the body temperature of the bird. The corrected MEI is applied to the next day of growth.

$$Thermostat = \int HP - Thermolysis\ Capacity\ X\ BW^{0.75} \qquad \text{(EQ.7)}$$

The environmental and feed variables are entered into the simulation table (figure 1). The environmental variables are selected based on recommendations from industry standards (Cobb, Hubbard, Ross). The feed variables are developed using the rations produced by the optimization model. The feed model provides rations and ingredient proportions for each scenario. These proportions are used to calculate ME, CP, K, P, and N for each phase of the feeds. These values the addition of each ingredients contribution for the feed's total property. ME is used as an example in equation 8.

$$Ration\ ME = \int Ingredient\ Contribution\ (\%)\ x\ ME\ Ingredient \qquad \text{(EQ.8)}$$

Feed Variables (User Inputs)		
Variable	Units	Value
Phase 1:		
Number of Days		10
1st Limiting EAA	%	100
Fine Particles	%	0
ME Content	kcal/kg	3035
Crude Protein	%	22%
ME:CP	kcal/%CP	141.1628
Phosphorus Content	%	0.45%
Potassium Content	%	1.00%
Phase 2:		
Number of Days		11
1st Limiting EAA	%	100
Fine Particles	%	0
ME Content	kcal/kg	3107
Crude Protein	%	20%
ME:CP	kcal/%CP	159.3333
Phosphorus Content	%	0.42%
Potassium Content	%	0.94%
Phase 3:		
Number of Days		19
1st Limiting EAA	%	100
Fine Particles	%	0
ME Content	kcal/kg	3179
Crude Protein	%	19%
ME:CP	kcal/%CP	171.8378
Phosphorus Content	%	0.38%
Potassium Content	%	0.86%

Environmental Variables (User Inputs)		
Variable	Units	Value
Phase 1:		
Number of Days		10
Indoor Temperature	C	34
Animal Density	kg/m2	42
Humidity	%	40
Airspeed	m/s	0.15
Phase 2:		
Number of Days		11
Indoor Temperature	C	31
Animal Density	kg/m2	42
Humidity	%	50
Airspeed	m/s	0.15
Phase 3:		
Number of Days		19
Indoor Temperature	C	24
Animal Density	kg/m2	42
Humidity	%	60
Airspeed	m/s	0.15

Figure 2. Growth model feed and environmental variable input interface in Excel ®. The variables were selected based on industry recommendations (Cobb, Hubbard, Ross) for broiler growth.

The Microsoft Excel ® growth model uses three variation tables to estimate the user-defined growth scenarios deviation from the Cobb standard for each phase (Figure 2). In the parameter column, there are several feed parameters (Ved, PAL, Ed, MEm, Prehensibility), as well as the environmental parameter, thermolysis capacity. For each of the parameters, a standard curve was developed based on the Cobb standard data (figure 2).

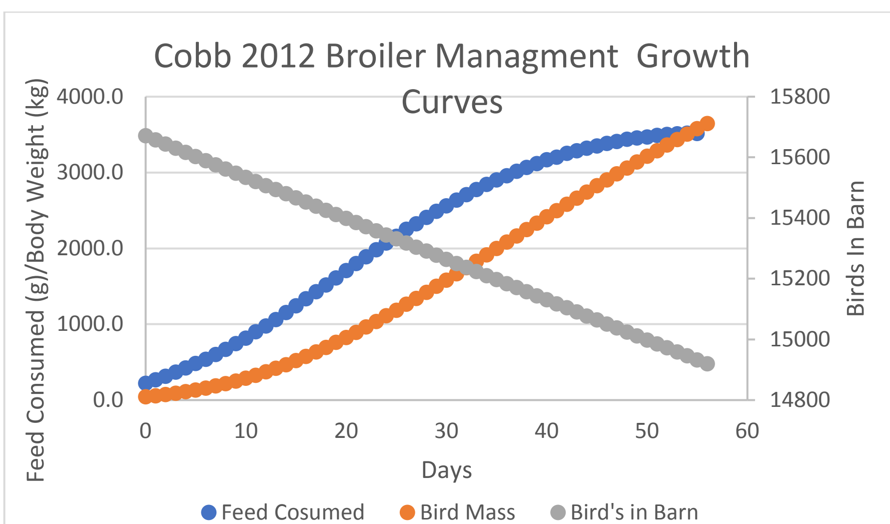


Figure 3. Feed consumed (g), body weight (g), and the number of birds in the barn provided by the Cobb 2012 Broiler Management guide.

The Microsoft Excel ® model uses linear interpolation to estimate the variation of the experimental scenarios from the Cobb standard. The variables, listed in figure 3, are interpolated based on the standard. These variables include 1st Limiting EAA, fine particles, ME, ME:CP, and Tp. As discussed earlier in this report, 1st limiting EAA and fine particles were not changed from the Cobb standard. Perceived temperature (Tp) is the temperature felt by the broiler in the barn and is based on temperature, humidity, and air speed. The total variation factor is calculated by multiplying the variation of each variable. The variation factor (VF) is used to demonstrate how the growth conditions influence the Ved.

	Phase 1					
Parameter	**1st limiting EAA**	**Fine Particles**	**ME Content**	**ME:CP**	**Perceived Temperature (Tp)**	**VF Product**
Ved	1		1	0.999965	1	**0.999965023**
Physical Activity Level (PAL)		1			1	**1**
Ed	1		1	0.999983	1	**0.999982512**
Mem					1	**1**
Thermolysis Capacity					1	**1**
Prehensibility	0.82					**0.82**

Figure 4. Microsoft Excel ® growth model variation table. The table uses linear interpolation to estimate the variation of the user input conditions from the Cobb standard. The VF product multiplies all the variable values (fine particles, ME, ME:CP, Tp, EAA) together for the variation estimation.

Depending on the composition and amount of feed consumed, the amount of litter, as well as P and K excretions will vary. The environment where the bird grows is also important to growth. If the temperature is too high or too low, the broiler will consume less feed and have less ME available for growth.

The amount of litter and nutrient excretions produced by the broiler will also vary under different feed conditions. For litter, the retention factor is a constant ratio of 0.6884 through the bird’s life. It is also dependent on the bird’s total feed intake, or the ratio of ME content to MEI simulated. The nutrient excretions for N, P, and K are calculated using a similar method. For N and K, the retention factor is constant throughout the bird’s life, and P decreases.

The feeds produced by the optimization model provide metabolizable energy, crude protein, phosphorus and potassium contents that can be used to estimate broiler growth. The metabolizable energy consumed by the bird will be used as the available energy for growth, activity, and the bird's maintenance. The phosphorus and potassium contents were used to predict the bird's excretions, or expelled waste matter. The environmental conditions will be used to estimate the bird's perceived temperature (Tp), or the actual temperature felt by the bird. Tp is calculated adding the effects of different factors to the indoor temperature. These factors include the animal's density, the barn's humidity, and the airspeed. For example, high airspeed will decrease the temperature felt by the bird.

i. Scenario Selection

The goal of this model is to simulate broiler growth at various environmental conditions and with a variety of different feeds to determine how they affect growth. The scenarios were developed based on current industry literature. The environmental scenarios were established based on industry management manuals provided by Cobb, Hubbard, and Ross (Cobb, 2012; Ross; 2014; Hubbard, 2016). The three manuals specify recommended temperatures, humidity, and airspeed ranges at various stages of the broiler's life. These ranges are recommended to maximize the broiler's growth and do not account for the time of day.

Scenarios have been developed from the three management manuals to determine the best growth conditions for the broiler. The scenarios vary temperature, relative humidity, and airspeed for the three phases to determine which conditions produce the largest broiler with the smallest food consumption, excreta production, and nutrient excretions. Tables 2-4 summarize the scenarios developed from the Hubbard, Ross, and Cobb broiler management guides (Hubbard, 2016; Ross, 2014; Cobb, 2012).

The temperatures and air speeds were selected based on the minimum and maximum values recommended by the management guides. For the humidity, a number within the suggested range was selected along with the minimum and maximum values. This method was used for all three growth phases and the three different management guides.

Table 2. Growth scenarios developed based on the Hubbard Broiler Management Guide (Hubbard, 2016) environmental recommendations.

Trial	Phase 1			Phase 2			Phase 3		
	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)
1	33	40	0.1	29	50	0.3	27	50	0.5
2	33	50	0.1	29	60	0.3	27	60	0.5
3	33	65	0.1	29	65	0.3	27	70	0.5
4	33	40	0.3	29	50	2.0	20	50	3.0
5	33	50	0.3	29	60	2.0	20	60	3.0
6	33	65	0.3	29	65	2.0	20	70	3.0
7	30	40	0.1	27	50	0.3	18	50	0.5
8	30	50	0.1	27	60	0.3	18	60	0.5
9	30	65	0.1	27	65	0.3	18	70	0.5
10	30	40	0.3	27	50	2.0	18	50	3.0
11	30	50	0.3	27	60	2.0	18	60	3.0
12	30	65	0.3	27	65	2.0	18	70	3.0

Table 3. Growth scenarios developed based on the Ross Broiler Management Guide (Ross, 2014) environmental recommendations.

Trial	Phase 1			Phase 2			Phase 3		
	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)
1	30.8	60	0.3	25.7	60	0.5	22.7	60	2.0
2	30.8	60	0.1	25.7	60	0.3	22.7	60	0.875
3	30.8	60	0.3	27.8	50	0.5	24.7	50	2.0
4	30.8	60	0.1	27.8	50	0.3	24.7	50	0.875

Table 4. Growth scenarios developed based on the Cobb Broiler Management Guide (Cobb, 2012) environmental recommendations.

Trial	Phase 1			Phase 2			Phase 3		
	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)
1	34	30	0.3	27	40	0.5	21	50	3.0
2	34	45	0.3	27	50	0.5	21	60	3.0
3	34	60	0.3	27	60	0.5	21	70	3.0
4	31	30	0.3	24	40	0.5	18	50	3.0
5	31	45	0.3	24	50	0.5	18	60	3.0
6	31	60	0.3	24	60	0.5	18	70	3.0
7	34	45	0.3	27	50	0.5	21	60	0.875
8	34	45	0.3	27	50	0.5	21	60	1.5
9	31	45	0.3	24	50	0.5	18	60	0.875
10	31	45	0.3	24	50	0.5	18	60	1.5

C. Life Cycle Assessment

i. General LCA Principles

Life cycle assessment (LCA) is widely accepted in many different industries, including agriculture, as a method to evaluate environmental impacts of production. The method is defined by the International Organization of Standardization (ISO) standards 14040 and 14044 (ISO, 2006a, b). LCA provides an assessment of a production process and measures the potential environmental impact of the product throughout its life cycle. For this method, a system boundary is chosen to determine the inputs and outputs related to the product. These inputs and outputs include energy, materials, and emissions associated with production. Then the process is evaluated for potential effects on human health and the environment.

Although LCA has proven to be a useful tool, there are a few challenges that should be noted, especially for the evaluation of agricultural processes. LCA is a data-intensive method, which requires generalization for complex food supply chains. There are also many different assumptions and methods commonly used in the LCA community, such as the type of system boundary, functional unit, allocation techniques, and impact assessment methods. These can affect the results of the study and make comparisons between two studies difficult. Agricultural systems also typically involve more than one output or product. For processes with more than one output, an allocation must be applied to assign burden to the different co-products.

ii. Functional Unit and System Boundary

The LCA completed in this study uses industry and literature data to approximate the average poultry production of a farm in the United States in 2015. In this assessment, the functional unit is one kg of live weight (LW) at the farm gate. The assessment includes a three-generation broiler production chain, from the feed production until the animal leaves the farm. Therefore, the system boundary for this LCA is cradle-to-farmgate. All post-farmgate aspects, such as transportation to the slaughterhouse, transport to the retail point, refrigeration during transport, and manufacture of the packaging, are not included in this study.

iii. Life Cycle Inventory

The LCA used in this study is an updated version of the 2010 broiler production LCA presented in the broiler production retrospective produced at the University of Arkansas (Putman, 2017). Some of the values were updated using more recent data, which is displayed in table 5. Average corn, wheat, and soybean crop data for the US, used in the bird's feed, have been updated using values from a separate corn retrospective project conducted at the University of Arkansas. The background unit processes, such as feed milling, transportation, electricity grid, tap water, liquefied petroleum gas, and wood shavings for bedding, were taken from the DataSMART database. These processes were applied, without modification, to the LCA.

Table 5. Inventory table to display the alterations made to the broiler retrospective (Putman, 2017) LCI.

Utility Use			
Broilers Produced – Kentucky	USDA NASS 2016	7,903,600	birds
Broilers Produced – Georgia	USDA NASS 2016	6,156,800	birds
Broilers Produced - Arkansas	USDA NASS 2016	1,784,700	birds
Parent Generation			
Hen Mortality	AA PS PO 2016	8.0	percent
Hen Spent Weight	AA PS PO 2016	3.86	kg
Pullet Weight	AA PS PO 2016	2.30	kg
Harvested Eggs	AA PS PO 2016	177	Eggs
Rooster Mortality	AA PS PO 2016	8.0	percent
Broilers			
Mortality Rate	NCC 2015	4.8	percent
Cycle Length	NCC 2015	48	days
Live Weight	NCC 2015	2.84	kg
Feed Conversion Ratio	NCC 2015	1.89	kg feed/ kg lw

iv. Allocation of Emissions Between Products and Byproducts

Agricultural processes are complex, and typically have more than one output for production processes. For example, a breeding hen will produce eggs, manure, and byproducts from slaughter. In LCA, allocation is required to distribute the burden of the GHG emissions to each of the co-products.

For the hen process, the outputs are the bird's litter, spent hens, and eggs, which are considered co-products. The litter can be classified as a co-product because it contributes revenue to the producer because it can be sold off. The allocation percentages are displayed in Table 6. The percentages were calculated using caloric energy as a basis. For this assessment, the co-products were allocated based on their caloric energy content. This method allowed for the materials and energy to follow the flow of caloric energy through both the ration and poultry production processes.

Table 6. Allocation of poultry outputs in LCA using approach outlined by LEAP (2015).

	Allocation percentages	
	Hens	*Broilers*
Eggs	50%	NA
Live weight	45%	91%
Litter	6%	9%

v. Life Cycle Impact Assessment

Individual impacts were assessed using the TRACI 2.0 methodology. The Tool for the Reduction of Assessment of Chemical and other environmental Impacts 2.0 (TRACI 2.0), allows the quantification of stressors that have potential environmental effects. These potential effects are divided into 10 impact categories (Bare, 2011). In this study, global warming potential (GWP), eutrophication (EP), acidification (AP), ecotoxicity (ECO), and fossil fuel depletion (FEU) for each scenario will be compared.

a. Global Warming Potential

Global warming potential (GWP) was developed to compare the global warming impacts of different gases (Myhre et al. 2013). The concentration of the greenhouse gases is measured as kg equivalents of CO_2, which is the relative GWP of a gas compared to CO_2. The larger the GWP, the more the given gas warms the earth compared to CO_2 over a specified time-period. (Bare 2011).

b. Eutrophication

Phosphates and nitrates can be beneficial in small amounts to the ecosystem. For example, plants use them as nutrients to live and grow. However, in excess they can cause a pollution called eutrophication (EP). Eutrophication stimulates the growth of algae that depletes the amount of oxygen in the water. Decreased levels of oxygen can lead to the death of plants and animals living in the water. Eutrophication potential is measured as kg equivalents of N, which is the relative EP in comparison to N (Bare, 2011). In broiler production, most of the nitrogen and phosphorus sources are related to growing the crops required for broiler feed.

c. Acidification

Acidification (AP) is the increasing concentration of the hydrogen ion (H^+) in the environment. This can be the result of adding substances that increase the acidity of the environment because of chemical reactions or biological activity (Bare, 2011). In the broiler production industry, acidity is effected by the ammonia emissions resulting from broiler emissions and crop production for feeds.

d. Ecotoxicity

Ecotoxicity (ECO) is the environmental toxicity. The emissions made by some substances, such as heavy metals, can have considerable effect on the environment. The assessment of this toxicity is based on the maximum concentrations in water for the ecosystem surrounding the farm (Bare, 2011). A majority of the heavy metals used in the broiler production process originate from fertilizers, herbicides, and other chemicals used to aid in crop growth for feed.

e. Resource Depletion – Fossil Fuels

Fossil fuel resource depletion, sometimes referred to as fossil energy use (FEU), is an energy use indicator for LCA's to demonstrate how energy intensive a process is. For broiler production, the amount of crude oil and gas is mostly used to produce feed crops.

