Application of non-linear modelling to efficiency and nutrient partitioning in broilers and broiler breeders

by

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ABSTRACT

Nutritive values of feedstuffs used in broiler rations vary significantly. Corn and wheat are the primary energy sources in many broiler diets, depending on geographical availability. As feed is a large proportion of live production costs, broiler operations may decrease diet nutrient density to reduce overall diet cost, however this reduction may have a negative impact on broiler performance and yield. The performance, yield, and allometric relationships were examined in broiler offspring from North American or European male lines crossed with Ross 708 breeder females (NA x 708; EU x 708, respectively), and fed diets of differing dietary balanced protein (DBP) levels. Growth and performance were examined on corn- (Corn Experiment) and wheat (Wheat Experiment) based diets. It was thought the EU x 708 broilers would have higher growth and yield performance on wheat-based diets compared to the NA x 708 broilers due to primary cereal use during genetic selection. In each experiment, 1,600 broilers were allocated into 32 pens of 50 birds with 4 replicate pens per treatment. Part 1 of the thesis focused on the growth performance, yield, efficiency and allometric growth of the pectoralis muscles, drum + thigh, liver, heart, fat-pad, and small intestines of the broiler. Results indicated DBP and genetic strain were significantly interrelated on the influence of growth and development of broilers.

Part 2 of the thesis studied the energy partitioning of broiler breeder pullets reared in commercial settings. Maintenance requirements are studied in broiler breeders due to the need for feed restriction to maintain healthy body weight and reproductive performance of the flock. However, many studies have been performed in research settings which can not replicate industry conditions. Metabolizable energy of maintenance (ME_m) was estimated utilizing data collected from 8,558 Ross 308 broiler breeders reared in floor housing at two commercial breeder operations. ME_m per metabolic body weight ($BW/kg^{0.67}$) requirements were lowest during periods of high feed restriction. Our estimation of maintenance was consistent with other studies under tightly regulated research settings.

PREFACE

This thesis is an original work by Airell DesLauriers. Funding for this project was provided by Aviagen, Alberta Chicken Producers, Alberta Livestock and Meat Agency Ltd., Alberta Hatching Egg Producers, Growing Forward, and Natural Sciences and Engineering Research Council of Canada. Publication is intended for Chapters 2 and 3 with co-authors D.R. Korver and M.J. Zuidhof. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Aviagen Broiler Strain Trial, No. 194/06/13; Improved hatchability via data handling best management practices in the broiler chick supply chain, No. AUP133.

DEDICATION

To those who wander and those who ponder.

To my parents, my brother, and Elyse who always encouraged me to pursue my goals.

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AA	Amino Acid
ADG	Average Daily Gain
AME	Apparent Metabolizable Energy
BW	Body Weight
CP	Crude Protein
CV	Coefficient of Variation
d	Day/s
DBP	Dietary Balanced Protein
DIT	Diet-induced Thermogenesis
df	Degrees of Freedom
EODES	Erratic Oviposition and Defective Egg Syndrome
EU	European
FCR	Feed Conversion Ratio
FI	Feed Intake
g	Gram
h	Hour
ME	Metabolizable Energy
ME_m	Metabolizable Energy of Maintenance
NA	North American
P. Major	*Pectoralis major*
P. Minor	*Pectoralis minor*
RFI	Residual Feed Intake
SS	Sum of Squares
wk	Week

1. Introduction

1.1 Origin of the domesticated chicken

Archeological evidence found in the Indus Valley of South East Asia shows domestication origins of the chicken (*Gallus gallus domesticus*) dating back to early 2000 BC (West and Zhou, 1989). According to an analysis of mitochondrial DNA, the Red Jungle Fowl (*Gallus gallus*) is the original matriarchic ancestor from which modern breeds were developed (Fumihito et al., 1994). There is some debate over which species was the first to be domesticated; however, the domestic chicken had some contributions from at least one other closely related species, the Grey Jungle Fowl (Eriksson et al., 2008). Chickens were first kept and domesticated not as a source of food but for entertainment purposes in the form of cockfighting in Asia, Africa, and Europe until the 1800's when cockfighting became illegal (Al-Nasser et al., 2007). It was at this point poultry breeders started to breed for exhibition where the birds were selected for uniformity and plumage coloration creating heritage breeds (Havenstein, 1991). Heritage breeds that have made major contributions in poultry production today are Cornish, Plymouth Rock, and the White Leghorn (Havenstein, 1991). The Plymouth Rock were used heavily in broiler selection for their body conformation and propensity for weight gain, whereas Leghorns were used for their high egg production (Al-Nasser et al., 2007).

1.2 Modernization of the broiler

Commercial broiler production in North America began in the 1930s with the multipurpose breed, Barred Plymouth Rock. In the 1930s and 1940s, Frederic Hutt and Randall Cole demonstrated that genetic progress was achievable on quantitative traits like egg production and disease resistance (Hunton, 2006). This began the long-term research to follow in the development of formal breeding programs. Shortly thereafter, several companies formed to develop their pedigree specialty breeds to improve productivity and efficiency. Breeding programs became focused on two primary purposes; poultry meat and eggs, leading to a divergence in poultry genetics.

Two main genetic types exist today, one for meat (broilers) and one focused on egg production (layers). Modern genetics have evolved substantially since 1957 as broilers at 42 d weighed 0.59 kg with a feed conversion ratio (FCR) of 2.8. A 42-d-old modern broiler weighs 2.90 kg with an FCR of under 1.70 (Schmidt et al., 2009; Zuidhof et al., 2014). Although advances in growth rate and efficiency have been affected by innovations in environmental equipment, infrastructure, and disease control, 85 to 90% is due to genetic improvement, and 10 to 15% is due to advances in nutrition (Havenstein et al., 1994, 2003).

1.3 Global demand for poultry

Through advances in efficiency, chicken meat has become more affordable, and global per capita consumption has doubled since the 1980s (National Chicken Council, 2019a). On a global scale, chicken has surpassed pork as the most consumed animal protein (OECD/FAO, 2019). Chicken has grown from a substitute for other meats to a staple on dinner plates globally. With the Earth's population expected to reach 9.1 billion by 2050, producers of today would have to produce 70% more food to adequately feed the world (FAOSTAT, 2019). Demand for animal-based proteins is increasing due to this population growth and a general increased trend of urbanization and income (FAO, 2018). Poultry meat is consumed across many religions, cultures, and geographic regions, making it key to food security and nutrition. Among the livestock sectors, poultry is the most efficient sector in the use of natural resources and providing protein to sustain the ever-growing population.