IV. Results and Discussion

A. Multi-Criteria Feed Optimization Results

The feed optimization model provides twenty-one different feed compositions of varying carbon footprint and cost for each of the outlined scenarios. The model provides the amount of each feed ingredient (kg), the cost ($/100 kg of feed), and carbon footprint (kg CO2/ 100 kg feed) for each phase of the scenarios. The optimal feed for each scenario can be determined by identifying the intersection of the cost versus carbon footprint linear trends of the plots produced by the model (Appendix A). Table 6 displays the optimal feeds for each of the seven multi-criteria optimization scenarios. Appendix B contains the percentage of each ingredient in the optimal feed for each of the seven scenarios.

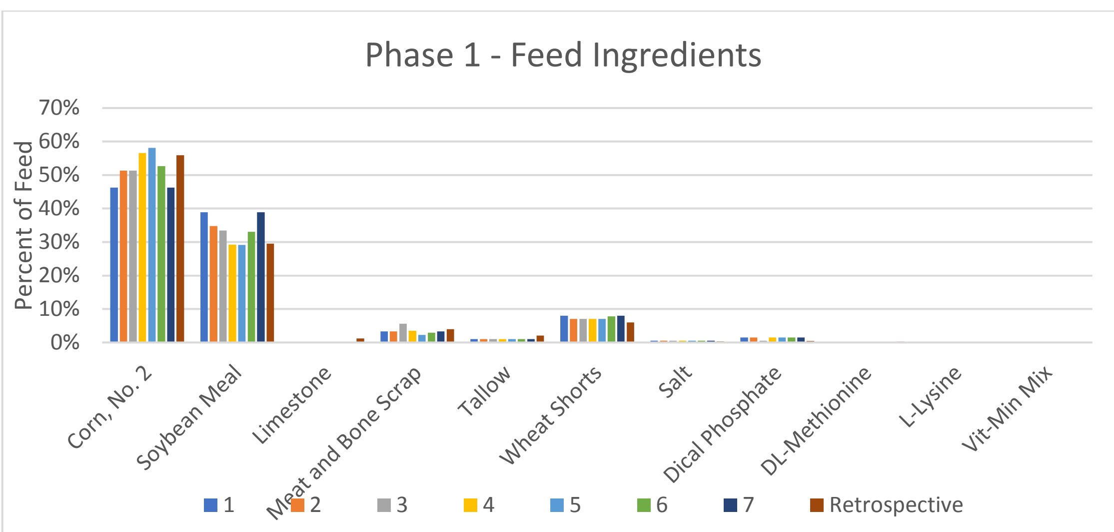


Figure 5. The phase 1 feed composition of each scenario produced by the multi-criteria feed optimization results (Appendix B).

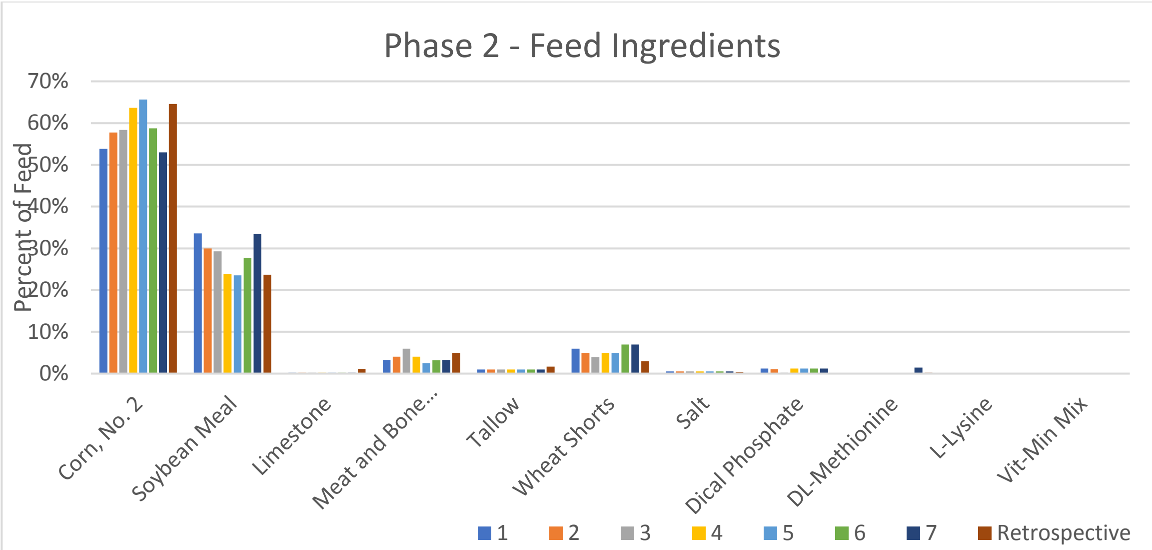


Figure 6. The phase 1 feed composition of each scenario produced by the multi-criteria feed optimization results (Appendix B).

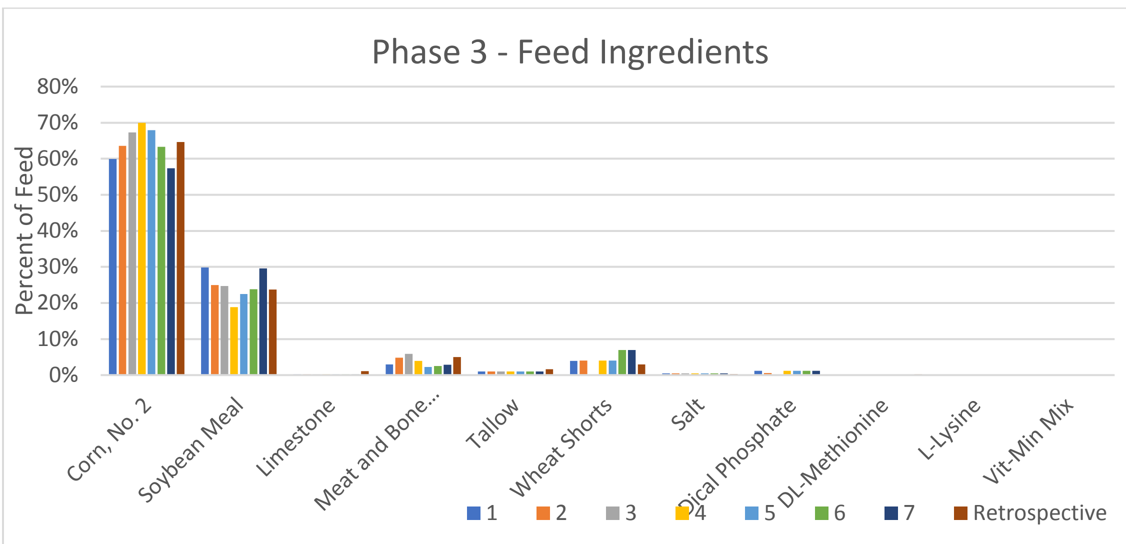


Figure 7. The phase 1 feed composition of each scenario produced by the multi-criteria feed optimization results (Appendix B).

Broiler rations are composed of many different ingredients, which can vary by producer because of cost, location, and type of bird. Typically, broiler rations have one main component that contributes at least 60% of the ration. Some of these include corn, wheat, and sorghum. For this study, corn based feeds are analyzed. For all seven scenarios, the rations are predominantly composed of corn grain (45-70%), soybean meal (18-40%), and wheat shorts (0-7%). This is consistent with the rations presented in the Commercial Poultry Nutrition textbook (Leeson and Summers, 2008), which present diets with approximately 60% corn, 3% wheat shorts, and 25% soybean meal.

As discussed in the methods section, the seven feed scenarios were developed based on the recommended nutrient content of several literature sources. The model uses data to provide a list of rations that will help the bird receive the specified amount of nutrients. The proportion of the feed ingredients is dependent on the nutrient specifications provided and the phase of growth. Baby chicks require more protein to promote rapid weight gain, therefore phase one of growth requires the largest proportion of soybean meal regardless of the feed scenario. Phases two and three contain the largest amount of corn across all seven scenarios. This occurs because the larger birds will require more energy to meet their maintenance requirements. Feed 5 contains the largest percentage of corn and small percentage of soybean meal in phases one and two. Feed 3 contains the largest amount of corn (69.94%) and the smallest amount of soybean meal (18.83%) in phase three. Feed 1 contains the largest amount of soybean meal in all three phases (38.87, 33.57, 29.88%). Feed 7 contains slightly smaller amounts of soybean meal and the smallest amount of corn in all three phases (46.29, 53.00, 57.35%).

Table 7. The cost ($/100kg of feed) and the carbon footprint (kg CO_2/100 kg of feed) for the optimal feed of each trial of the multi-criteria feed optimization model. The total cost and carbon footprint are estimated based on the amount of feed required for each phase.

Feed Number	Phase 1		Phase 2		Phase 3		Total	
	Cost ($/100 kg feed)	CF (kg CO_2/100 kg feed)	Cost ($/100 kg feed)	CF (kg CO_2/100 kg feed)	Cost ($/100 kg feed)	CF (kg CO_2/100 kg feed)	Cost ($/100 kg feed)	CF (kg CO_2/100 kg feed)
1	26.19	65.52	24.95	65.44	24.22	63.13	144734.81	376516.82
2	26.14	64.71	24.42	70.00	22.77	74.01	138105.46	426601.84
3	24.71	79.51	23.93	82.16	22.57	81.67	135920.25	481240.27
4	24.58	67.61	23.38	70.58	22.29	69.60	135473.64	410812.64
5	24.13	58.59	22.95	60.13	22.74	58.77	135029.71	348341.27
6	26.70	60.680	24.90	63.01	23.81	58.88	143233.12	353686.87
7	26.18	65.66	24.91	65.12	24.10	62.17	144205.90	372272.94

Table 8 presents the market price for each feed ingredient as of December 2016 (NCC, 2016). The amino acid DL-Methionine is significantly more expensive ($4.63/kg) than the other feed ingredients. Some of the other more expensive ingredients include the vitamin mix ($1.058/kg) and L-Lysine ($1.521/kg). The crop based ingredients, such as corn, soybean meal, meat and bone meal, and wheat shorts are significantly cheaper.

Table 8. Cost ($/kg dry) of each feed ingredient for the multi-criteria feed optimization model in decreasing order (NCC, 2016).

Ingredient	$/kg
DL-Methionine	4.630
L-Lysine	1.521
Vitamin Pre-mix	1.058
Dicalcium Phosphate	0.812
Tallow	0.485
Soybean Meal	0.350
Meat and Bone Meal	0.305
Limestone	0.198
Corn, No. 2	0.165
Wheat Shorts	0.143
Salt	0.060

Feed 1 has the highest cost for phases two and three, as well as the highest total cost. This feed contains the largest amounts of soybean meal with between 29.88 and 38.87 percent depending on the phase (Appendix B). The feed also contains some of the smallest amounts of corn (46.28 – 59.97 percent) and larger amounts of wheat shorts (3.98 – 7.99 percent) compared to the other feed scenarios. The most economical feed is the Hubbard scenario (feed 5), which contains the smallest proportion of soybean meal (22.50 - 29.12 percent). It also is composed of the large amounts of corn (58.07 - 67.94 percent) and wheat shorts (4.00 - 7.00 percent). Soybean meal is used in poultry feed because of its high protein and amino acid content (Leeson and Summers, 2009). Therefore, omitting or decreasing soybean meal significantly is not recommended.

Carbon footprint is the amount of greenhouse gases associated with the growth or production a product or process. For this study, the carbon footprint related to the broiler's ration is of interest. Table 9 provides the carbon footprint for each of the feed ingredients. The animal product and nutrient based ingredients have the highest carbon footprint. The crop based ingredients, such as corn, soybean meal, and wheat shorts, have lower carbon footprints.

Table 9. Carbon footprint (kg CO_2/kg dry) of each feed ingredient for the multi-criteria feed optimization model in decreasing order (NRC, 2016).

Ingredient	kg CO2/kg
Meat and Bone Meal	6.9000
L-Lysine	6.1800
Vitamin Pre-mix	5.4500
DL-Methionine	5.1300
Tallow	4.3800
Dicalcium Phosphate	1.4900
Soybean Meal	0.4000
Corn, No. 2	0.3700
Salt	0.2700
Wheat Shorts	0.2400
Limestone	0.0300

The Hubbard scenario (feed 5) produced the lowest carbon footprint feed for all three growth phases. This scenario contains the smallest percentage of meat and bone meal (2.24 – 2.29 percent), as well as higher percentages of crop based ingredients. Feed 3 contains the largest amount of meat and bone meal (5.60 – 5.93 percent) and produced the highest carbon footprint. Since the amount of DL-Methionine, L-Lysine, and vitamin mix are very small, typically less than 0.20 percent, their contribution to the carbon footprint is also very small. The amount of meat and bone meal in the feed is much greater. Therefore, this ingredient is the cause of the increased carbon footprint in the feeds.

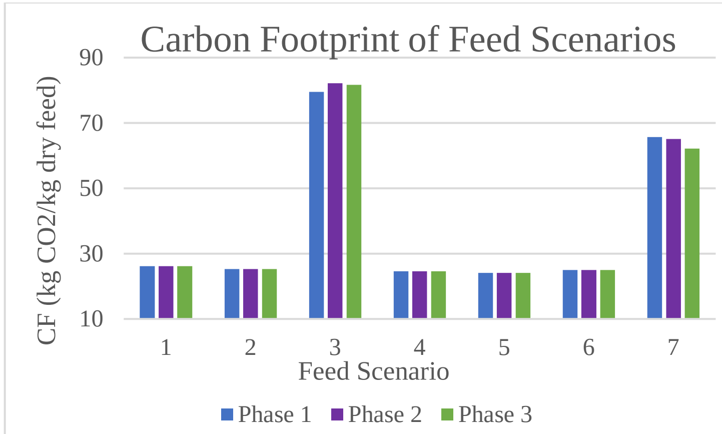


Figure 8. Carbon footprint (kg CO_2/kg dry feed) for each growth phase and all 7 feed scenarios from the multi-criteria feed optimization model.

B. Growth Model Results

i. Variable Feed Composition and Constant Environmental Variables

There are many factors that must be examined when choosing a feed for broiler production. Ideally, producers would like to use a low cost, low carbon footprint feed that results in large broilers with a high feed conversion ratio. As discussed in the previous section, it can be difficult to balance the carbon footprint, cost of the feed, and optimizing the broiler's growth performance. Adding the bird's growth environment and how the feed ingredients affect it, increase the difficulty of determining the best feed.