There has been a variety of changes in product packing techniques to allow for versatility, convenience, and microbial safety of products (Kerry et al., 2006). Packing improvements have allowed for a significant shift in the marketing structure of poultry meat; for instance, in 1962, 83% of broilers were marketed as whole birds, 17% as cut-up and further processed in the United States (National Chicken Council, 2019b). However, in 2019 12% of broilers went to whole bird markets with 88% marketed as cut-up and further processed (National Chicken Council, 2019b). Due to the changes in marketing of broiler meat, there is an increased focus on the rapid growth, yield, and conversion of edible portions.

The current global production of chicken meat is forecast to reach a record 98.4 million tons annually by the end of 2019 (USDA, 2019). Global demand for poultry is projected to increase faster than any other protein source (USDA, 2019). Leading this global demand the past five years is China, in part due to the outbreaks of African Swine Fever drawing consumers toward other protein sources; this increase in demand will likely spur further expansion in the global poultry marketplace (USDA, 2019).

1.4 Influence of genetic selection

1.4.1 Body Weight

In the 1950s, a typical broiler grew substantially slower and require more feed than a modern broiler. Significant genetic progress has occurred over the past 25 years; in 1985, in 35 days, a broiler consumed 3.22 kg of feed and weighed 1.40 kg. In 2010 they consumed 3.66 kg of feed and weighed 2.44 kg (Siegel, 2014). Several studies have attempted to categorize the progress due to genetics and advances in nutrition. A study examining the Athens-Canadian Randombred Control (ACRBC) with a modern line from 1976 determined that of the 225% increase in growth rate, 90% of this increase was due to advancement in genetics (Sherwood, 1977). Similar studies were conducted in 1991 and 2001 comparing the ACRBC line with a modern Arbor Acres line. A 1957 random-bred strain male grew to 858 g in 56 d compared to 3,368 g in 1991 (Havenstein et al., 1994). The 1991 Arbor Acres line was 3.92 times heavier at 56 d of age, with over 91% of the increase attributed to genetics (Havenstein et al., 1994). In 2001 the Ross 308 was 4.77 times heavier than the ACRBC, with over 95% of this accounted by genetic advancement. Using diet formulations for the Ross 308, a random-bred strain from 1957, 1978, and 2005 grew to 905 g; 1,808 g; 4,202 g; respectively at 56 d (Zuidhof et al., 2014). Broiler growth rates have increased by over 400% from 1957 to 2005, with a 50% reduction in FCR overall (Zuidhof et al., 2014). Significant changes in feed intake and nutritional profile for the modern broiler have led to an overall reduction in the number of days required to market a 2.3 kg broiler; from ~52 days in 1985 to 36 days in 2019 (Aviagen, 2019a).

1.4.2 Feed Intake

Traditionally it was thought that broilers will adjust feed intake relative to dietary energy requirements (Leeson et al., 1996). Two mechanisms regulate dietary intake in the heritage chicken: the glucostatic and lipostatic feed regulation theories. The glucostatic theory states that birds attempt to maintain blood glucose levels by increased appetite when blood glucose levels are low and suppressed appetite when there are high blood glucose levels (Ferket and Gernat, 2006; Fagundes et al., 2019). The lipostatic theory relates to the regulation of feed intake (FI) based on body fat content; an increase in body fat-suppressed intake through satiety sensors (lipid hormone) and increase appetite when fat reserves are low (Ferket and Gernat, 2006). These theories are not entirely confirmed through scientific studies. Commercial strains utilized in the 1950's regulated feed intake to meet dietary energy requirements (Hill et al., 1956; Donaldson et al., 1957). When examining the modern broiler, there is evidence that FI has been influenced by intense genetic selection for high body weight (BW) and yield (Havenstein et al., 2003). Growth and FI were estimated to have a genetic correlation of 0.7, indicating that 70% of genetic variation in growth is associated with FI (Pym and Nicholls, 1979). Early studies observed lines selected for high BW resulted in increased FI; due to the intense selection pressures for growth, broilers may have a modified satiety system (Burkhart et al., 1983). Broilers are perpetually hungry and will frequently eat to crop physical capacity (Bokkers and Koene, 2003). It has been proposed that this is due to changes in nutrient requirements (Havenstein et al., 2003) as well as changes in the hypothalamic control of FI (Burkhart et al., 1983). Several factors have shown to influence food intake in genetic lines that have undergone selection over 58 generations for low or high juvenile BW. Factors include melanocyte-stimulating hormone (MSH) (Cline et al., 2008), corticotrophin-releasing factor (CRF) (Cline et al., 2009), insulin (Smith et al., 2011), amylin (Cline et al., 2010), ghrelin (Xu et al., 2011), and neuropeptide AF (Newmyer et al., 2010).

With the significant changes in genetic potential of the modern broiler and the strong propensity for intake, many of the influences for feed intake have changed. Modern broiler breeders have lost the ability to regulate intake for reproduction, therefore if broiler breeders are left to consume feed ad libitum, poor reproduction and laying abnormalities such as erratic oviposition and defective egg syndrome (EODES) will result (Yu et al., 1992). Historical studies demonstrated that FI and subsequent BW gain is a complex interaction between protein, fat, and metabolizable energy content of the feed (Pesti and Smith, 1984). This did not support the original theory of birds eating to meet energy requirements. Further study in this area concluded that higher amino acids (AA) levels have a positive relationship on overall FI, however, this is dependent upon the stage of development (Sterling et al., 2006; Razuki and Rawi, 2007; Kumar et al., 2016).

1.5 Dietary Amino Acid Formulation

AA are essential constituents of all protein and animal tissues and have a major effect on the growth and performance of broilers (Faridi et al., 2015). Understanding the broiler’s nutritional requirements for individual AA allows for the optimization of ingredients to precise AA levels instead of least-cost formulation on a crude protein basis. This has allowed feed to be formulated to optimize essential amino levels resulting in better performance and overall lower feed costs for the producer (Cerrate and Corzo, 2019).

1.5.1 Limiting Amino Acids

Liebig's law of the minimum can be applied to many aspects of agriculture production. It states that growth is dictated by the scarcest resource available, not by the total amount of resources. This is true in protein synthesis, where protein synthesis can only proceed until the first limiting AA is depleted. In the event that an AA is in the incorrect balance and is limiting, the production of protein is halted, and unused AA are deaminated and catabolized as an energy source.

In poultry, the first two limiting AA in corn-soy and wheat-soy broiler diets are methionine and lysine, respectively (Vieira et al., 2004). In diet formulation, synthetic AA have become a common means of increasing limiting amino acids. Synthetic AA such as lysine, methionine, threonine, and valine are frequently used in poultry diets due to the cost advantage of adding individual amino acids vs adding AA-rich ingredients such as soybean meal. Due to the overall cost savings for including synthetic AA to boost limiting AA, they are utilized widely in modern formulations.

1.5.2 Ideal Protein

The ideal protein concept is that poultry require AA in balance with each other to optimize the growth and production of animals. The ideal protein concept was first conceptualized by Fraps (1943), and the first ideal protein diet met the requirements of growing chicks through the use of purified ingredients (Mitchell, 1962). The experiment was moderately successful for optimizing growth and efficiency; however, the concept of an ideal protein was refined using lysine as the reference AA. The ideal protein concept was first developed in pigs; therefore, as lysine is first limiting in swine diets; all other AA were then kept in an ideal ratio to the reference level of lysine. This was done for several reasons 1) lysine is an essential AA, and the ideal ration of indispensable AA to lysine should be unchanged; 2) it is economical to supplement; 3) analysis of lysine in diets is relatively simple, 4) lysine is used mostly for protein synthesis and maintenance, 5) lysine requirements of swine were readily available at the time (Emmert and Baker, 1997). Several studies further refined the ideal protein ratios outlined for poultry (Baker and Han, 1994; National Research Council, 1994; Emmert and Baker, 1997; Corzo et al., 2003; Wu, 2014). Overall ideal AA ratios are fairly consistent, however ideal ratios between individual AA and lysine are affected by age, environmental temperature, and stress. Although lysine is generally the second limiting AA in most wheat-soy and corn-soy commercial diets, lysine is the reference AA due to its importance in protein synthesis and, therefore, meat production (Emmert and Baker, 1997). These ideal ratios are not consistent throughout a broiler's lifetime, as they vary through phases of development and production (Gous et al., 1990). This was confirmed as increases in dietary balanced protein (DBP) levels did not cause an isometric linear increase in breast meat and carcass composition throughout phases (Smith and Pesti, 1998). The importance of feeding AAs in ideal ratios is in part due to AA that are similar in structure; this causes AA to compete for transporters and are antagonists during intestinal absorption.

Antagonism also exists between arginine and lysine; this relationship was first noted in chicks in the 1960s (Jones, 1961, 1964). Aviagen indicates ideal Arg:Lys ratios of 1.05, 1.06, and 1.05 for 0 to 10 d, 11 to 24 d, and 25 to 40 d, respectively (Aviagen, 2019b), however ideal Arg:Lys ratios in the literature range between 0.90–1.18 (Mack et al., 1999; Balnave and Brake, 2002). In meat-type ducks, increased dietary levels of arginine reduced adipose deposition and adipose cell size (diameter and volume; Wu et al., 2011). Ross 308 broilers had reduced abdominal fat yield when dietary arginine was increased from 0.80 % to 1.25% of the diet (Corzo et al., 2003). A similar response was observed when arginine levels increased from 1.05 to 1.31%. Investigations in the late 1960s documented that arginine and lysine compete for absorption due to a similar AA structure (Fisher et al., 1960; Jones, 1961; Dean and Scott, 1968); however, Arg:Lys levels between 1.10 and 1.40 failed depress broiler performance (Mendes et al., 1997). When the Arg:Lys ratio was increased further from 1.05 to 1.70, no depression on BW gain was observed (Szabó et al., 2014). Recent studies have proposed ideal Arg:Lys ratios of 1.15, 1.15, 1.16, and 1.17 for 0 to 12, 13 to 22, 23 to 33, and 34 to 43 days (Zampiga et al., 2018). A decrease in FCR was observed with higher Arg:Lys ratios, but FCR was not affected by ratios from 1.17 to 2.10 (Fouad et al., 2013), or in diets containing arginine levels to either meet (100%) or exceed (105% to 110%) National Research Council (NRC, 1994) recommendations (Laika and Jahanian, 2017).

Methionine, lysine, and arginine are important in ideal ratios to satisfy the needs of protein synthesis as they are frequently the first three limiting AA and limit excessive fat deposition. In chickens methionine, arginine, and lysine regulate several metabolic processes and influence immune function (Lee et al., 2002; Corzo et al., 2003; Mirzaaghatabar et al., 2011; Wu et al., 2012; Jankowski et al., 2016). Higher dietary ratios of methionine and arginine to lysine increased the immunological status of poultry (Lee et al., 2002; Corzo et al., 2003). Arginine, in particular, is important for development of the thymus and spleen and lymphocyte and macrophage functions (Kwak et al., 1999, 2001; Jahanian and Khalifeh-Gholi, 2018). Methionine and arginine are of particular importance as they regulate many metabolic pathways and are referred to as functional amino acids (Wu, 2013; Jankowski et al., 2014). Relative lysine, arginine and methionine levels are also critical as dietary interrelationships exists (Chamruspollert et al., 2002; Jahanian and

Khalifeh-Gholi, 2018). A study performed with Ross x Ross broilers found excess lysine depressed muscle creatine concentration; however, only when lower concentrations of arginine and methionine were fed (Chamruspollert et al., 2002). If one AA is provided in a less than ideal ratio, this can lead to deamination of excess AAs and breakdown of the ketoacid as an energy source (Pesti, 2009). When energy-containing nutrients are provided in excess of requirements, it will undergo lipid synthesis to be deposited as fat.

Recently, Arg:Lys ratios have undergone significant scrutiny due to their involvement in breast muscle myopathies. A reduction in woody breast scores was observed in 45-d-old broilers when levels of dietary arginine to lysine ratios were increased from 1.12 to 1.20; 1.14 to 1.26; 1.15 to 1.26; 1.14 to 1.26 in the starter (1 to 12 days), grower (13 to 24 days), finisher (25 to 36 days), and withdrawal (37 to 45 days) phases respectively (Bodle et al., 2018). Subsequent studies found that increasing Arg:Lys ratios by 30% reduced some white striping (intermuscular lipid deposits), woody breast (overly hard in texture), and spaghetti breast (separation of muscle fiber bundles) meat abnormalities (Zampiga et al., 2019).

1.5.3 Low Amino Acid Density Diets

Because proteins are composed of specific AA chains, and poultry have a requirement for essential AA plus sufficient amino nitrogen to synthesize non-essential AA, expressing requirements for crude protein (CP) has become outdated. Over the last 16 years of broiler production, the general trend is towards lower inclusions of dietary CP in exchange for lysine and crystalline AA supplementation (Cerrate and Corzo, 2019). One reason for developing reduced-CP broiler diets is to reduce the nitrogen excretion to the environment, and for overall gut health. Reducing nitrogen excretion has a positive impact on bird welfare and decreases the incidence of footpad dermatitis (Van Harn et al., 2019). Feeding reduced crude protein diets also improve overall gut health by reducing the protein unabsorbed by the small intestine and available for cecal microbes. Crude protein can successfully be reduced in broilers with no effect on performance given that essential AA and sufficient non-specific amino nitrogen are provided (Corzo et al., 2005a). In the same timeframe, broilers have become 19% more efficient in utilizing digestible lysine (Cerrate and Corzo, 2019). Several synthetic AA have become inexpensive to produce; therefore, their use in feeding programs has increased and has allowed the reduction of dietary CP while still meeting AA requirements. The general trend in broiler production has been to reduce CP level in exchange for meeting individual AA requirements. Commercially, lower CP feeds are achieved through fortification of feeds with crystalline sources of lysine, methionine, threonine, and valine. Isoleucine is also commercially available; however, current costs of production are prohibitive for viable use in diets (Berres et al., 2010). Broiler performance is minimally impacted by diets marginal in CP, but fortified with synthetic sources of methionine and lysine (Parr and Summers, 1991; Pesti, 2009; Rawat et al., 2018). Broilers utilize excess dietary AA as energy in metabolic processes; however, through this process, deamination occurs, and amino groups are excreted as uric acid (Dalólio et al., 2016). It is thought that the reduction of CP in broiler diets is energetically advantageous as energy is required to excrete AA that are provided in excess of requirements or in excess of an ideal ratio to the first limiting AA.