From a growth standpoint, the best feed produces large broilers with high feed conversion ratio, and the lowest excretions possible. The growth model determines the difference between the simulation ME:CP and the reference ratio. A linear relationship was developed based on the reference data from Cobb 2012. Using this line and the difference between the ratios, the variation in ME:CP is determined.

Table 10. Metabolizable energy, crude protein, phosphorous and potassium content for each phase of the seven ration scenarios based on the results produced by the multi-criteria ration optimization model. These values are used as inputs for the feed factors of the broiler growth model.

Scenario	Phase 1			
	ME	P	K	CP
1	3430.48	0.72%	1.11%	25.40%
2	3420.94	0.69%	1.03%	23.73%
3	3440.18	0.80%	1.01%	24.30%
4	3405.34	0.66%	0.93%	21.75%
5	3408.16	0.60%	0.92%	21.04%
6	3414.27	0.66%	1.00%	22.94%
7	3430.61	0.72%	1.11%	25.40%
Scenario	Phase 2			
	ME	P	K	CP
1	3433.79	0.67%	1.00%	23.20%
2	3425.74	0.68%	0.93%	22.05%
3	3448.64	0.77%	0.91%	22.63%
4	3405.32	0.64%	0.81%	19.77%
5	3410.19	0.56%	0.80%	18.88%
6	3410.64	0.64%	0.90%	20.99%
7	3427.9	0.68%	1.00%	23.22%
Scenario	Phase 3			
	ME	P	K	CP
1	3434.93	0.61%	0.91%	21.45%
2	3612.34	0.68%	0.83%	20.35%
3	3696.99	0.70%	0.79%	20.46%
4	3535.2	0.59%	0.71%	17.63%
5	3475.3	0.53%	0.77%	18.28%
6	3475.4	0.58%	0.83%	19.14%
7	3417.16	0.63%	0.93%	21.49%

The growth model was used to determine how the different environmental scenarios and rations developed from the literature sources affect growth. To evaluate the feed's effect on growth, the environmental conditions were held constant. The conditions were developed from the Cobb broiler management guide and use as the environmental reference (Cobb, 2012). The metabolizable energy, crude protein percentage, and phosphorus content for the feed variable reference conditions can be viewed in table 9. The feed variable inputs were based on the results from the multi-criteria feed optimization model. Using the Cobb standard, metabolizable energy, crude protein, phosphorus, and potassium content of each ingredient, the total content of each feed was calculated to use for the growth model inputs (Table 11).

Table 11. Feed variable reference conditions for the growth model based on the Cobb broiler management guide (Cobb, 2012).

Phase 1:		
ME Content	kcal/kg	3035
Crude Protein	%	22%
Phosphorus Content	%	0.45%
Phase 2:		
ME Content	kcal/kg	3107
Crude Protein	%	20%
Phosphorus Content	%	0.42%
Phase 3:		
ME Content	kcal/kg	3179
Crude Protein	%	19%
Phosphorus Content	%	0.38%

Table 12. Growth model results for the feeds produced by the multi-criteria ration optimization model with constant environmental variables. The environmental variables are based on the reference conditions used for the model (Cobb, 2012).

Feed	Body Weight (kg)	Feed Intake (kg)	Dry Matter (kg)	Nitrogen Excretion (kg)	Phosphorus Excretion (kg)	Potassium Excretion (kg)
1	3.9314	7.0388	1.9301	0.0968	0.0246	0.0530
2	3.9303	6.8157	1.8689	0.0894	0.0262	0.0469
3	3.9298	6.6919	1.8350	0.0886	0.0268	0.0441
4	3.9306	7.0313	1.9280	0.0803	0.0238	0.0417
5	3.9310	7.0946	1.9454	0.0831	0.0215	0.0452
6	3.9310	7.0557	1.9347	0.0871	0.0234	0.0481
7	3.9315	7.0640	1.9370	0.0978	0.0254	0.0544

The results of the multi-criteria ration optimization model indicated that the Hubbard feed (feed 5) is the best ration when looking at cost and carbon footprint. When examining the growth model results, ration 5 did not produce the largest bird. However, it should be noted that the difference between the ration 5 broiler and the largest bird (ration 7) is only 0.00056 kg. The feed conversion ratio, which is the feed consumed divided by the weight gain, is the highest (1.80). This value demonstrates the birds low feed to growth efficiency. The nutrient emissions produced by the bird are dependent on amount of each ingredient. For example, wheat shorts and soybean meal contain amount of potassium. Therefore, feeds with more of those two ingredients will result in the bird consuming more of the nutrient. The broiler's body will not use all the nutrients it consumes, so this will result in increased potassium excretions. For the Hubbard feed, the nutrients provide the lowest levels of nitrogen, as well as relatively low potassium and phosphorus emissions.

The broiler body weight remained relatively constant through the seven feed scenarios. There was only a difference of 0.0017 kg between the scenarios with the smallest and largest birds, which is not significant. The largest broiler was produced by the Ross scenario (feed 7). The Ross broiler required more feed and produced the high levels of excretions. In comparison, the feed producing the lowest body weight (feed 3), had the highest feed conversion ratio and variable nutrient emissions. The feed produced the highest amount of phosphorus excretions, relatively low potassium excretions, and mid-range nitrogen excretions. Table 13 was constructed to use as a comparison tool for the seven scenarios. Each category is rated on a scale of 1-7 for the feeds. The value 1 is designated as the most favorable outcome. For example, low excretions, low carbon footprint, and large body weight are desirable outcomes. The lowest value, 7, is allotted to the most undesirable outcome.

Using this table, it can be noted that feed 5 is still a good feed option based on its cost, carbon footprint, and nutrient emissions. However, the feed conversion is low. Another good growth option may be the Commercial Poultry Nutrition textbook feed (feed 4). This feed is a low-cost feed with low phosphorous, nitrogen, and potassium excretions. The feed conversion ratio is slightly higher than that of feed 3, but the carbon footprint is significantly higher.

Table 13. Tool used to compare the results of the multi-criteria ration optimization model and the growth model. The values indicate the feed scenario number and are in ascending order for all six categories.

Cost	CF	Body Weight	Feed Conversion	P Excretion	N Excretion	K Excretion
5	5	3	5	5	4	4
4	6	2	7	6	5	3
3	7	4	6	4	6	5
2	1	5	1	1	3	2
6	4	6	4	7	2	6
7	2	1	2	2	1	1
1	3	7	3	3	7	7

ii. Constant Ration Composition and Variable Environment

A separate analysis was conducted to determine the best environmental conditions for broiler growth. The analysis was completed using the growth model, which uses temperature, relative humidity, and airspeed to predict the perceived temperature of the broiler. The perceived temperature of the bird is very important in determining the best conditions for broiler growth. For example, a bird in a high temperature, high humidity environment with low airspeed with have a perceived temperature greater than the actual temperature. A warm broiler will spend more of its time panting and consuming water, to decrease its body temperature, than consuming food for growth. To assess the environmental conditions, the feed variables were held constant in the growth model. The feed variables were set using the Cobb Broiler Management Guide and used as the standard for the model (Cobb, 2012). The results of the scenarios are presented in tables 2-4 are presented in tables 14-16.

Table 14. Growth model results for the Hubbard management scenarios presented in table 1. The feed variables were held constant using the standards developed from the Cobb management guide.

Scenario	Weight (kg)	Total Feed Intake (kg)	Dry Matter Excretion (kg)	Nitrogen Excretion (kg)	Phosphorus Excretion (kg)	Potassium Excretion (kg)
1	3.93	7.68	2.11	0.091	0.017	0.054
2	3.93	7.68	2.11	0.091	0.017	0.054
3	3.93	7.68	2.11	0.091	0.017	0.054
4	3.93	7.64	2.09	0.091	0.017	0.054
5	3.93	7.64	2.09	0.091	0.017	0.054
6	3.93	7.64	2.09	0.091	0.017	0.054
7	3.93	7.59	2.08	0.090	0.017	0.054
8	3.93	7.59	2.08	0.090	0.017	0.054
9	3.93	7.59	2.08	0.090	0.017	0.054
10	3.93	7.54	2.07	0.090	0.016	0.053
11	3.93	7.54	2.07	0.090	0.016	0.053
12	3.93	7.54	2.07	0.090	0.016	0.053

Table 15. Growth model results for the Ross management scenarios presented in table 2. The feed variables were held constant using the standards developed from the Cobb management guide.

Scenario	Weight (kg)	Total Feed Intake (kg)	Dry Matter Excretion (kg)	Nitrogen Excretion (kg)	Phosphorus Excretion (kg)	Potassium Excretion (kg)
1	3.93	7.63	2.09	0.091	0.017	0.054
2	3. 93	7.65	2.10	0.091	0.017	0.054
3	3. 93	7.71	2.11	0.092	0.017	0.055
4	3.94	7.74	2.12	0.092	0.017	0.055
5	3.94	7.80	2.14	0.093	0.017	0.055
6	3.94	7.83	2.15	0.093	0.017	0.055
7	3.94	7.88	2.16	0.094	0.017	0.056
8	3.94	7.91	2.17	0.094	0.017	0.056

Table 16. Growth model results for the Cobb management scenarios presented in table 3. The feed variables were held constant using the standards developed from the Cobb management guide.

Scenario	Weight (g)	Total Feed Intake (g)	Dry Matter Excretion (g)	Nitrogen excretion (g)	Phosphorus Excretion (g)	Potassium Excretion (g)
1	3.93	7.42	2.04	0.088	0.016	0.053
2	3.93	7.42	2.04	0.088	0.016	0.053
3	3.93	7.42	2.04	0.088	0.016	0.053
4	3.93	7.43	2.04	0.088	0.016	0.053
5	3.93	7.43	2.04	0.088	0.016	0.053
6	3.93	7.43	2.04	0.088	0.016	0.053
7	3.93	7.47	2.05	0.088	0.016	0.053
8	3.93	7.44	2.04	0.088	0.016	0.053
9	3.93	7.48	2.05	0.089	0.016	0.053
10	3.93	7.45	2.04	0.089	0.016	0.053
11	3.93	7.60	2.08	0.090	0.017	0.054
12	3.93	7.57	2.08	0.090	0.016	0.054

Most of the broiler manuals recommend phase one temperatures from 29-33°C, phase two temperatures from 24-31°C, and phase three temperatures from 18-27°C. The growth model results (Appendix D) showed that best temperature for broiler growth was from 29°C for phase one, 27-29°C for phase two, and 24-27°C for phase 3. All the growth scenarios showed that relative humidity has little effect on the bird's growth in this model. This is not expected because at conditions with high humidity, the birds have difficulty cooling themselves. Also, at low humidity the birds will feel cooler due to the evaporative cooling process. This suggest that the model does not account for humidity's contribution to perceived temperature well.

For the Hubbard scenario, the results (table 14) show that the size of the broiler remains relatively constant regardless of the conditions. The difference in body weight between the largest and smallest bird for these scenarios is 0.004 kg. The amount of nutrient excretions also remained consistent in all the scenarios. However, there were some noticeable differences in feed consumed and excretions. The scenarios containing the high phase 1 airspeed (0.3 m/2) and the lower phase 1 temperature (30°C) produced birds with the lowest feed intake and dry matter excretions. It was observed that the humidity of the barn did not influence the broilers growth as expected.

The Ross scenario results (table 15) show an increase in body weight of 0.1kg between the broilers grown at the lower phase 1 temperature (29.2°C). As seen in the Hubbard scenario results, the birds grown in barns with high airspeed consume less food and produce less dry excretions. The larger broilers were produced by the low phase 1 temperature conditions, except for scenario 4. These scenarios also produced birds that required more feed and produced more dry excretions. The N and K excretions were not constant across all the scenarios, as in the Hubbard scenarios. The birds in the low phase 1 and 3 temperatures and high phase 2 temperature produced the most. The P excretions remained constant through these scenarios.

The Cobb scenario results (table 16) show the body weight of the broiler remained constant though all the scenarios. The feed intake and dry matter excretions were the largest in scenarios 11. This barn features low phase 1 temperature with high airspeed, high phase 2 temperature with high airspeed, and low phase 3 temperatures with low airspeed. The nutrient excretions were also the highest in this scenario.

Based on the scenario results from the three broiler management guides, a new set of scenarios were developed to determine the best growth environment for the broilers. The temperatures and airspeeds were chosen from the scenarios that produced the larger broilers with the lowest amount of emissions. These new scenarios were created to determine the optimum phase temperatures and airspeeds. The scenarios and results are available in Appendix C and D respectively.

The difference between the largest and smallest broiler's weight was 0.01 kg. All the low phase 1 temperature scenarios produced the larger broiler. These barn conditions also produce birds that consume more feed and produce more excreta. As with the broiler management guide scenarios, the amount of P excretions remained constant. The larger broilers also produced more K and N excretions.

The scenarios that provided the largest broiler body weight from Appendix C had a lower phase 1 temperature (29°C). For those scenarios, phase two air speed made little impact on the broiler growth. However, higher airspeed at resulted in a decrease in feed consumption and excretions. In the third phase, a higher temperature required a higher airspeed for successful broiler growth and a lower airspeed for low temperatures.

iii. Variable Feed and Environment Growth Model Results

Ten environmental scenarios were selected from the scenarios outlined in Appendix C and the results produced by the growth model (Appendix D). The ten scenarios that produced the largest broiler were chosen for the variable feed and environmental condition scenarios (Table 17). These conditions, along with the seven rations produced by the multi-criteria feed optimization model were run together in the growth model. The results can be viewed in Appendix E.

Table 17. Growth scenarios selected for variable feed and environment scenarios based on the weight of the broiler produced by the growth model. The scenarios were developed based on results of the variable feed with constant environment scenarios and the constant feed and variable environment scenarios.

Trial	Phase 1			Phase 2			Phase 3		
	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)
38	29	50	0.3	29	60	0.3	27	60	2.000
40	29	50	0.3	29	60	1.0	27	60	2.000
45	29	50	0.3	29	60	0.3	24	60	0.500
47	29	50	0.3	29	60	1.0	24	60	0.500
54	29	50	0.3	27	60	0.3	27	60	2.000
56	29	50	0.3	27	60	1.0	27	60	2.000
61	29	50	0.3	27	60	0.3	24	60	0.500
62	29	50	0.3	27	60	0.3	24	60	0.875
63	29	50	0.3	27	60	1.0	24	60	0.500
64	29	50	0.3	27	60	1.0	24	60	0.875

The results of the growth model show that feed has a larger impact on the broiler's body weight, excretions, and feed consumption than the environmental conditions. Feeds 1 and 7 produced the largest broiler, regardless of the environmental scenario. Feed 7 resulted in the largest broiler, but these birds also required the most feed and produced the most excretions. Feed 1 resulted in a slightly smaller bird with slightly less feed consumption and excretions. Feed 6 produces a bird only about 0.0007 kg smaller than feed 7, but it results in decreases in emissions. The best feed scenario, based on the emissions produced by the bird, is feed 4. The broiler is slightly smaller (0.0013 kg), but the decrease in emissions is significant.

Regardless of the feed scenario, environmental scenarios 47, 61, and 63 produced the largest broilers in each feed scenarios. Although the birds' body weight was consistent in the three scenarios, the amount of feed consumed and excretion varies. The differences in feed consumption is caused by changes in the bird's perceived temperature.

C. Broiler LCA Results

Based on the growth model results, a series of scenarios have been developed for the broiler LCA created in OpenLCA. The scenarios were chosen to assess how the changes in feed and the growth environment will change KPI's. The broiler process in OpenLCA contains all the inputs required to produce 1 kg live weight of broiler, as well as the output and emission produced by the process. The original values were calculated following a methodology similar to the broiler retrospective (Putnam, 2017). These calculations are based on broiler production data collected by the USDA ERS and NCC (MacDonald, 2014; NCC 2015). These values (Table 18) are used as the control conditions.