Increased concerns regarding the agriculture sector's contribution to nitrogen pollution in the environment have put significant pressure on mitigating nitrogen excretion from broiler operations. Fertilizer, as well as animal production contributions to these emissions, have been identified by a European directive (European Council, 2010). From this directive, several proposed techniques for emission reduction have been identified to be adopted in the intensive rearing of poultry and swine (European Comission, 2015). Suggested approaches include reduction of dietary CP by using balanced diets based on digestible AA, multi-phase feeding, and the use of enzyme technologies (European Comission, 2015). Through these changes, it is suggested that emissions can be reduced from 600 g to 200 g total nitrogen excretion per broiler per year (European Council, 2010). Several legislative bodies globally are imposing guidelines on broiler production to reduce overall nitrogen excretions and implement on farm nitrogen management controls. An ordinance defining best practices has been released by the German Federal Ministry of Food and Agriculture with total restrictions of nitrogen excretions of 385 to 413 g/location/year associated with broilers grown to 39 days or longer (German Federal Ministry of Justice and Consumer Protection, 2017). Currently, there are no consequences outlined for not meeting requirements; however, it is expected that these environmental controls will only become more stringent in the future.

1.6 Efficiency

The concept of efficiency has been traditionally defined as a ratio of inputs to outputs. This allows for indices of efficiency to been utilized where a weighted average of inputs is compared with outputs. The goal of defining these relationships is to determine the maximum output that can be derived with a set amount of inputs. Generally, this relationship is utilized in the animal production sector to determine the least-cost efficiency of production. That is, to ensure that production is obtained at the lowest possible per-unit cost. This ideology has been utilized when determining the least-cost formulation when evaluating broiler rations, by reducing the input cost into the animal, the costs of producing the same output product are reduced. Due to this relationship, efficiency is commonly expressed as a relative expression of feed to gain or FCR.

Within the context of bio-economic modelling, inputs are defined as the amount of feed given to an animal and generally, the outputs are meat gain, milk production, egg production, etc. This is important to determine the efficiency of each of the animals in a particular production system;

however, we may also examine the economic efficiency of the whole system, also factoring in natural and human resources required to produce food for humans.

1.6.1 Energetic efficiency

Efficiency is the ratio of useful energy delivered by a dynamic system; to the energy supplied to it (Merriam-Webster, 2020). The term biological efficiency is usually applied when examining the efficiency of a biological system from the perspective of energy utilization. Evolution has led to selection for optimal survival strategies rather than increased biological efficiency (Stevens, 1991). Typically, biological systems run at less than ideal capacities. In the poultry industry, 26% of total energy required to produce 1 kg of meat is in the form of feed; the remainder is in the form of gasoline (43%), natural gas (21%), and electricity (10%); the cost of feed is also the highest overall cost (Sefat et al., 2014). In a neural network modelling studying of broiler production unit efficiency, 97% of the total output of chemical energy was in the form of meat, and the remaining 3% was in the form of manure (Sefat et al., 2014). FCR, the ratio of g of feed consumed:g of BW gain, was one of the first measures of efficiency in livestock. Within the livestock sector, poultry production is estimated to be the most efficient subsector (Mottet et al., 2017).

Energetic efficiency is difficult to quantify in biological systems due to difficulties in accurately determining the energy loss and transfer from one form to another (Nascimento et al., 2017). In order to determine the energetic efficiency of a system, we need to define efficiency. There are several methods to partition energy in biological systems that account for different types of energetic losses in poultry. Determining the ideal energy systems to use when measuring efficiency is critical to account for all energetic losses of the system. The importance of biological energetic efficiency in animal production is to reduce the amount of energy released as heat and other losses to the environment therefore increasing the energy that is converted to usable forms.

1.6.2 Energy conservation

In animal nutrition, energy in two forms are of concern, energy in the form of chemical bonds and heat. Energy can take many different forms in a system; however, with any system, whether it is biological or non-living, the laws of thermodynamics will hold true. All measurements of energy conversions are measured in the form of thermal energy or joules (J). With many conversions of energy, there is an energy ‘cost’ lost in the form of heat associated with the conversion. Therefore, when examining the conversion of animal feed to body mass, there will be an energetic loss that will take place. The energy that is lost as heat during the conversion of a particular feedstuff to muscle or fat is lost as diet-induced thermogenesis (DIT). This is the energy cost of nutrient absorption, transport, and assimilation, together with the energy cost of synthetic processes (Rothwell et al., 1982). Chicks are constantly converting energy that is stored in chemical bonds into ATP through the Krebs cycle (Hu et al., 2017).

Diet-induced thermogenesis may play a role in the regulation of energy balance within poultry due to BW being accompanied by an increase in metabolic rate (Sims et al., 1973; Barzegar et al., 2020). The purpose of energetics is to determine an accurate representation of the energy balance of an individual given BW, activity level, sex, physiological state, environmental temperature, and feed intake (Spratt et al., 1990; Wu et al., 2019). The findings of these studies have been used to develop several species-specific feeding recommendations as published by the NRC. Each species has unique energy requirements, however there is significant genetic variation within a species. In order to determine variations between animals it has become vital to examine the efficiency in which these conversions are happening (Baldwin, 1984).

1.6.2.1 Energy Systems

As a by-product of metabolism, energy is inevitably lost to the environment in many forms such as fecal matter, gaseous or urinary losses, and heat. As feed formulation can affect overall body composition, it is important to take into account the energy content and losses of feedstuffs when formulating diets (Sibbald, 1980). Energy models are vital for determining variances in energetic efficiencies due to animal and dietary differences. There has been much controversy concerning the optimum energy system for standardizing energy requirements and the energy content of feeds.

Different energy systems can be utilized to compare requirements and feedstuff energy content. The metabolizable energy (ME) system is the most common form of energy partitioning currently used in the poultry industry. ME is the energy remaining after fecal, urinary, and gaseous energy losses are removed from the gross energy (GE) or total energy of a feedstuff. Another system is the net energy system (NE), which takes into account the heat increment, urinary, gaseous, and fecal energy losses of a particular feedstuff (Noblet et al., 1994).

The major issue with the implementation of the NE system to poultry diets is the determination of NE in feeds. The value of moving from a ME system to a NE is still a subject of much debate (Van der Klis and Jansman, 2019).

Currently, feed composition databases including NE values are limited, and therefore more research is required for poultry feed formulation based on NE. However, promising techniques have been developed for predicting NE of feeds that may reduce the costs (Pirgozliev and Rose, 1999).

The NE system builds on the ME system by accounting for the heat increment losses and biochemical inefficiencies into feed formulation. Although the ME system takes into account the losses from excretion of urinary waste; the NE system takes one step further to account for the energetic cost of excreting excess nitrogenous wastes (Birkett and de Lange, 2001). Noblet et al. (1994) demonstrated that when swine were fed diets formulated using NE, feed costs were significantly reduced. The use of the NE system in swine has reduced of the overall cost of feeding due to adjustments accounting for the heat increment associated with crude fibre in the hindgut of pigs (Patience, 2012). In poultry feeds, crude fibre content and therefore cecal fermentation is a relatively insignificant sources of energy. A possible environmental advantage of utilizing a NE system is feeding precisely to requirements, thereby reducing the excess excretion of nitrogen and phosphorous, increasing overall energy utilization. An increase in feed efficiency would also lead to less use of resources and, therefore, could reduce water use and greenhouse gas emissions. Due to the complexity, accuracy, and cost associated with estimating NE content of feeds the merits of the NE system for use in poultry feeding is still undergoing much debate (Mateos et al., 2019; Van der Klis and Jansman, 2019).

1.6.3 Measuring efficiency

1.6.3.1 Residual feed intake

There have been several approaches to measure the efficiency of animals. Efficiency is becoming a greater concern due to the recent focus on environmental concerns of intensive agriculture. This is a potential area for improvement as feed costs currently make up 60 to 70% of the total cost of poultry production (Donohue and Cunningham, 2009). Producers are motivated to reduce feed costs to increase profit margins. In the past, many other types of production parameters were utilized as selection tools, however, they have been replaced with more focus on the economic feasibility rather than direct production levels.

Residual feed intake (RFI) was first proposed in cattle as an alternate measure of feed efficiency (Koch et al., 1963). Residual feed intake is a measure of the residual portion between the amount an animal's actual feed intake compared to expected feed intake at a given level of production or growth (Koch et al., 1963). RFI is a measure of efficiency, when an animal has a lower RFI they are more efficient than the average animal at a given production level. Therefore, by selecting animals with low RFI, animals are selected to eat less with the same level of production. Since residual feed intake is the difference between actual feed intake and expected feed intake of the animal, at a given BW, weight gain, and egg production it is independent of production level (Koch et al., 1963). This method is advantageous as it accounts for feed intake, BW, and production traits in evaluation. It is an improvement from the traditionally used FCR, also taking into account maintenance costs by using the metabolic BW (Koch et al., 1963). The selection of cattle based on RFI has been utilized through the use of automated feed and growth data provided by GrowSafe® and similar systems (Okine et al., 2004; Wang et al., 2006). A reduction in the feed intake of cattle without a decrease in performance was observed by utilizing RFI as a selection criterion (Okine et al., 2004). This allows for increased efficiencies leading to a reduction in methane gas produced. When RFI of cattle was measured, there was a 28% reduction in methane from low RFI cows compared to high RFI cows (Nkrumah et al., 2006). This is important for finding energy-efficient ways to produce consumable protein and reducing the carbon footprint of livestock production.

The popularity of utilizing RFI in egg layers has increased, as it has intermediate heritability (Luiting and Urff, 1991b); however, it also has high phenotypic variability (Luiting, 1990). Increases in growth efficiencies have been observed through the use of RFI in genetic selection criteria in broilers. Several studies have been performed using divergent selection based on positive (R+) or negative (R-) RFI values. The less efficient R+ broilers had larger feed intakes than the R- birds (Gabarrou et al., 1998). The more efficient R- birds had lower ME intake (Luiting and Urff, 1991a) and lower heat production (Katle, 1991) than R+ birds at the same level of production, however only when the birds were in a fed state (Luiting and Urff, 1991a). In a fasted state, heat production between the R- and R+ birds was not significantly different; therefore, the differences observed were due to increases in DIT (Gabarrou et al., 1998). In another study in laying hens, R- hens had increased shell thickness (Bordas and Merat, 1981), hatching and fertilization rate, and decreased early embryo death in layer breeders (Morisson et al., 1997). In R+ layers, an increase in corticosterone was observed (Luiting et al., 1994). This is an important issue for selection in broilers, as increases in corticosterone reduce meat quality (Kannan et al., 1997). Although many studies have been conducted in layers, there is a lack of current research in this area in broilers and broiler breeders.

1.6.3.2 Maintenance Requirements

Selection based strictly on a single measure of productivity may not increase every aspect of production. Negative impacts of low RFI selection were also observed, examples being increases in adiposity in laying hens (Katle, 1991), and reduced mean egg weight (Katle, 1991; Bordas et al., 1992). A reduction in egg weight can be explained by a severe fault not accounted for by the RFI system. RFI fails to separate the heat production of maintenance of existing tissues from that of production; since the maintenance of adipose tissues contributes less heat than lean tissue (Close, 1990). Selection based purely on RFI may reduce maintenance cost, thereby favouring less maintenance-intensive adipose tissue rather than muscle. This results in birds that are more efficient but with higher adipose tissue deposition. A factor that will favour a reduced FI in RFI selection is DIT. High feed intake results in greater DIT, with the animals consequently losing more energy as heat to their environment. When selecting birds based strictly on RFI, the selection process will be skewed to select for more productive but less consuming animals (Romero et al., 2009a).

1.6.3.2.1 RME_m

Inadvertently, with increased pressure for selection of low RFI scoring animals, a reduction in overall BW may be observed (Romero et al., 2009a). This has led to the development of the concept of residual metabolizable energy of maintenance (RME_m), which is the residual between estimated ME requirements and ME intake (Romero et al., 2009a). This methodology attempts to correct for the bias of selecting smaller and less productive animals by removing the confounding effect of feed intake and the resulting DIT (Romero et al., 2009a). A nonlinear model to estimate ME intake of broiler breeders is used to determine RME_m (Romero et al., 2009a). As RME_m takes into account the differences in DIT, it is an excellent tool for genetic selection (Romero et al., 2009a). However, further understanding of the heritability and effects RME_m has on other production traits are required before the implementation of RME_m as a selection criterion (Romero et al., 2009a).