To determine the amount of feed consumed by each broiler in the 2010 retrospective and the 2015 control, growth data presented by Arbor Acres (Arbor Acres, 2014) is analyzed. The manual provides the amount of feed the male and female birds consume daily. The life of the bird is separated into three phases based on the bird's age. Starters are from 0-15 days, growers are from day 16 through 30, and the finisher phase occurs starting on day 31. The total amount of feed consumed by the bird in each phase is calculated by adding up the feed consumed by the living birds in that time-period. Using the ration compositions presented by the Commercial Poultry Nutrition textbook (Leeson and Summers, 2009), the amount of each ingredient in the feed can be determined.

Table 18. Broiler production inputs for OpenLCA using data from USDA ERS and NCC (MacDonald, 2014; NCC 2015). These conditions are used as the OpenLCA control for the broiler process inputs and outputs.

Inputs		
Unit Process		Units
Transport	71.88	tkm
Baby Chickens; Broilers	88000.00	birds
Electricity	14732.46	kWh
Broiler Feed Ration	1.00	ration
Liquefied Petroleum Gas (LPG)	2058.94	gal
Water	1863889.64	kg
Bedding Material	17600.00	kg
Mortality Management	26280.00	kg
Manure Application Emissions	0.032	p
Outputs/Emissions		
Name	Value	Units
Broilers	41096	birds
Litter	83778	kg
CH4	231.4520548	kg
N2O	69.46633509	kg
NH3	4294.282533	kg

Table 19. Control feed developed using Arbor Acres broiler performance objectives and the Commercial Poultry Nutrition textbook (Arbor Acres, 2014; Leeson and Summers, 2009).

Feeds	Mass of Feed Item (kg)	Phase 1	Phase 2	Phase 3
Corn, No. 2	449842	55.90%	64.60%	72.60%
Soybean Meal	153,962	29.50%	23.70%	19.20%
Limestone	7,689	1.20%	1.13%	1.13%
Meat and Bone Scrap	33,320	4.00%	5.00%	5.00%
Tallow	10,646	2.10%	1.64%	1.31%
Wheat Shorts	15,509	6.00%	3.00%	0.00%
Salt	2,349	0.39%	0.35%	0.33%
Dicalcium Phosphate	1,011	0.46%	0.15%	0.07%
DL-Methionine	1,549	0.26%	0.25%	0.18%
L-Lysine	547	0.09%	0.08%	0.08%
Vit-Min Mix	677	0.10%	0.10%	0.10%
Totals (kg)	676,422	53,474	410,029	213,596

The results produced by the OpenLCA control scenario, which is presented in tables 18 and 19, will be used to compare with the various feed and environmental scenarios. The 2015 OpenLCA control scenario was evaluated using the TRACI 2.1 method. The life cycle impact assessment control results are presented and compared to the broiler retrospective (Putman, 2017) in table 20. The impact category results for the 2015 LCA are higher in all three categories.

Table 20. Life cycle impact assessment results from 1 kg of LW poultry produced for human consumption in 2010 and 2015. The 2010 results are from the broiler retrospective (Putnam, 2017).

		1kg LW Poultry	
Impact category	Unit	*2010*	*2015*
GWP	kg CO_2 eq.	1.28000	1.33555
Acidification	kg SO_2 eq.	0.04575	0.04741
Eutrophication	kg N eq.	0.02100	0.03332

i. Variable Feed Composition and Constant Environmental Variables

The growth model provided results for the seven different feed scenarios with constant environmental conditions. The model provided live weight, feed consumption, dry matter excretion, and nitrogen excretions. These values are used to calculate new OpenLCA process values (Table 21).

Total electricity and LPG use for each scenario is calculated by determining the live weight of all the broilers produced by the barn and multiplying that value by the amount per kg live weight.

$$Total\ LPG = LW\ x\ Number\ of\ Broilers\ x\ 0.0087\,\frac{gal}{kg} \qquad \text{(EQ.8)}$$

$$Total\ electricity = LW\ x\ Number\ of\ Broilers\ x\ 0.0619\,\frac{kWh}{kg} \qquad \text{(EQ.9)}$$

The growth model provides the total amount of feed consumed by a bird during its growth. This value is used to determine the total amount of feed required per year.

$$Total\ Feed = Feed\ per\ Broiler\ x\ Number\ of\ Broilers \qquad \text{(EQ.10)}$$

The amount of water used for broiler production includes drinking water and cooling water. Cooling water was assumed to stay constant with about 6 kg of water per broilers per year. Drinking water is dependent on the amount of feed consumed by the bird. The bird drinks approximately 2 kg of water per kg of feed.

$$Total\ Water = Cooling\ Water + \ 2\ x\ Total\ Feed \qquad \text{(EQ.11)}$$

The amount of N_20 and NH_3 emissions are dependent on the bird's live weight. The typical average animal mass (TAM) for the broilers is determined using equation 12. The annual amount of nitrogen excreted per year is calculated using the TAM and the rate of excretion from the growth model (EQ.13). The amount of N volatilized and leached is dependent on the amount of birds produced in the cycle. For volatilization, about 0.4 kg of N is retained per kg N consumed by the bird (EQ.14). For leaching, this value is 0.1 $\frac{kg\ N\ retained/animal/year}{kg\ N\ intake/animal/year}$ (EQ.15). The amount N from N_20 is calculated by determining the amount of nitrogen excreted per year for all the birds produced and the volatilized nitrogen (EQ.16). The amount of N from NH3 is determined by calculating the amount of N contributing the volatilized gases.

$$TAM = BW\ x\ 0.067 \qquad \text{(EQ.12)}$$

$$N - EX = \frac{TAM}{1000}\ x\ Nitrogen\ Excretion\ x\ 365\ days \qquad \text{(EQ.13)}$$

$$N - Vol = (8800x\frac{48}{365})\ x\ (N - EX)\ x\ 0.4 \qquad \text{(EQ.14)}$$

$$N - Leach = (8800x\frac{48}{365})\ x(N - EX)\ x\ 0.1 \qquad \text{(EQ.15)}$$

$$N_20 = (8800x\frac{48}{365})\ x\frac{(N-EX)}{1000}\ x\ \frac{44}{28} + \frac{(N-Vol)}{1000}x\frac{44\ kg\ N20}{28\ kg\ N2} \qquad \text{(EQ.16)}$$

$$NH_3 = (N - Vol)\, x \frac{17\ kg\ NH3}{14\ kg\ N} \qquad \text{(EQ.17)}$$

The composition of each ration must also be calculated for input for the life cycle assessment. The multi-criteria ration optimization model provides the proportion of each feed ingredient in percent (Appendix B). The amount of each ingredient is determined by multiplying the total amount of feed consumed, based on the growth model output, and the proportions presented by the ration model.

Table 21. OpenLCA broiler process inputs calculated from the growth model results presented in table 6 with constant environmental conditions. The environmental conditions are based on the reference conditions used for the model (Cobb, 2012).

Feed Scenario	Live Weight (kg)	Electricity (kWh)	LPG (gal)	Feed (kg)	Water (kg)	Litter (kg)	N20 (kg)	NH3 (kg)
1	3.93	20394.12	2850.19	589697.85	1690440.69	34584.88	84.62	5230.99
2	3.93	20388.34	2849.38	571004.35	1653053.70	34046.45	78.13	4829.87
3	3.93	20385.92	2849.05	560632.85	1632310.70	33747.73	77.38	4783.58
4	3.93	20389.88	2849.60	589071.41	1689187.82	34566.83	70.19	4338.72
5	3.93	20391.80	2849.87	594368.38	1699781.76	34719.40	72.61	4488.81
6	3.93	20391.98	2849.89	591116.42	1693277.85	34625.73	76.09	4704.01
7	3.93	20394.71	2850.27	591811.12	1694667.23	34645.74	85.52	5286.59

Table 22 OpenLCA LCIA results for the scenarios ration scenarios presented in table 1 using TRACI 2.1 for 1 kg LW.

Ration Scenario	GWP (kg CO_2 eq)	EU (kg N eq)	AP (kg SO_2 eq)	ECO (CTUe)	FEU (MJ Surplus)	Cost ($/100 kg dry feed)
1	1.01106	0.01826	0.04138	2.10829	0.59471	144,734.81
2	1.02227	0.01965	0.03965	2.11536	0.58308	138,105.46
3	0.90450	0.01728	0.03754	1.74213	0.51306	135,920.25
4	0.99929	0.01897	0.03611	2.02067	0.58052	135,473.64
5	1.00560	0.01913	0.03724	2.03720	0.58158	135,029.71
6	1.02292	0.01895	0.03842	2.18359	0.59483	143,233.12
7	1.05982	0.01856	0.04183	2.27490	0.66302	144,205.90

The growth model results for all seven ration scenarios show that the broilers consume less feed than estimated for the control and 2010 retrospective. Since feed crops contribute the most to the impact categories, there is a significant decrease across all five impact categories (Table 22). Feed 3, one of the experimental feeds, produced the lowest life cycle impact assessment results across all five impact categories. This ration contains almost half the amount of tallow, 10 percent of the l-lysine, and 20 percent of the dl-methionine found than the control ration. All three of these ingredients have high carbon footprints.

Feed 2 produced the highest eutrophication potential. This ration contains the large amounts of corn and soybean meal, which are the greatest contributors to all the impact categories. Feed 7 (Ross) produced the largest global warming potential, ecotoxicity, acidification, and fossil fuel depletion. This ration contains the largest amount of dl-methionine and wheat shorts, as well as large amounts of tallow and soybean meal. All four ingredients make contributions to the impact categories.

ii. Constant Feed Composition and Variable Environmental Factors

To assess the environmental scenarios developed using the growth model results, calculations were completed to update the utilities, feed consumption, and outputs for the LCA broiler process. Most of the calculations were similar to those done for the constant environmental variables scenarios. The calculation for the feed ingredients is different. Since the feed composition is held constant and the feed ingredient proportions are held constant, only the total amount of each ingredient will change. The updated inputs and outputs are listed in table 23.

Table 23. OpenLCA broiler process inputs determined calculated from the growth model results presented in table 6 with constant feed composition. The feed variables are based on the reference conditions used for the model (Cobb, 2012) and the feed composition presented by the Commercial Poultry Nutrition textbook (Leeson and Summers, 2009).

Env. Scenario	Live Weight (kg)	Electricity (kWh)	LPG (gal)	Feed (kg)	Water (kg)	Litter (kg)	N_20 (kg)	NH_3 (kg)
38	3.94	20437.30	2856.23	669407.38	1849859.8	36880.72	83.48	5160.81
40	3.94	20437.30	2856.23	669154.96	1849354.9	36873.45	83.45	5158.78
45	3.94	20438.45	2856.39	667039.46	1845123.9	36812.52	82.23	5083.21
47	3.94	20438.45	2856.39	666787.04	1844619.1	36805.25	82.65	5109.53
54	3.94	20437.30	2856.23	668862.82	1848770.6	36865.04	83.41	5156.44
56	3.94	20437.30	2856.23	668613.49	1848272.0	36857.86	83.38	5154.44
61	3.94	20438.45	2856.39	666494.89	1844034.8	36796.84	82.16	5078.84
62	3.94	20435.49	2855.97	664913.89	1840872.8	36751.30	82.79	5117.95
63	3.94	20438.45	2856.39	666245.56	1843536.1	36789.65	82.58	5105.16
64	3.94	20435.49	2855.97	664664.56	1840374.1	36744.12	82.76	5115.94

Table 24. OpenLCA LCIA results for the environmental scenarios presented using TRACI 2.1 for 1 kg LW. The feed variables are based on the reference conditions used for the model (Cobb, 2012) and the feed composition presented by the Commercial Poultry Nutrition textbook (Leeson and Summers, 2009).

Feed Scenario	GWP (kg CO_2 eq)	Eutrophication (kg N eq)	Acidification (kg SO_2 eq)	Ecotoxicity (CTUe)	Resource Depletion - Fossil Fuels (MJ Surplus)
38	1.05734	0.02087	0.04108	1.99224	0.63164
40	1.06077	0.02095	0.04113	1.99940	0.63401
45	1.05724	0.02087	0.04071	1.99409	0.63227
47	1.05727	0.02087	0.04084	1.99348	0.63206
54	1.05991	0.02093	0.04111	1.99634	0.63352
56	1.06007	0.02093	0.04110	1.99805	0.63358
61	1.05654	0.02085	0.04068	1.99279	0.63183
62	1.05529	0.02082	0.04085	1.98910	0.63061
63	1.05656	0.02085	0.04080	1.99210	0.63161
64	1.05684	0.02086	0.04086	1.99234	0.63169

The variation in the environment conditions had little effect on the life cycle assessment impact categories (Table 24). Scenario 62, which uses utilizes low phase two and three temperatures and high fan speeds, produced the lowest global warming potential, eutrophication, ecotoxicity, and fossil fuel depletion. Scenario 61, which uses low phase two and three temperatures and low fan speeds, provided the lowest eutrophication potential. The scenario with the greatest impact across all five categories is scenario 40, which features warmer phase two and three conditions. This environmental scenario produced the largest amount of excreta and resulted in high levels of excretions. Once again, the growth model results are consistent with the results of the LCA.

iii. Variable Feeds and Environment

The ten environmental scenarios, selected based on the size of the broiler they produced in the growth model, and the seven feeds, from the multi-criterial feed optimization, were chosen for the variable ration and environmental conditions. The ration ingredients and utility inputs, as well as the outputs and emissions were calculated as discussed in the previous sections. The inputs and outputs of the process are outlined in Appendix F.

The results for the LCIA categories, using the TRACI 2.1 method, are outlined in Appendix G. The results are consistent with the separate ration and environmental scenarios conducted in OpenLCA. Changing the proportions of the ration ingredients still contributes the most to the impact assessment categories. The feed that produced the largest broiler (feed 7), also produced the largest environmental impacts in all categories. Feed 3 produced the lowest global warming potential, eutrophication, ecotoxicity, and fossil fuel depletion. This feed produced the smallest broiler with the lowest feed intake. However, the body weight changes of the bird are negligible. Since feed contributes to most of the broiler's GWP, the results are consistent between the two models. Feed 4 produced the lowest eutrophication potential. In the growth model, feed 4 produced the lowest levels of nitrogen and potassium excretions, as well as relatively low phosphorus excretion.

As with the growth model results, the environmental conditions varied the results only slightly. Environmental scenario 40 requires the largest amounts of feed for growth. This scenario produced the largest values across all five life cycle impact assessment categories. Scenario 64 produced the lowest global warming potential, acidification, eutrophication, ecotoxicity, and fossil fuel depletion.

V. Conclusions

This study provides a starting point for connecting broiler growth related models to LCA to determine the best conditions for growth, including feed ingredients and barn environment. The multi-criteria ration optimization model was used to formulate a variety of poultry rations by minimizing the cost and carbon footprint. The results showed that a feed containing lower contributions of soybean meal and meat and bone meal can result in lower cost and carbon footprint.

The broiler growth model showed only small variations in body weight across all the scenarios, however it still served as a valuable tool to evaluate growth conditions. The model appropriately showed that the birds are more susceptible to the barn's temperatures. It also demonstrated that an increase in feed consumption will lead to increased excretions by the animal. The feed ingredients also play an important role in the bird's growth. Feeds with a large ME:CP ratio resulted in the largest broilers. The emissions produced by the birds is dependent on the feed ingredients, for example the amount of phosphorus excretions are directly dependent on the amount of Dicalcium phosphate in the feed. It was established that feeds 3 and 4 (CPN) produced the broilers with the best feed conversion and relatively low excretion levels.