Most production models are developed utilizing research data, and in these settings, many factors affecting maintenance are tightly controlled. The development of a theoretical model that accurately represents industry data is complex due to many factors that affect efficiency. The coefficients utilized in the RME_m model are not generalized for utilization in general industry settings. By collecting industry data and determining the average maintenance energy coefficients, a more accurate model of bird requirements can be developed. With a data set obtained from an industry setting and by comparing model-calculated feed intake values to actual feed intake values, the accuracy of the model can be determined. Some of the factors that influence the maintenance requirement for poultry are environmental temperature (Donkoh, 1989), gut microflora (Muramatsu et al., 1994), activity, feather cover (Richards, 1977) and immune response (Amat et al., 2007).

With selection for decreased maintenance energy requirements of birds, it is important to ensure that through severe selection for one production parameter, others are not adversely affected. During inflammatory stress, the bird will produce higher levels of heat (Liu et al., 2015). A concern with severe selection focused on the reduction of maintenance expenditures is the negative effect it may have on the immunological status of the bird. By selecting for a reduction in maintenance energy requirement, birds with a less active immune system may be indirectly selected. There has been no adverse effect on immunological strength with selection based on RFI (Van Eerden et al., 2004). This could be attributed to the percentage of RFI utilized by the acquired immune system under unchallenged conditions being relatively small (Korver, 2012). However, as it becomes possible to isolate maintenance energy more precisely utilizing RME_m, the energy utilized by the immune system may be examined for increased efficiency.

With selection based on RME_m as a measure of efficiency at the pedigree and great-grandparent breeder level, primary breeders are able to increase efficiency without sacrificing production, thereby increasing profit margins. Through development of selection procedures using RME_m genetics companies can enhance the efficiency and productivity of the poultry industry.

1.7 Unintended consequences of selection

One of the major concerns with the selection and improvement of broilers through genetics is how to raise the parents of the genetic stock in a welfare-friendly manner. Broiler breeders are the chickens responsible for producing the offspring used for consumption of meat products. With growth-focused selection, often other essential components of livability may not be accurately represented in the selection process; for example; mortality of ad-libitum fed broiler breeders is 50% due to morbid obesity after ~360 days (Katanbaf et al., 1989). The major problem is that the parent stock (broiler breeders) have the same genetic growth potential as the broilers. This may cause problems in broiler breeders because they do not grow at an appropriate rate for optimal reproduction.

Allowing broiler breeders to eat *ad-libitum* causes leg issues, joint problems, decreased immune function as well as negative effects on fertility, egg production, and hatchability (Su et al., 1999; Whitehead, 2002; Renema and Robinson, 2004).

Broiler breeders have the same genetic growth potential as broilers, which means they must be managed differently to avoid reproductive challenges. A concern with the management of broiler breeders is the control of BW during the rearing and reproduction phases. Broiler breeders are feed-restricted due to the negative relationship between adipose tissue and egg production (Decuypere et al., 2010). Excess energy intake is deposited primarily as fat, therefore to prevent excessive fat deposition, broiler breeders are fed at close to maintenance requirements. Feed restriction is most severe in the rearing stage and feed intake is restricted to 15 to 33% of *ad-libitum* compared to 50 to 90% in the laying stage (Van Krimpen and De Jong, 2014). Feed restriction during rearing is critical in programming egg production, health status, and longevity of the bird, making it vital to determine the degree of feed restriction during this period correctly.

1.7.1 Welfare concerns of feed restriction

The industry has attempted to deal with the welfare implications of *ad-libitum* feeding through feed restriction, and although these birds are physically hungry, it reduces the incidence of metabolic disorders in the flock (Hocking and Duff, 1989; Decuypere et al., 2010). Feed restriction is cost-effective because it increases feed efficiency of the flock, leading to a decrease in feed costs as well as a decrease in the maintenance requirement of the birds. However, problems have been observed with feed restriction due to hunger such as feather pecking, increased aggression, and stress behaviour before or during feeding times (Hocking and Duff, 1989; Mench, 2002; Sandilands et al., 2006).

When considering the welfare of any animal, it is important to consider if the five freedoms of the animal are met (Webster, 2007). Feed restriction has been criticized as it violates the first freedom, the freedom from thirst, hunger and malnutrition (Webster, 2007). Feed restriction increases the secretion of corticosterone, and can be elevated for up to 10 weeks after the introduction of feed restriction (Rosales, 1994; Mench, 2002). Feed restriction also impacts immune function; a study on feed restricted broiler breeder hens found no differences in eosinophil, basophil, and monocyte counts among feeding regimes; although, feed-restricted birds had normal antibody titers, broiler offspring from feed restricted hens resulted in offspring that have a reduced immune response to a lipopolysaccharide injection (Bowling et al., 2018). It can also be argued that the fifth freedom to express normal behaviours is violated as normal behaviour may be repressed during a period of high stress when feed is restricted leading to an increase in the prevalence of stress-induced destructive behaviours such as feather pecking, vent pecking, and cannibalism (Rosales, 1994).

1.8 Feeding of broilers

Feed costs as a percentage of live production costs have increased substantially through the years, from 51.8% in 2001 to 68.7% in 2008 to approximately 80% in 2015, due to greater economies of scale (Donohue and Cunningham, 2009; Rufino et al., 2015). Due to the closer proximity and lower price of wheat compared to corn, western Canadian poultry producers include wheat as a primary feedstuff in broiler diets.

In the European broiler market, it is relatively common for wheat to be used as the primary feedstuff in broiler diets due to reduced cost and absence of carotenoid pigments that may cause undesired coloration of the carcass skin (Gutiérrez del Álamo, 2009). Traditionally, genetic selection for broiler growth and performance for US broiler strains were performed on corn-based diets, whereas UK strains were selected on wheat-based diets. Moran, et. al, (1993) observed a large reduction of broiler performance in US strains when fed wheat-based diets compared to UK strains. This suggests a synergistic relationship between strain and the primary cereal source; therefore, different commercially-fed broilers strains may respond differently to dietary wheat inclusion.

Previous research has shown the sensitivity of breast muscle development to reduced lysine levels (Tesseraud et al., 1996a; Kidd et al., 1998). Acar et al. (1991) observed an increased breast muscle yield and greater lysine need in a UK broiler strain than in a US strain. Lysine fed at above the requirements for growth significantly increased breast yield; signifying that optimal lysine levels for optimal breast yield is higher than that for optimal growth (Hickling et al., 1990; Acar et al., 1991; Bilgili et al., 1992).

In some cases in Europe, wheat is utilized for 50 to 55% of total apparent metabolizable energy (AME) and 35 to 40% of the protein in the feed (Wiseman et al., 2000). Crude protein levels of wheat can be highly affected by genotype, year, cultivation site, and fertilizer (Gutiérrez del Álamo, 2009). Growth performance of broilers fed different wheat samples can differ by up to 13% due to differences in AME; however, this variation is reduced through the addition of an exogenous xylanase and glycanase enzyme (Scott et al., 1998a; b). Total tract starch digestibility of different Western Canadian wheat cultivars in Ross 308 broilers only differed by 0.9% when xylanase was present, however the location where absorption occurred varied within the small intestine (Karunaratne et al., 2018).