LCA was used to evaluate the changes to the broiler production process on the environment using TRACI 2.1. These changes were a result of the different proportions of feed ingredients, amount of feed, and utilities required to maintain the barn's environment. The results were consistent with literature and with the results produced by the growth model. The scenarios that resulted in the highest values for the life cycle impact assessment methods were directly related to the amount of feed the bird consumed. For most of the categories, feed contributes most of the impact (60-80% contribution). As with the growth model, the environmental conditions contributed less to the growth than the feed.

There is room for improvements in several areas of the growth model that would provide a more accurate representation of broiler growth. It was noted throughout the report that the model's account for humidity was not accurate. Although it did provide some very small changes in growth, this is not representative of actual observations. Humidity plays an important role in temperature regulation of broilers. Low humidity allows for evaporative cooling to be used in the barn. This process creates a lower perceived temperature for the bird. High humidity creates the opposite effect and produces a difficult environment for the broiler to cool itself. More improvements could be made to the model's calibration parameters (IM, AF, Genotype Factor). These values were found using the solver application in Microsoft Excel ®. More research might allow for improvements to these calculations to more accurately represent the broiler's growth.

Although the study could use some improvements, it laid groundwork to connect different forms of broiler simulations to estimate growth and environmental impact. Advancement of this study could lead to user-friendly models that connect one or more of the methods used in this study to help other researchers or even broiler producers.

References

Arbor Acres, 2014. *Broiler Performance Objectives*. Aviagen Resource Center.

Arbor Acres, 2011a. *Grandparent Stock Performance Objectives*. Aviagen Resource Center.

Arbor Acres, 2011b. *Parent Stock Performance Objectives*. Aviagen Resource Center.

Bare, J., 2012. *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI): Version 2.1 User's Manual*. EPA. United States Environ. Prot. Agency.

Boggia A. Paolotti L. Castellini C. 2010. *Environmental impact evaluation of conventional, organic and organic-plus poultry production systems using life cycle assessment*. World's Poult. Sci. J. 66:95–114.

Bonnet, S., P.A. Geraert, M. Lessire, B. Carre and S. Guillaumin, 1997. Effect of high ambient temperature on feed digestibility in broilers. Poult. Sci., 76: 857-863.

Burek, J., Putman, W., Bandekar, P., Tsai, T.C., Popp, J., Ulrich, R., Maxwell, C., Thoma, G., 2017. *Sustainability of pig diets through the looking glass of the multi-objective optimization*. Ecol. Appl. J

Cobb (2013). Broiler Management Guide. Available at: http://images.agriprofocus.nl/upload /cobb-broiler-management-guide-20121469468173.pdf Accessed 08 05 2016

Dale, N.M. and H.L. Fuller, 1980. Effect of diet composition on feed intake and growth of chicks under heat stress. Poult. Sci., 59: 1434-1441.

Deaton, J.W., Reece, F.N., McNaughton, J.L. (1978), *The Effect of Temperature During the Growing Period Performance* Poultry Science, 57 (4): 1070-1074.

Donkoh, A. Int J Biometeorol (1989) 33: 259. doi:10.1007/BF01051087

Engberg, R. M., M. S. Hedemann, and B. B. Jensen. 2002. The influence of grinding and pelleting of feed on the microbial composition and activity in the digestive tract of broiler chickens. *Br. Poult. Sci.* 43:569–579.

Hacina, A.B., P.A. Geraert, J.C. Padilha and G. Solanage, 1996. Chronic heat exposure enhances fat deposition and modifies muscle and fat partition in Broiler carcasses. Poult. Sci., 75: 505-513.

Har, L., D. Rong and Z.Y. Zhang, 2000. The effect of thermal environment on the digestion of broilers. Anim. Physiol., 83: 57-64.

Hubbard (2016). Broiler Management Manual, Fast Growth. Available at: http://www.hubbardbreeders.com/media/manual_broiler_management_en___013796700_1441_27062016.pdf Accessed 08 05 2016.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme.

IPCC, 2013. *Climate Change 2013: The Phsical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds)]. Cambridge Univeristy Press, Cambridge, Uniged Kingdom, and New York, NY, USA.

LEAP, 2015a. *Greenhouse gas emissions and fossil energy demand from poultry supply chains: Guidelines for assessment*. FAO, Rome, Italy.

LEAP, 2015b. *Environmental performance of animal feeds supply chains: Guidelines for assessment*. FAO, Rome, Italy.

Leeson, S., Caston, L., Summer, J.D. (1996). Broiler Response to Diet Energy. Poultry Science, 75 (4):529-535

Leeson, S., Summers, J. (2008). *Commercial Poultry Nutrition*, Third Edition. Thrumpton, Nottingham: Nottingham University Press.

Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I. (2012), *Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Broiler production systems* Poultry Science, 91 (1): 8-25.

Lv, M., Yan, L., Wang, Z., An, S., Wu, M., Lv, Z. (2015), *Effect of feed form and feed particle size on growth performance, carcass characteristics, and digestive tract development of broilers* Animal Nutrition, 2 (3): 252-256.

MacDonald, James M. *Technology, Organization, and Financial Performance in U.S. Broiler Production*, EIB-126, U.S. Department of Agriculture, Economic Research Service, June 2014.

MacLeod, M., Gerber, P., Mottet, A., Tempio, G., Falcucci, A., Opio, C., Vellinga, T., Henderson, B. & Steinfeld, H. 2013. *Greenhouse gas emissions from pig and chicken supply chains – A global life cycle assessment.* Food and Agriculture Organization of the United Nations (FAO), Rome.

May, J.D. and B.D. Lott, 1992. Feed and water consumption patterns of broilers at high environmental temperatures. Poult. Sci., 71: 331- 336.

Meda, B., Quentin, M.Lescoat, P., Picard, M., Bourvarel, I. (2015). INAVI: a practical tool to study the influence of nutritional and environmental factors on broiler performance. In *Nutritional Modelling for Pigs and Poultry* (pp. 106-124).

Nahashon, S.N., Adefope, N., Amenyenu, A., Wright, D. (2005), *Effects of dietary* *metabolizable energy and crude protein concentrations on growth performance and carcass characteristics of French guinea broilers* Poultry Science, 84 (2): 337-344.

National Chicken Council, 2015. US Broiler Performance [WWW Document]. URL http://www.nationalchickencouncil.org/about-the-industry/statistics/u-s-broiler-performance/ (accessed 8.5.16).

Nir, I.,R. Hillel, I. Ptichi, and G. Shefet. 1995. Effect of particle size on performance. 3. Grinding pelleting interactions. *Poult. Sci.* 74: 771–783.

Pelletier, N. (2008), *Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions* Agricultural Systems, 98 (2): 67-73.

Purswell, Joseph `L.; Dozier, William A. III; Olanrewaju, Hammed A.; Davis, Jeremaiah D.; Xin, Hongwei; and Gates, Richard S., "Effect of Temperature-Humidity Index on Live Performance in Broiler Chickens Grown From 49 To 63 Days of Age" (2012). *Agricultural and Biosystems Engineering Conference Proceedings and Presentations*. 157.

Pyne, C.G., 1966. Environmental temperature and egg production. In: Physiology of domestic fowl. Horton- Smith, C. London. England.

Ross (2014). Broiler Management Handbook. Available at: http://en.aviagen.com/assets /Tech_Center /Ross_Broiler/ Ross-Broiler-Handbook-2014i-EN.pdf Accessed 08 05 2016.

Stocker, T. F., Qin, D., Plattner, G. K., Alexander, L. V., Allen, S. K., Bindoff, N. L., ... & Forster, P. (2013). Technical summary. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 33-115). Cambridge University Press.

Svihus, B., K. H. Klovstad, V. Perez, O. Zimonja, S. Sahlstrom, and R. B. Schuller. 2004. Physical and nutritional effects of pelleting of broiler chicken diets made from wheat ground to different coarsenesses by the use of roller mill and hammer mill. *Anim. Feed Sci. Technol.*117: 281–293.

United States Department of Agriculture, 2017. Livestock and Poultry: World Markets and Trade. URL https://apps.fas.usda.gov/psdonline/circulars/livestock_poultry.pdf

Zang, J.J., Piao, X.S., Huang, D.S., Wang, J.J., Ma, X., Ma, Y.X. (2009), Effects of Feed Particle Size and Feed Form on Growth Performance, Metabolizability, and Intestinal Morphology in Broiler Chickens. Asian-Australian J. Anim. Sci, 22(1): 107-112.

Appendices

A-1. Multi-Criteria Ration Optimization Matlab script for the least squares regression for each of the desired KPI's (cost and carbon footprint). The script formulates diets for a single objective linear model by varying the ration's ingredients based on the provided minimums and maximums. It formulates diets for each of the single objectives, or KPI's and minimizes the squared errors.

```
%function [x,fval,exitflag,output,lambda] =
cost_run(Cost,FeedNutrients,LowerNutrientLimits,SumFeed,Total,LowerFeedLimits,UpperFeedLimits)
%% This is an auto generated MATLAB file from Optimization Tool.
% matlab.mat
%% Start with the default options

options = optimoptions('linprog');
%% Modify options setting
%options = optimopions(options,'Display', 'off');
options = optimoptions(options,'Display', 'iter');
options = optimoptions(options,'MaxIter', 1000);
options = optimoptions(options,'TolFun', 1E-8);
options = optimoptions(options,'Algorithm', 'Interior-point');
% myOBf has rows representing objectives and columns values for defined
% number of feed ingredients:
% defined number of feed ingredients = 114
% myOBf(1,:) = cost values for defined number of feed ingredients ($/kg
% feed)
% myOBf(2,:) = climate change impact values for defined number of feed
% ingredients (kgCO2e/kg feed)
% myOBf(3,:) = water depletion values for defined number of feed
% ingredients (m3/kg feed)
% myOBf(4,:) = land occupation values for defined number of feed
% ingredients (m2a/kg feed)
% xMinOBf - diet formulations for single-objective linear modeling
% xMinOBf(1,:) - least cost diet result
% xMinOBf(2,:) - least climate change impact diet result
% xMinOBf(3,:) - least water depletion diet result
% xMinOBf(4,:) - least land occupation diet result
% MinOBf - the result for single-objective diets
% MinOBf(1,:) = total least cost of one diet phase
% MinOBf(2,:) = total least climate change impact of one diet phase
% MinOBf(3,:) = total least water depletion of one diet phase
% MinOBf(4,:) = total least land occupation of one diet phase
% Calculates single-objective diet - Least cost diet:

%Calculating linear minimums of single-objectives

xMinOBfCost=zeros(14,3);
MinOBfCost=zeros(1,3);



    for m=1:3

[xMinOBfCost(:,m),MinOBfCost(1,m),exitflagCost,~,~] = ...
linprog(myOBf(1,:),-FeedNutrients,-
LowerNutrientLimits(m,:),SumFeed(m,:),Total(m),LowerFeedLimits(m,:),UpperFeedLimits(m,:),[],options);

    end

xMinOBfCF=zeros(14,3);
MinOBfCF=zeros(1,3);


    for m=1:3

% Calculates single-objective diet - Least climate change impact diet(CF):
[xMinOBfCF(:,m),MinOBfCF(1,m),exitflagCF,~,~] = ...
```

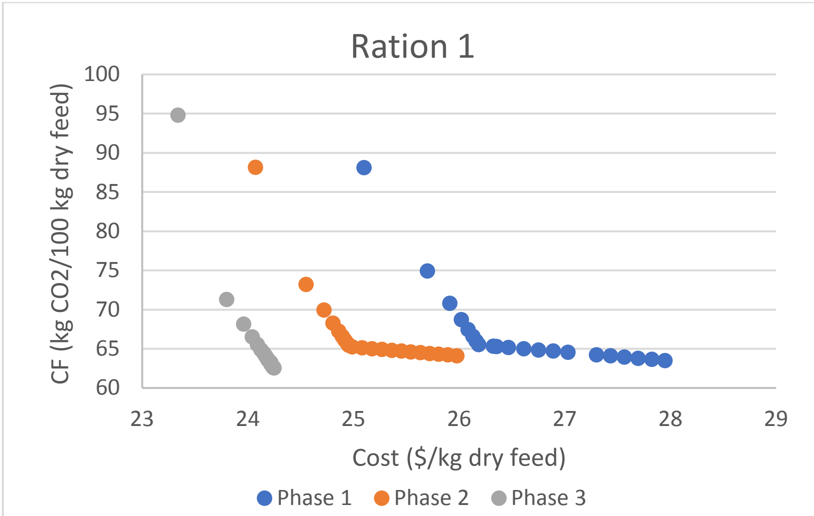
```
linprog(myOBf(2,:),-FeedNutrients,-
LowerNutrientLimits(m,:),SumFeed(m,:),Total(m),LowerFeedLimits(m,:),UpperFeedLimits(m,:),[],options);


    end

xMinOBfWF=zeros(14,3);
MinOBfWF=zeros(1,3);



    for m=1:3

% Calculates single-objective diet - Least water depletion diet (WF):
[xMinOBfWF(:,m),MinOBfWF(1,m),exitflagWF,~,~] = ...
linprog(myOBf(3,:),-FeedNutrients,-
LowerNutrientLimits(m,:),SumFeed(m,:),Total(m),LowerFeedLimits(m,:),UpperFeedLimits(m,:),[],options);

    end



xMinOBfLF=zeros(14,3);
MinOBfLF=zeros(1,3);

    for m=1:3

% Calculates single-objective diet - Least land use diet (LU):
[xMinOBfLF(:,m),MinOBfLF(1,m),~,~,~] = ...
linprog(myOBf(4,:),-FeedNutrients,-
LowerNutrientLimits(m,:),SumFeed(m,:),Total(m),LowerFeedLimits(m,:),UpperFeedLimits(m,:),[],options);


    end
```

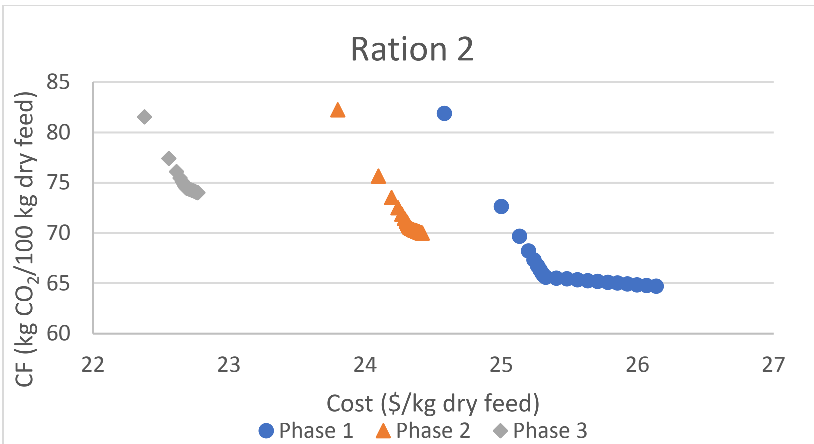
A-2. Multi-Criteria Ration Optimization Matlab script for the Pareto Optimization. This optimization changes the ration results by increasing at least one of the KPI's. The final set of solutions includes various ration formulations. Each of these solutions is based on various trade-offs between the optimality criteria.