1.9 Objectives for the study

When comparing corn- to wheat-based broiler diets, efficiency differences must be considered to ensure any reduction in performance is warranted by a reduction in feed costs. This study allows for a clearer understanding of the response of modern genetic strains to wheat inclusion in the diet. This will have a benefit to the Canadian poultry industry as well as globally when formulating diets to obtain productive benchmarks. It has previously been observed that Western Canadian chicken producers in particular have lower broiler performance as compared to global production. The purpose of this study is to examine if a reduction in AA levels or a strain x diet interaction is a contributing factor in the observation of lower broiler performance.

The DBP concept is to provide each essential AA in an exact amount that meets animal requirements precisely; therefore, all essential AA are provided with no deficiency or excess (Emmert and Baker, 1997). With this concept, all AA requirements are represented as a ratio to lysine.

Genetic selection criteria have evolved substantially as broiler time to market weight has reduced by approximately 0.5 days per year. Therefore, it is important to examine the performance of modern high-yield broiler genetics on various dietary cereal sources.

Due to regional differences where the broilers will be grown, the North American pedigree line is thought to be selected primarily on corn diets, whereas the European pedigree line is thought to be selected on wheat diets. As a result, the objectives of this thesis were to specifically examine the growth and efficiency (Chapter 2) and allometric development (Chapter 3) of a North American strain and a European strain raised on either corn- and wheat-based diets.

Chapter 4 of the thesis utilized industry data to estimate and validate existing estimates of maintenance requirements in broiler breeders. The estimation of these coefficients has primarily been in controlled research settings, therefore, validation of models to accurately describe commercial settings is required.

The main research questions for this thesis were: Do North American and European broiler respond difference on wheat- and corn-based diets? Does a reduction in AA levels contribute to the differences in broiler performance on wheat- vs corn-based diets? Can we accurately estimate maintenance requirements for commercially reared broiler breeder pullets?

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2. Effect of dietary balanced protein on performance and carcass characteristics in offspring of two broiler male-lines

2.1 Abstract

Amino acid nutrition has a significant impact on the growth rate, feed efficiency, yield and carcass composition of broilers, and may interact with broiler strain. Two 2 x 2 factorial experiments were conducted to observe growth and yield differences in broilers from North American or European male lines crossed with Ross 708 females (NA x 708; EU x 708, respectively), fed diets containing dietary balanced protein at 100% (DBP100) or 90% (DBP90) of the Ross 708 recommendations. Performance was examined using corn- (Corn Experiment) and wheat- (Wheat Experiment) based diets. We hypothesized that EU x 708 birds would have higher growth and yield performance on wheat-based diets relative to NA x 708 birds due to wheat-based diets being used during selection. We hypothesized that DBP100 would increase growth and yield relative to DBP90 diets. Broilers obtained for this study were offspring from 43-wk-old Ross 708 female breeders crossed to either a NA or an EU male line. In each experiment, 1,600 broilers were allocated into 32 pens of 50 birds with 4 replicate pens per treatment at a stocking density of 0.069 m^2/bird. Pen BW gain and feed intake data were collected at 0, 10, 25, and 35 d and feed conversion ratio (FCR) was calculated. At 35 d of age, 144 broilers from each experiment were processed to collect carcass, portion weights, and yields. In the Wheat Experiment, *Pectoralis (P.) major and P. minor* yields were 10.5% and 5.04% higher, respectively in the NA x 708 broilers fed DBP100 than the EU x 708 broilers fed DBP100; the EU x 708 fed DBP90 yielded 21.2% and 11.7% less, respectively than the NA x 708 DBP100 treatment. EU x 708 broilers had 9.5% and 4.8% lower, respectively *P. major and P. minor* yield than the NA x 708 fed DBP100; however, no significant difference was found between strains when fed DBP90 (P = 0.005 and 0.042, respectively). The NA x 708 strain was less susceptible to reduced DBP compared to the EU x 708.

Keywords: broiler chicken, strain, efficiency, carcass composition, dietary balanced protein

2.2 Introduction

Feed costs as a percentage of live production costs have increased dramatically since 2001, from 51.8% to approximately 70% in 2013 due to economies of scale (Donohue and Cunningham, 2009; Willems et al., 2018). Many areas that are suitable for wheat production globally are also well suited for poultry production. Due to the local availability and lower price of wheat compared to corn and the absence of carotenoid pigments that may cause undesired coloration of the carcass skin for that market, producers may include wheat as a primary feedstuff in broiler diets (Gutiérrez del Álamo, 2009). Diets from regions that utilize wheat as a primary cereal grain tend to be higher in protein and lower in energy than diets that contain a high proportion of corn.

Acar et al. (1991) observed an increased breast muscle yield and greater lysine requirement in an EU broiler strain than in a US strain. Moran et al. (1993) observed a 1.2% reduction of broiler performance in US strains when fed wheat diets compared to EU strains. This suggests a relationship between the broiler strain and protein source utilized during selection and primary protein source used in production. Different commercial broiler crosses may respond differently to dietary cereal type. In some cases, wheat provides 50 to 55% of the total apparent metabolizable energy (AME) and 35 to 40% of protein in the feed (Wiseman et al., 2000). Since wheat can constitute approximately 35 to 70% of the total diet, the amino acid (AA) profile of the wheat plays an important role in diet AA supply. Growth performance of broilers fed different wheat sources can differ by 13% (Scott et al., 1998a; b) because crude protein levels of the wheat are highly variable and are affected by genotype, crop year, cultivation site, and fertilizer used (Gutiérrez del Álamo, 2009). Increasing dietary crude protein (CP) density increases performance and breast meat yield and reduces fat deposition (Johnson et al., 2019). This is of high importance to processing sectors in which breast meat is the highest value part of the carcass.

Optimizing meat production is a significant issue facing the global poultry industry. Carcass composition is profoundly affected by AA intake, specifically lysine affects lean composition of the carcass, abdominal fat content, and breast yield (Han and Baker, 1993; Tesseraud et al., 1996b, 2001; Leclercq, 1998; Kidd et al., 2005; Sterling et al., 2006; Kidd and Tillman, 2016; Sharma et al., 2018). The dietary lysine level that supports maximum breast yield is higher than that of the breeder recommendations for optimal growth (Acar et al., 1991; Bilgili et al., 1992; Sharma et al., 2018). Feed cost is the greatest variable cost of production, but the effect and value of the cutup carcass need to be considered when calculating profitability. This will enable decisions surrounding the suitability of the NA x 708 and the EU x 708 in different broiler markets. The objective of this study was to examine if a reduction in AA levels is a contributing factor in reduced broiler performance on wheat- vs corn-based diets. It was hypothesized that DBP100 would increase BW growth and lean yield relative to DBP90 diets in each of corn-and wheat-based diets.