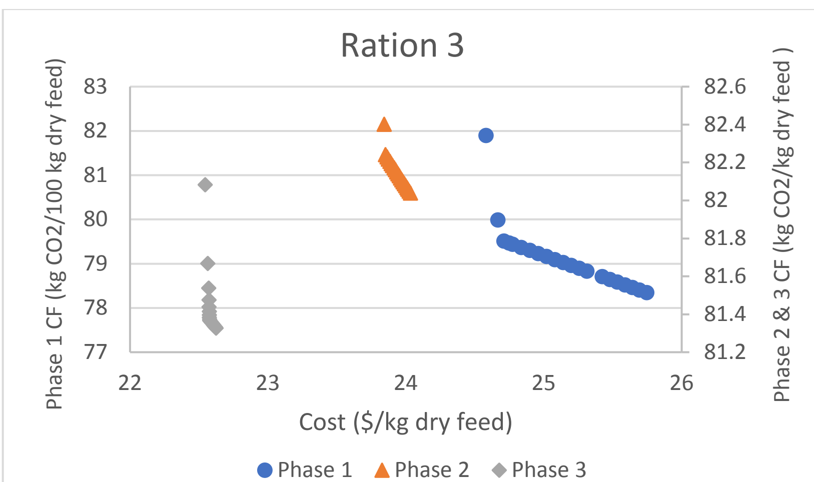
```
%Phase1

%% Start with the default options
%options = optimoptions('fgoalattain');
%% Modify options setting
options=optimset('disp','iter','LargeScale','off','TolFun',.001,'MaxIter',100000,'MaxFunEvals',100000);

options.GoalExactAchieve=2;

nf=2; %number of objective functions
N=20; %number of points for plotting

FgoalattainRationPhase1=zeros((N+1),15);

FgoalattainfvalPhase1=zeros(N+1,nf);

XInitial = xMinOBfCost(:,1)';

Goal=[MinOBfCost(1,1),MinOBfCF(1,1)];


onen=1/N;

for r=0:N
t=onen*r;

weight=[t,1-t];


[FgoalattainRationPhase1(r+1,:),FgoalattainfvalPhase1(r+1,:),attainfactor,exitflag,output,lambda] = ...
fgoalattain(@(Ration)multiobj(Ration,myOBf),XInitial,Goal,weight,-FeedNutrients,-
LowerNutrientLimits(1,:),SumFeed(1,:),Total(1,:),LowerFeedLimits(1,:),UpperFeedLimits(1,:),[],options);
end


figure
plot(FgoalattainfvalPhase1(:,1),FgoalattainfvalPhase1(:,2),'k.');


xlabel('costPhase1 ($/100 kg feed)')
ylabel('CFPhase1 (CO2e/100 kg feed)')


%Phase2

%% Start with the default options
%options = optimoptions('fgoalattain');
%% Modify options setting
options=optimset('disp','iter','LargeScale','off','TolFun',.001,'MaxIter',100000,'MaxFunEvals',100000);

options.GoalExactAchieve=2;

nf=2; %number of objective functions
N=20; %number of points for plotting



FgoalattainRationPhase2=zeros((N+1),15);

FgoalattainfvalPhase2=zeros(N+1,nf);



XInitial = xMinOBfCost(:,2)';

Goal=[MinOBfCost(1,2),MinOBfCF(1,2)];
```

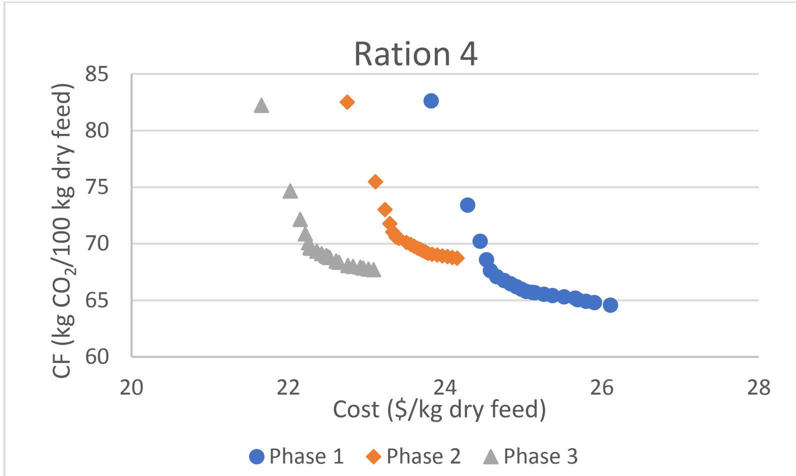
```
onen=1/N;

for r=0:N
t=onen*r;

weight=[t,1-t];


[FgoalattainRationPhase2(r+1,:),FgoalattainfvalPhase2(r+1,:),attainfactor,exitflag,output,lambda] = ...
fgoalattain(@(Ration)multiobj(Ration,myOBf),XInitial,Goal,weight,-FeedNutrients,-
LowerNutrientLimits(2,:),SumFeed(2,:),Total(2,:),LowerFeedLimits(2,:),UpperFeedLimits(2,:),[],options);
end


figure
plot(FgoalattainfvalPhase2(:,1),FgoalattainfvalPhase2(:,2),'k.');


xlabel('costPhase2 ($/100 kg feed)')
ylabel('CFPhase2 (CO2e/100 kg feed)')

%Phase3
%% Start with the default options
%options = optimoptions('fgoalattain');
%% Modify options setting
options=optimset('disp','iter','LargeScale','off','TolFun',.001,'MaxIter',100000,'MaxFunEvals',100000);

options.GoalExactAchieve=2;

nf=2; %number of objective functions
N=20; %number of points for plotting



FgoalattainRationPhase3=zeros((N+1),15);

FgoalattainfvalPhase3=zeros(N+1,nf);




XInitial = xMinOBfCost(:,3)';

Goal=[MinOBfCost(1,3),MinOBfCF(1,3)];


onen=1/N;

for r=0:N
t=onen*r;

weight=[t,1-t];


[FgoalattainRationPhase3(r+1,:),FgoalattainfvalPhase3(r+1,:),attainfactor,exitflag,output,lambda] = ...
fgoalattain(@(Ration)multiobj(Ration,myOBf),XInitial,Goal,weight,-FeedNutrients,-
LowerNutrientLimits(3,:),SumFeed(3,:),Total(3,:),LowerFeedLimits(3,:),UpperFeedLimits(3,:),[],options);
end


figure
plot(FgoalattainfvalPhase3(:,1),FgoalattainfvalPhase3(:,2),'k.');


xlabel('costPhase3 ($/100 kg feed)')
ylabel('CFPhase3 (CO2e/100 kg feed)')



xlswrite('Multi_2_objective_US_Diet_Cost_CF.xlsx', [FgoalattainfvalPhase1 FgoalattainfvalPhase2
FgoalattainfvalPhase3],'Fgoalattainfvals');
xlswrite('Multi_2_objective_US_Diet_Cost_CF.xlsx',[FgoalattainRationPhase1;FgoalattainRationPhase2;Fgoa
lattainRationPhase3],'ParetoDiet');
```

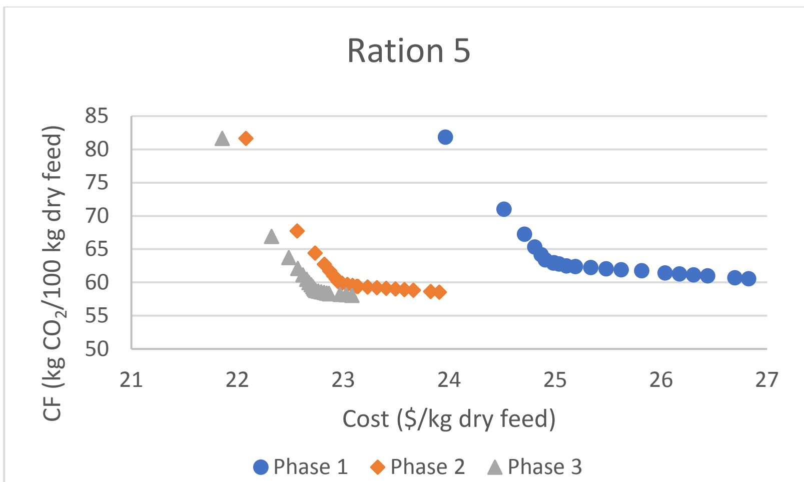
B-1. Carbon footprint (kg CO_2/kg dry feed) versus cost ($/kg of feed) for the three broiler growth phases of all seven ration scenarios from the feed optimization model. The model adjusts the amount of each ingredient to minimize the two objective functions.

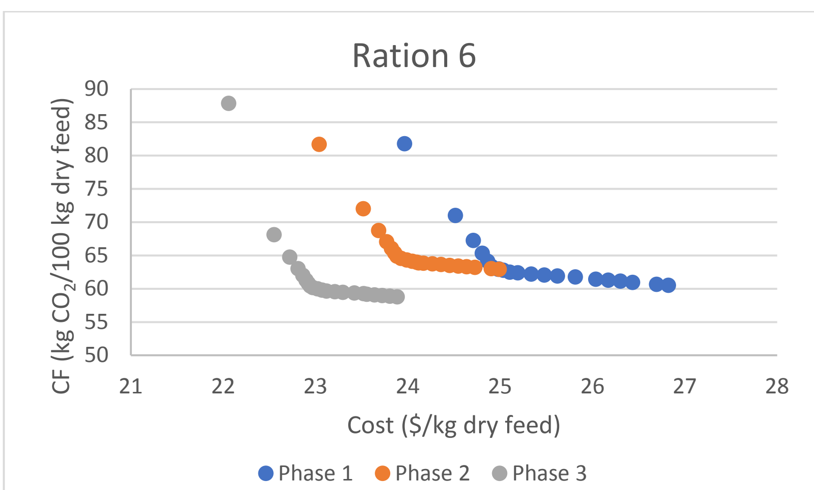


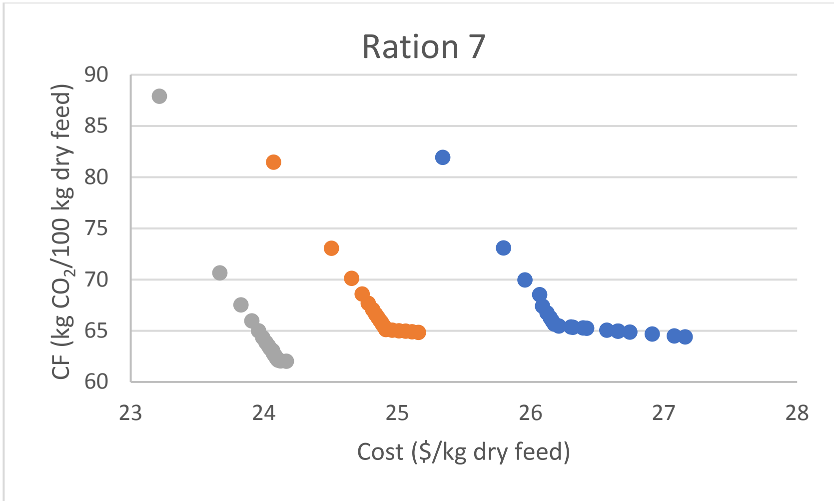





Ration 4
CF (kg CO_2/100 kg dry feed)
85
80
75
70
65
60
20
22
24
26
28
Cost ($/kg dry feed)
Phase 1
Phase 2
Phase 3


Ration 5
CF (kg CO_2/100 kg dry feed)
85
80
75
70
65
60
55
50
21
22
23
24
25
26
27
Cost ($/kg dry feed)
Phase 1
Phase 2
Phase 3


Ration 6
CF (kg CO_2/100 kg dry feed)
90
85
80
75
70
65
60
55
50
21
22
23
24
25
26
27
28
Cost ($/kg dry feed)
Phase 1
Phase 2
Phase 3



Ration 7
CF (kg CO2/100 kg dry feed)
90
85
80
75
70
65
60
23
24
25
26
27
28
Cost ($/kg dry feed)

C-1. The feed composition of the experimental ration (feed 1) produced by the multi-criteria feed optimization model. The nutrient and feed ingredient limits were set using industry standards (Cobb 2015, Hubbard 2016, Ross 2014) and the Commercial Poultry Nutrition textbook (CPN 2008).

	Feed 1		
	Phase 1	Phase 2	Phase 3
	Percent of Ration		
Corn, No. 2	46.28%	53.87%	59.97%
Soybean Meal	38.87%	33.57%	29.88%
Limestone	0.20%	0.20%	0.20%
Meat and Bone Scrap	3.27%	3.31%	2.94%
Tallow	1.00%	1.00%	1.00%
Wheat Shorts	7.99%	6.00%	3.98%
Salt	0.50%	0.50%	0.50%
Dical Phosphate	1.50%	1.19%	1.16%
DL-Methionine	0.17%	0.15%	0.14%
L-Lysine	0.01%	0.01%	0.01%
Vit-Min Mix	0.10%	0.10%	0.10%

C-2. The feed composition of the experimental ration (feed 2) produced by the multi-criteria feed optimization model. The nutrient and feed ingredient limits were set using industry standards (Cobb 2015, Hubbard 2016, Ross 2014) and the Commercial Poultry Nutrition textbook (CPN 2008).

	Feed 2		
	Phase 1	Phase 2	Phase 3
	Percent of Ration		
Corn, No. 2	51.30%	57.78%	63.61%
Soybean Meal	34.81%	30.00%	25.00%
Limestone	0.20%	0.20%	0.20%
Meat and Bone Scrap	3.32%	4.05%	4.83%
Tallow	1.00%	1.00%	1.00%
Wheat Shorts	7.00%	5.00%	4.00%
Salt	0.50%	0.50%	0.48%
Dical Phosphate	1.49%	1.03%	0.55%
DL-Methionine	0.13%	0.13%	0.01%
L-Lysine	0.01%	0.01%	0.01%
Vit-Min Mix	0.10%	0.10%	0.10%

C-3. The feed composition of the experimental ration (feed 3) produced by the multi-criteria feed optimization model. The nutrient and feed ingredient limits were set using industry standards (Cobb 2015, Hubbard 2016, Ross 2014) and the Commercial Poultry Nutrition textbook (CPN 2008).

	Feed 3		
	Phase 1	Phase 2	Phase 3
	Percent of Ration		
Corn, No. 2	51.36%	58.38%	67.26%
Soybean Meal	33.47%	29.32%	24.70%
Limestone	0.20%	0.20%	0.20%
Meat and Bone Scrap	5.60%	5.96%	5.93%
Tallow	1.00%	1.00%	1.00%
Wheat Shorts	7.00%	4.00%	0.00%
Salt	0.50%	0.50%	0.50%
Dical Phosphate	0.50%	0.20%	0.08%
DL-Methionine	0.12%	0.12%	0.01%
L-Lysine	0.01%	0.01%	0.01%
Vit-Min Mix	0.10%	0.10%	0.10%

C-4. The feed composition of the CPN ration (feed 4) produced by the multi-criteria feed optimization model. The nutrient and feed ingredient limits were set using the Commercial Poultry Nutrition textbook (CPN 2008).

	Feed 4		
	Phase 1	Phase 2	Phase 3
	Percent of Ration		
Corn, No. 2	56.60%	63.68%	69.94%
Soybean Meal	29.20%	23.93%	18.83%
Limestone	0.20%	0.20%	0.20%
Meat and Bone Scrap	3.50%	4.02%	3.99%
Tallow	1.00%	1.00%	1.00%
Wheat Shorts	7.00%	5.00%	4.00%
Salt	0.50%	0.50%	0.50%
Dical Phosphate	1.48%	1.20%	1.20%
DL-Methionine	0.16%	0.12%	0.15%
L-Lysine	0.15%	0.14%	0.08%
Vit-Min Mix	0.10%	0.10%	0.10%

C-5. The feed composition of the Hubbard ration (feed 5) produced by the multi-criteria feed optimization model. The nutrient and feed ingredient limits were set using the Hubbard Broiler Management Guide (Hubbard, 2016).

	Feed 5		
	Phase 1	Phase 2	Phase 3
	Percent of Ration		
Corn, No. 2	58.07%	65.67%	67.94%
Soybean Meal	29.12%	23.56%	22.50%
Limestone	0.20%	0.20%	0.20%
Meat and Bone Scrap	2.24%	2.50%	2.29%
Tallow	1.00%	1.00%	1.00%
Wheat Shorts	7.00%	5.00%	4.00%
Salt	0.50%	0.50%	0.50%
Dical Phosphate	1.50%	1.19%	1.20%
DL-Methionine	0.13%	0.12%	0.12%
L-Lysine	0.03%	0.06%	0.05%
Vit-Min Mix	0.10%	0.10%	0.10%

C-6. The feed composition of the Cobb ration (feed 6) produced by the multi-criteria feed optimization model. The nutrient and feed ingredient limits were set using the Cobb Broiler Management Guide (Cobb, 2012).

	Feed 6		
	Phase 1	Phase 2	Phase 3
	Percent of Ration		
Corn, No. 2	52.70%	58.74%	63.34%
Soybean Meal	33.04%	27.77%	23.83%
Limestone	0.20%	0.20%	0.20%
Meat and Bone Scrap	2.88%	3.17%	2.55%
Tallow	1.00%	1.00%	1.00%
Wheat Shorts	7.78%	7.00%	7.00%
Salt	0.50%	0.50%	0.50%
Dical Phosphate	1.50%	1.20%	1.20%
DL-Methionine	0.14%	0.15%	0.12%
L-Lysine	0.05%	0.07%	0.05%
Vit-Min Mix	0.10%	0.10%	0.10%

C-7. The feed composition of the CPN ration (feed 7) produced by the multi-criteria feed optimization model. The nutrient and feed ingredient limits were set using the Ross Broiler Management Guide (Ross, 2014).

	Feed 7		
	Phase 1	Phase 2	Phase 3
	Percent of Ration		
Corn, No. 2	46.29%	53.00%	57.35%
Soybean Meal	38.85%	33.46%	29.54%
Limestone	0.20%	0.20%	0.20%
Meat and Bone Scrap	3.29%	3.28%	2.85%
Tallow	1.00%	1.00%	1.00%
Wheat Shorts	8.00%	7.00%	7.00%
Salt	0.50%	0.50%	0.50%
Dical Phosphate	1.49%	1.20%	1.20%
DL-Methionine	0.17%	1.47%	0.14%
L-Lysine	0.01%	0.01%	0.02%
Vit-Min Mix	0.10%	0.10%	0.10%

D-1. Growth scenarios developed from industry standards (Hubbard 2016, Ross 2014, Cobb 2012). The scenarios were chosen using the minimum and maximum values for temperature, humidity, and airspeed from the three different broiler management guides to evaluate which conditions promote broiler growth.

Trial	Phase 1			Phase 2			Phase 3		
	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)	Temp (C)	Humidity (%)	Airspeed (m/s)
1	31	50	0.1	29	60	0.3	27	60	0.500
2	31	50	0.1	29	60	0.3	27	60	0.875
3	31	50	0.1	29	60	1.0	27	60	0.500
4	31	50	0.1	29	60	1.0	27	60	0.875
5	31	50	0.3	29	60	0.3	27	60	0.500
6	31	50	0.3	29	60	0.3	27	60	0.875
7	31	50	0.3	29	60	1.0	27	60	0.500
8	31	50	0.3	29	60	1.0	27	60	0.875
9	31	50	0.1	29	60	0.3	24	60	0.500
10	31	50	0.1	29	60	0.3	24	60	0.875
11	31	50	0.1	29	60	1.0	24	60	0.500
12	31	50	0.1	29	60	1.0	24	60	0.875
13	31	50	0.3	29	60	0.3	24	60	0.500
14	31	50	0.3	29	60	0.3	24	60	0.875
15	31	50	0.3	29	60	1.0	24	60	0.500
16	31	50	0.3	27	60	1.0	24	60	0.875
17	31	50	0.1	27	60	0.3	27	60	0.500
18	31	50	0.1	27	60	0.3	27	60	2.000
19	31	50	0.1	27	60	1.0	27	60	0.500
20	31	50	0.1	27	60	1.0	27	60	2.000
21	31	50	0.3	27	60	0.3	27	60	0.500
22	31	50	0.3	27	60	0.3	27	60	2.000
23	31	50	0.3	27	60	1.0	27	60	0.500
24	31	50	0.3	27	60	1.0	27	60	2.000
25	31	50	0.1	27	60	0.3	24	60	0.500
26	31	50	0.1	27	60	0.3	24	60	0.875
27	31	50	0.1	27	60	1.0	24	60	0.500
28	31	50	0.1	27	60	1.0	24	60	0.875
29	31	50	0.3	27	60	0.3	24	60	0.500
30	31	50	0.3	27	60	0.3	24	60	0.875
31	31	50	0.3	27	60	1.0	24	60	0.500
32	31	50	0.3	27	60	1.0	24	60	0.875

33	29	50	0.1	29	60	0.3	27	60	0.500
34	29	50	0.1	29	60	0.3	27	60	2.000
35	29	50	0.1	29	60	1.0	27	60	0.500
36	29	50	0.1	29	60	1.0	27	60	0.875
37	29	50	0.3	29	60	0.3	27	60	0.500
38	29	50	0.3	29	60	0.3	27	60	2.000
39	29	50	0.3	29	60	1.0	27	60	0.500
40	29	50	0.3	29	60	1.0	27	60	2.000
41	29	50	0.1	29	60	0.3	24	60	0.500
42	29	50	0.1	29	60	0.3	24	60	0.875
43	29	50	0.1	29	60	1.0	24	60	0.500
44	29	50	0.1	29	60	1.0	24	60	0.875
45	29	50	0.3	29	60	0.3	24	60	0.500
46	29	50	0.3	29	60	0.3	24	60	0.875
47	29	50	0.3	29	60	1.0	24	60	0.500
48	29	50	0.3	27	60	1.0	24	60	0.875
49	29	50	0.1	27	60	0.3	27	60	0.500
50	29	50	0.1	27	60	0.3	27	60	2.000
51	29	50	0.1	27	60	1.0	27	60	0.500
52	29	50	0.1	27	60	1.0	27	60	2.000
53	29	50	0.3	27	60	0.3	27	60	0.500
54	29	50	0.3	27	60	0.3	27	60	2.000
55	29	50	0.3	27	60	1.0	27	60	0.500
56	29	50	0.3	27	60	1.0	27	60	2.000
57	29	50	0.1	27	60	0.3	24	60	0.500
58	29	50	0.1	27	60	0.3	24	60	0.875
59	29	50	0.1	27	60	1.0	24	60	0.500
60	29	50	0.1	27	60	1.0	24	60	0.875
61	29	50	0.3	27	60	0.3	24	60	0.500
62	29	50	0.3	27	60	0.3	24	60	0.875
63	29	50	0.3	27	60	1.0	24	60	0.500
64	29	50	0.3	27	60	1.0	24	60	0.875

E-1. Summary of the environmental growth scenario results produced by the broiler growth model. The environmental scenarios (B-1) were developed from the minimum and maximum values presented by the Cobb, Hubbard, and Ross Broiler Management Guides (Cobb 2012, Hubbard 2016, Ross 2014).

Scenario	Weight (g)	Total Feed Intake (g)	Dry Matter Excretion (g)	Nitrogen excretion (g)	Phosphorus Excretion (g)	Potassium Excretion (g)
1	3.93	7.78	2.13	0.092	0.017	0.055
2	3.93	7.77	2.13	0.092	0.017	0.055
3	3.93	7.78	2.13	0.092	0.017	0.055
4	3.93	7.78	2.13	0.092	0.017	0.055
5	3.93	7.81	2.14	0.093	0.017	0.055
6	3.93	7.80	2.14	0.093	0.017	0.055
7	3.93	7.80	2.14	0.093	0.017	0.055
8	3.93	7.80	2.14	0.093	0.017	0.055
9	3.94	7.71	2.12	0.092	0.017	0.055
10	3.93	7.69	2.11	0.091	0.017	0.055
11	3.94	7.71	2.11	0.092	0.017	0.055
12	3.93	7.69	2.11	0.091	0.017	0.055
13	3.94	7.74	2.12	0.092	0.017	0.055
14	3.94	7.72	2.12	0.092	0.017	0.055
15	3.94	7.74	2.12	0.092	0.017	0.055
16	3.94	7.72	2.12	0.092	0.017	0.055
17	3.93	7.77	2.13	0.092	0.017	0.055
18	3.94	7.74	2.12	0.092	0.017	0.055
19	3.93	7.77	2.13	0.092	0.017	0.055
20	3.94	7.73	2.12	0.092	0.017	0.055
21	3.93	7.80	2.14	0.093	0.017	0.055
22	3.94	7.76	2.13	0.092	0.017	0.055
23	3.93	7.80	2.14	0.093	0.017	0.055
24	3.94	7.76	2.13	0.092	0.017	0.055
25	3.94	7.71	2.11	0.092	0.017	0.055
26	3.93	7.69	2.11	0.091	0.017	0.055
27	3.94	7.70	2.11	0.092	0.017	0.055
28	3.93	7.68	2.11	0.091	0.017	0.054
29	3.94	7.73	2.12	0.092	0.017	0.055
30	3.94	7.72	2.12	0.092	0.017	0.055
31	3.94	7.73	2.12	0.092	0.017	0.055
32	3.94	7.71	2.11	0.092	0.017	0.055

33	3.94	7.99	2.19	0.095	0.017	0.057
34	3.94	7.95	2.18	0.095	0.017	0.056
35	3.94	7.99	2.19	0.095	0.017	0.057
36	3.94	7.95	2.18	0.094	0.017	0.056
37	3.94	8.03	2.20	0.095	0.017	0.057
38	3.94	7.99	2.19	0.095	0.01	0.057
39	3.94	8.02	2.20	0.095	0.017	0.057
40	3.94	7.99	2.19	0.095	0.017	0.057
41	3.94	7.93	2.17	0.094	0.017	0.056
42	3.94	7.91	2.17	0.094	0.017	0.056
43	3.94	7.92	2.17	0.094	0.017	0.056
44	3.94	7.90	2.17	0.094	0.017	0.056
45	3.94	7.96	2.18	0.095	0.017	0.056
46	3.94	7.94	2.18	0.094	0.017	0.056
47	3.94	7.96	2.18	0.095	0.017	0.056
48	3.94	7.94	2.18	0.094	0.017	0.056
49	3.94	7.98	2.19	0.095	0.017	0.057
50	3.94	7.95	2.18	0.094	0.017	0.056
51	3.94	7.98	2.19	0.095	0.017	0.057
52	3.94	7.94	2.18	0.094	0.017	0.056
53	3.94	8.02	2.20	0.095	0.017	0.057
54	3.94	7.98	2.19	0.095	0.017	0.057
55	3.94	8.02	2.20	0.095	0.017	0.057
56	3.94	7.98	2.19	0.095	0.017	0.057
57	3.94	7.92	2.17	0.094	0.017	0.056
58	3.94	7.92	2.17	0.094	0.017	0.056
59	3.94	7.90	2.17	0.094	0.017	0.056
60	3.94	7.90	2.17	0.094	0.017	0.056
61	3.94	7.96	2.18	0.095	0.017	0.056
62	3.94	7.94	2.18	0.094	0.017	0.056
63	3.94	7.95	2.18	0.095	0.017	0.056
64	3.94	7.93	2.18	0.094	0.017	0.056

F-1. Summary of the growth scenario results for the scenarios using the feed optimization model scenarios and the variable environmental scenarios. The feed optimization scenarios (Feeds 1-7) were developed industry standards (Cobb 2012, Ross 2014, Hubbard 2016, CPN 2008). The variable environmental scenarios (B-1) developed from the Broiler Management Guide's min and max for temperature, humidity, and airspeed.

Trial (F+E)	Weight (g)	Total Feed Intake (g)	Dry Matter Excretion (g)	Nitrogen excretion (g)	Phosphorus Excretion (g)	Potassium Excretion (g)
1 + 38	3.92	6.6969	1.84	0.093	0.023	0.051
2 + 38	3.94	7.1195	1.95	0.093	0.027	0.049
3 + 38	3.94	6.9884	1.92	0.092	0.028	0.046
4 + 38	3.94	7.34	2.01	0.084	0.025	0.044
5 + 38	3.94	7.41	2.03	0.087	0.023	0.047
6 + 38	3.94	7.37	2.02	0.091	0.025	0.050
7 + 38	3.94	7.39	2.03	0.102	0.027	0.057
1 +40	3.94	7.36	2.02	0.102	0.026	0.055
2 +40	3.94	7.12	1.95	0.093	0.027	0.049
3 +40	3.94	6.99	1.92	0.092	0.028	0.046
4 +40	3.94	7.34	2.01	0.084	0.025	0.044
5 +40	3.94	7.40	2.03	0.087	0.022	0.047
6 +40	3.94	7.37	2.02	0.091	0.025	0.050
7 +40	3.94	7.39	2.03	0.102	0.027	0.057
1 + 45	3.94	7.33	2.01	0.101	0.026	0.055
2 + 45	3.94	7.09	1.95	0.093	0.027	0.049
3 + 45	3.94	6.96	1.91	0.092	0.028	0.046
4 + 45	3.94	7.31	2.01	0.084	0.025	0.043
5 + 45	3.94	7.38	2.02	0.086	0.022	0.047
6 + 45	3.94	7.34	2.01	0.091	0.024	0.050
7 + 45	3.94	7.36	2.02	0.102	0.027	0.057
1 + 47	3.94	7.33	2.01	0.101	0.026	0.055
2 + 47	3.94	7.09	1.94	0.093	0.027	0.049
3 + 47	3.94	6.96	1.91	0.092	0.028	0.046
4 + 47	3.94	7.31	2.00	0.083	0.025	0.043
5 + 47	3.94	7.38	2.02	0.086	0.022	0.047
6 + 47	3.94	7.34	2.01	0.091	0.024	0.050
7 + 47	3.94	7.36	2.02	0.102	0.027	0.057
1 + 54	3.94	7.35	2.01	0.102	0.026	0.055
2 + 54	3.94	7.11	1.95	0.093	0.027	0.049
3 + 54	3.94	6.98	1.91	0.092	0.028	0.046

4 + 54	3.94	7.33	2.01	0.084	0.025	0.044
5 + 54	3.94	7.40	2.03	0.087	0.022	0.047
6 + 54	3.94	7.36	2.02	0.091	0.024	0.050
7 + 54	3.94	7.38	2.02	0.102	0.027	0.057
1 + 56	3.94	7.35	2.02	0.102	0.026	0.055
2 + 56	3.94	7.11	1.95	0.093	0.027	0.049
3 + 56	3.94	6.98	1.91	0.092	0.028	0.046
4 + 56	3.94	7.33	2.01	0.084	0.025	0.044
5 + 56	3.94	7.40	2.03	0.087	0.022	0.047
6 + 56	3.94	7.36	2.02	0.091	0.024	0.050
7 + 56	3.94	7.38	2.02	0.102	0.027	0.057
1 + 61	3.94	7.33	2.01	0.101	0.026	0.055
2 + 61	3.94	7.0882	1.94	0.093	0.027	0.049
3 + 61	3.94	6.9576	1.91	0.092	0.028	0.046
4 + 61	3.94	7.3060	2.00	0.083	0.025	0.043
5 + 61	3.94	7.3751	2.02	0.086	0.022	0.047
6 + 61	3.94	7.3384	2.01	0.091	0.024	0.050
7 + 61	3.94	7.3561	2.02	0.102	0.027	0.057
1 + 62	3.94	7.3098	2.00	0.101	0.026	0.055
2 + 62	3.94	7.0713	1.94	0.093	0.027	0.049
3 + 62	3.94	6.9410	1.90	0.092	0.028	0.046
4 + 62	3.94	7.2883	2.00	0.083	0.025	0.043
5 + 62	3.94	7.3573	2.02	0.086	0.022	0.047
6 + 62	3.94	7.3208	2.01	0.090	0.024	0.050
7 + 62	3.94	7.3386	2.01	0.102	0.026	0.056
1 + 63	3.94	7.3245	2.01	0.101	0.026	0.055
2 + 63	3.94	7.0855	1.94	0.093	0.027	0.049
3 + 63	3.94	6.9549	1.91	0.092	0.028	0.046
4 + 63	3.94	7.3032	2.00	0.083	0.025	0.043
5 + 63	3.94	7.3723	2.02	0.086	0.022	0.047
6 + 63	3.94	7.3357	2.01	0.091	0.024	0.050
7 + 63	3.94	7.3534	2.02	0.102	0.027	0.057
1 + 64	3.94	7.31	2.00	0.101	0.026	0.055
2 + 64	3.94	7.07	1.94	0.093	0.027	0.049
3 + 64	3.94	6.94	1.90	0.092	0.028	0.046
4 + 64	3.94	7.29	2.00	0.083	0.025	0.043
5 + 64	3.94	7.35	2.02	0.086	0.022	0.047
6 + 64	3.94	7.32	2.01	0.090	0.024	0.050
7 + 64	3.94	7.34	2.01	0.102	0.026	0.056

G-1. Life cycle assessment inputs for the variable feed and environmental conditions

Feed Scenario	Live Weight (kg)	Electricity (kWh)	LPG (gal)	Feed (kg)	Water (kg)	Litter (kg)	N_20 (kg)	NH_3 (kg)
1 + 38	3.917	20321.49	2840.04	561052.89	1633150.8	33759.44	80.66	4986.41
2 + 38	3.937	20422.65	2854.18	596457.47	1703959.9	34779.36	81.68	5049.12
3 + 38	3.936	20420.06	2853.82	585474.18	1681993.4	34463.44	80.88	4999.78
4 + 38	3.937	20423.69	2854.33	614804.85	1740654.7	35308.24	73.36	4535.24
5 + 38	3.938	20426.28	2854.69	620602.29	1752249.6	35475.44	75.91	4692.78
6 + 38	3.938	20426.80	2854.76	617502.50	1746050.0	35385.68	79.59	4920.24
7 + 38	3.938	20430.43	2855.27	618960.24	1748965.5	35427.92	89.59	5538.28
1 +40	3.938	20429.91	2855.20	616304.48	1743654.0	35351.36	88.97	5500.24
2 +40	3.937	20422.65	2854.18	596222.89	1703490.8	34773.20	81.68	5049.12
3 +40	3.936	20420.06	2853.82	585247.97	1681541.0	34456.40	80.88	4999.78
4 +40	3.937	20423.69	2854.33	614561.90	1740168.8	35301.20	73.28	4529.82
5 +40	3.938	20426.28	2854.69	620367.71	1751780.4	35468.40	75.91	4692.78
6 +40	3.938	20426.80	2854.76	617267.93	1745580.9	35379.52	79.59	4920.24
7 +40	3.938	20430.43	2855.27	618734.04	1748513.1	35420.88	89.50	5532.87
1 + 45	3.939	20430.95	2855.34	614352.45	1739749.9	35295.04	88.72	5484.28
2 + 45	3.937	20423.69	2854.33	594337.89	1699720.8	34718.64	81.42	5033.14
3 + 45	3.937	20421.09	2853.96	583388.10	1677821.2	34402.72	80.62	4983.80
4 + 45	3.937	20424.73	2854.47	612584.74	1736214.5	35244.00	73.11	4519.23
5 + 45	3.938	20427.32	2854.83	618382.17	1747809.4	35411.20	75.65	4676.78
6 + 45	3.938	20427.84	2854.91	615299.14	1741643.3	35322.32	79.33	4904.25
7 + 45	3.939	20431.47	2855.41	616773.64	1744592.3	35364.56	89.24	5516.91
1 + 47	3.939	20430.95	2855.34	614126.25	1739297.5	35288.00	88.72	5484.28
2 + 47	3.937	20423.69	2854.33	594103.31	1699251.6	34711.60	81.42	5033.14
3 + 47	3.937	20421.09	2853.96	583161.90	1677368.8	34396.56	80.62	4983.80
4 + 47	3.937	20424.73	2854.47	612350.16	1735745.3	35236.96	73.02	4513.82
5 + 47	3.938	20427.32	2854.83	618139.22	1747323.4	35404.16	75.65	4676.78
6 + 47	3.938	20427.84	2854.91	615064.56	1741174.1	35315.28	79.25	4898.83
7 + 47	3.939	20431.47	2855.41	616547.44	1744139.9	35358.40	89.24	5516.91
1 + 54	3.938	20429.91	2855.20	616044.77	1743134.5	35343.44	88.97	5500.24
2 + 54	3.937	20422.65	2854.18	595963.18	1702971.4	34765.28	81.68	5049.12
3 + 54	3.936	20420.06	2853.82	584979.89	1681004.8	34449.36	80.79	4994.37
4 + 54	3.937	20423.69	2854.33	614293.81	1739632.6	35293.28	73.28	4529.82
5 + 54	3.938	20426.28	2854.69	620091.24	1751227.5	35460.48	75.83	4687.37
6 + 54	3.938	20426.80	2854.76	616999.84	1745044.7	35371.60	79.50	4914.82
7 + 54	3.938	20430.43	2855.27	618465.95	1747976.9	35413.84	89.50	5532.87

1 + 56	3.938	20429.91	2855.20	615818.57	1742682.1	35337.28	88.89	5494.83
2 + 56	3.937	20422.65	2854.18	595728.60	1702502.2	34759.12	81.59	5043.71
3 + 56	3.936	20420.06	2853.82	584753.68	1680552.4	34442.32	80.79	4994.37
4 + 56	3.937	20423.69	2854.33	614059.23	1739163.5	35286.24	73.19	4524.41
5 + 56	3.938	20426.28	2854.69	619856.67	1750758.3	35453.44	75.83	4687.37
6 + 56	3.938	20426.80	2854.76	616773.64	1744592.3	35364.56	79.50	4914.82
7 + 56	3.938	20430.43	2855.27	618248.13	1747541.3	35406.80	89.41	5527.45
1 + 61	3.939	20430.95	2855.34	613858.16	1738761.3	35280.96	88.63	5478.87
2 + 61	3.937	20423.69	2854.33	593835.22	1698715.4	34703.68	81.33	5027.73
3 + 61	3.937	20421.09	2853.96	582893.81	1676832.6	34388.64	80.53	4978.39
4 + 61	3.937	20424.73	2854.47	612082.07	1735209.1	35229.92	73.02	4513.82
5 + 61	3.938	20427.32	2854.83	617871.13	1746787.3	35396.24	75.57	4671.37
6 + 61	3.938	20427.84	2854.91	614796.48	1740638.0	35307.36	79.25	4898.83
7 + 61	3.939	20431.47	2855.41	616279.35	1743603.7	35350.48	89.16	5511.49
1 + 62	3.938	20427.84	2854.91	612400.42	1735845.9	35238.72	88.44	5467.21
2 + 62	3.937	20421.09	2853.96	592419.37	1695883.7	34663.20	81.15	5016.27
3 + 62	3.936	20417.98	2853.53	581503.10	1674051.2	34349.04	80.35	4966.81
4 + 62	3.937	20422.13	2854.11	610599.20	1732243.4	35186.80	72.83	4502.42
5 + 62	3.937	20424.21	2854.40	616379.88	1743804.8	35353.12	75.38	4659.83
6 + 62	3.937	20424.73	2854.47	613321.98	1737689.0	35265.12	79.06	4887.26
7 + 62	3.938	20428.36	2854.98	614813.23	1740671.5	35308.24	88.97	5499.83
1 + 63	3.939	20430.95	2855.34	613631.96	1738308.9	35273.92	88.63	5478.87
2 + 63	3.937	20423.69	2854.33	593609.02	1698263.0	34697.52	81.33	5027.73
3 + 63	3.937	20421.09	2853.96	582667.61	1676380.2	34382.48	80.53	4978.39
4 + 63	3.937	20424.73	2854.47	611847.49	1734740.0	35222.88	72.93	4508.41
5 + 63	3.938	20427.32	2854.83	617636.55	1746318.1	35389.20	75.57	4671.37
6 + 63	3.938	20427.84	2854.91	614570.27	1740185.6	35301.20	79.25	4898.83
7 + 63	3.939	20431.47	2855.41	616053.15	1743151.3	35344.32	89.16	5511.49
1 + 64	3.938	20427.84	2854.91	612174.22	1735393.5	35232.56	88.35	5461.79
2 + 64	3.937	20421.09	2853.96	592193.17	1695431.3	34657.04	81.15	5016.27
3 + 64	3.936	20417.98	2853.53	581276.90	1673598.8	34342.00	80.35	4966.81
4 + 64	3.937	20422.13	2854.11	610364.62	1731774.2	35180.64	72.75	4497.01
5 + 64	3.937	20424.21	2854.40	616145.30	1743335.6	35346.96	75.38	4659.83
6 + 64	3.937	20424.73	2854.47	613095.78	1737236.6	35258.96	78.97	4881.85
7 + 64	3.938	20428.36	2854.98	614595.41	1740235.8	35302.08	88.88	5494.41

H-1. Life cycle impact assessment results for variable environmental and feed parameters

Scenario	Weight (kg)	GWP (kg CO_2 eq)	EU (kg N eq)	AP (kg SO_2 eq)	ECO (CTUe)	FEU (MJ Surplus)
1+38	3.917	0.97406	0.01749	0.03967	2.02493	0.57169
1+40	3.937	1.04489	0.01901	0.04322	2.17825	0.61560
1+45	3.936	1.04219	0.01895	0.04309	2.17240	0.61392
1+47	3.937	1.04191	0.01894	0.43090	2.17174	0.61374
1+54	3.938	1.04457	0.01900	0.04321	2.17749	0.61540
1+56	3.938	1.04421	0.01899	0.04318	2.17683	0.61519
1+61	3.938	1.04153	0.01894	0.04306	2.17099	0.61354
1+62	3.938	1.03971	0.01890	0.04297	2.16699	0.61238
1+63	3.937	1.04124	0.01893	0.04305	2.17032	0.61333
1+64	3.936	1.03935	0.01889	0.04294	2.16631	0.61218
2+38	3.937	0.98395	0.01853	0.03990	2.01375	0.56104
2+40	3.938	0.98367	0.01852	0.03989	2.01311	0.56087
2+45	3.938	0.98112	0.01847	0.03977	2.00769	0.55933
2+47	3.938	0.98085	0.01846	0.03977	2.00700	0.55916
2+54	3.939	0.98336	0.01852	0.03989	2.01239	0.56067
2+56	3.937	0.98302	0.01851	0.03985	2.01178	0.56050
2+61	3.937	0.83110	0.01608	0.03566	1.53103	0.45139
2+62	3.937	0.97873	0.01841	0.03965	2.00262	0.55790
2+63	3.938	0.98020	0.01845	0.03973	2.00572	0.55880
2+64	3.938	0.97846	0.01841	0.03965	2.00200	0.55773
3+38	3.939	0.93414	0.01797	0.03906	1.80070	0.53078
3+40	3.939	0.93388	0.01797	0.03905	1.80016	0.53062
3+45	3.937	0.93151	0.01791	0.03893	1.79544	0.52921
3+47	3.937	0.93124	0.01791	0.03893	1.79487	0.52902
3+54	3.937	0.93349	0.01794	0.03877	1.79942	0.53041
3+56	3.938	0.93324	0.01794	0.03876	1.79887	0.53025
3+61	3.938	0.92898	0.01789	0.03889	1.78639	0.52788
3+62	3.939	0.92929	0.01786	0.03882	1.79108	0.52790
3+63	3.938	0.93062	0.01789	0.03889	1.79367	0.52867
3+64	3.937	0.92903	0.01785	0.03881	1.79051	0.52772
4+38	3.936	1.03253	0.01972	0.03755	2.09014	0.60086
4+40	3.937	1.03214	0.01971	0.03752	2.08939	0.60063
4+45	3.938	1.02949	0.01965	0.03742	2.08374	0.59900
4+47	3.938	1.02911	0.01965	0.03739	2.08305	0.59877
4+54	3.938	1.03180	0.01971	0.03751	2.08863	0.60041

4+56	3.938	1.03146	0.01970	0.03748	2.08801	0.60024
4+61	3.937	1.02878	0.01964	0.03739	2.08234	0.59857
4+62	3.936	1.02690	0.01960	0.03730	2.07837	0.59742
4+63	3.937	1.02842	0.01963	0.03735	2.08168	0.59836
4+64	3.938	1.02652	0.01959	0.03727	2.07770	0.59720
5+38	3.938	1.03940	0.01989	0.03874	2.10799	0.60215
5+40	3.938	1.02276	0.01996	0.03885	2.20207	0.65103
5+45	3.939	1.03636	0.01982	0.03861	2.10160	0.60027
5+47	3.937	1.03850	0.01987	0.03864	2.10643	0.60168
5+54	3.937	1.03869	0.01988	0.0387	2.10655	0.60171
5+56	3.937	1.03841	0.01987	0.03869	2.10592	0.60154
5+61	3.938	1.03566	0.01981	0.03857	2.10019	0.59986
5+62	3.938	1.03380	0.01977	0.03849	2.09627	0.59873
5+63	3.939	1.03538	0.01980	0.03857	2.09956	0.59968
5+64	3.938	1.03350	0.01976	0.03848	2.09562	0.59853
6+38	3.937	1.05787	0.01971	0.03999	2.26149	0.61622
6+40	3.936	1.05755	0.01971	0.03998	2.26073	0.61599
6+45	3.937	1.05478	0.01965	0.03986	2.25458	0.61431
6+47	3.937	1.05440	0.01964	0.03983	2.25386	0.61410
6+54	3.937	1.05715	0.01970	0.03995	2.25994	0.61578
6+56	3.938	1.05682	0.01969	0.03994	2.25920	0.61552
6+61	3.939	1.05413	0.01963	0.03982	2.25319	0.61392
6+62	3.937	1.05218	0.01959	0.03974	2.24881	0.61271
6+63	3.937	1.05379	0.01963	0.03982	2.25238	0.61371
6+64	3.937	1.05182	0.01958	0.03971	2.24812	0.61253
7+38	3.938	1.09738	0.01933	0.04361	2.35897	0.68797
7+40	3.938	1.09702	0.01933	0.04358	2.35825	0.68776
7+45	3.939	1.09416	0.01927	0.04345	2.35182	0.06972
7+47	3.938	1.09383	0.01926	0.04345	2.35100	0.68560
7+54	3.937	1.09666	0.01932	0.04357	2.35738	0.68749
7+56	3.936	1.09630	0.01931	0.04354	2.35667	0.68728
7+61	3.937	1.09340	0.01925	0.04342	2.35014	0.68534
7+62	3.937	1.09149	0.01921	0.04333	2.34579	0.68407
7+63	3.937	1.11535	0.01969	0.04377	2.40344	0.70121
7+64	3.938	1.09112	0.01920	0.04330	2.34506	0.68386