2.3 Materials and Methods

2.3.1 Experimental design

Two experiments were conducted to determine the relationship between broiler genetic strain and dietary protein level on broiler growth and development. In each experiment, broilers were randomly assigned into a 2 x 2 factorial arrangement of treatments examining the relationship between broiler strain and dietary balanced protein (DBP) levels. All research protocols were approved by the University of Alberta Animal Care and Use Committee for Livestock and followed the principles established by the Canadian Council on Animal Care (Canadian Council on Animal Care, 2009).

2.3.1.1 Genetic Strains

Two genetic lines were utilized, the offspring of a European male line crossed with Ross 708 hens (EU x 708) and the offspring of a North American male line crossed with the same flock of Ross 708 hens (NA x 708).

2.3.1.2 Diets

The study was conducted using two different levels of DBP in either corn-based diets (Corn Experiment; Table 2-1) or wheat-based diets (Wheat Experiment; Table 2-2); the experiments ran concurrently. A three-phase feeding program was used in each experiment: starter (0 to 10 d of age), grower (11 to 25 d of age) and finisher (26 to 35 d of age). Avizyme® 1302; (Xylanase, 5,000 U g^{-1}; Protease, 1,600 U g^{-1}; Danisco Animal Nutrition, Marlborough, Wiltshire, UK), and Quantum Blue Phytase (5,000 U g^{-1}; AB Vista, Marlborough, Wiltshire, UK) were included. Within each experiment, the DBP100 diet was formulated to contain at least 100% of 2007 Aviagen's 708 recommendations (Aviagen, 2007a) for lysine, methionine, total sulfur amino acids (TSAA), threonine, valine, isoleucine, arginine, and tryptophan for each dietary phase. The DBP90 diet was formulated to contain lysine at 90% of Aviagen recommendations, with each of the first 7 limiting AA fed at constant digestible lysine:AA ratios across the diets within each phase, based on the Aviagen recommendations (Aviagen, 2007; Table 2-1). Although diets were formulated to the same digestible AA specifications in each experiment, analyzed levels of lysine were on average 7.85% lower than expected in the Wheat Experiment (Table 2-2).

2.3.2 Birds and management

At hatch, a total of 1,600 mixed-sex broilers from each strain were placed in a light-tight facility, in 32 pens with four replicate pens of 50 birds per pen (0.069 m^2/bird). At placement, 10% of the chicks were randomly selected and individually identified using wing bands. Birds received

23 h of light/d at 20 to 30 lux for the first 7 days. After day 7, the lighting program was 20L:4D at 5 to 10 lux.

2.3.3 Data Collection

Individual BW of wing-banded birds were recorded twice weekly. Pen BW were measured weekly. Dissections were performed at 36 days of age on randomly predetermined birds, identified at placement, feed was withdrawn 24 hours prior. The selected birds were euthanized humanely by cervical dislocation. At sampling time, whole BW, *Pectoralis (P) major*, *P. minor*, drum, thigh, and wing weights were determined; percent yield of each was calculated on an eviscerated carcass basis. Eviscerated carcass weight did not include the abdominal and neck fat weight. Feed intake and feed conversion ratios were recorded. Mortality was recorded and weighed; group weights and feed conversion ratios (FCR; kg feed/group BW) were corrected for mortality. Sex was determined at dissection.

2.3.4 Analysis

2.3.4.1 Chemical Analysis

Analysis of each diet was performed using the following methods of AOAC (2006) for crude protein (Method 984.13, (A-D)), crude fat (Method 920.39 (A)) and crude fiber content (Method 978.10); total phosphorus and calcium content were analyzed utilizing inductively-coupled plasma-optical emission spectroscopy (AOAC Method 985.01 (A,B,D)); AA profile without tryptophan (AOAC Official Method 982.30 E(A,B)). All feed analyses were performed at the Experiment Station Chemical Laboratories, University of Missouri-Columbia.

2.3.4.2 Statistical Analysis

Body weight, FCR, and portion yield data were subjected to ANOVA using the MIXED procedure of SAS (SAS Institute, 2009). Means were separated using a Tukey's Test to reduce the possibility of a type I statistical error. Differences are reported significant at $P < 0.05$. Nearly significant differences are presented when $P \leq 0.07$.

Expected average daily metabolizable energy intake (ADMEI) for each age, was estimated with the following model based on the Gompertz (1825) growth function:

$$ADMEI = aBW^{0.75} + bG + \varepsilon$$

where $ADMEI$ was metabolizable energy intake (kcal/day), $BW^{0.75}$ was metabolic BW ($kg^{0.75}$), G was gain (g/d), $a = 366 \pm 51.2$, and $b = 0.3075 \pm 0.7566$. Coefficients were estimated by utilizing data from the entire flock. The residual feed intake (RFI) was determined on a pen basis by taking the difference between actual FI and expected FI. RFI were then subjected to ANOVA using the MIXED procedure of SAS (SAS Institute, 2009) with pen as a source of random variation. Means were calculated using the least-squares method.

2.4 Results

2.4.1 Corn Experiment

2.4.1.1 Live Weight

The NA x 708 cross had a 6.7% higher BW at day 10 than the EU x 708 strain ($P = 0.006$, Table 2-3). The BW of DBP100 broilers was 5.4% larger than the DBP90 broilers at day 10 ($P = 0.021$; Table 2-3). At day 25, DBP90 decreased the BW of the EU x 708 broilers, however in the NA x 708 broilers, DBP level had no effect ($P=0.034$; Table 2-3). At day 25, broiler BW was 13.9% lower in the EU x 708 broilers fed DBP90 than those fed DBP100, although there was no effect of DBP on the NA x 708 broilers at this age ($P=0.034$; Table 2-3). At day 35, the reduction in DBP decreased BW by 12.4% in the EU x 708 strain, compared to a 6.2% reduction in the NA x 708 strain ($P = 0.004$; Table 2-3).

Overall, there were no strain or DBP main effects on feed intake from 0 to 10 d nor from 25 to 35 d (Table 2-4). Feed intake for the NA x 708 strain was 8.8% higher from 10 to 25 d than for the EU x 708 strain ($P=0.041$); intake was also 4.3% higher for the DBP100 vs the DBP90 treatment ($P<0.001$; Table 2-4).

2.4.1.2 Efficiency

The EU x 708 broilers had a significantly lower RFI than NA x 708 from 10 to 25 days and from 25 to 35 d ($P <0.001$ and $P = 0.009$, respectively, Table 2-5). The DBP 100 broilers had a significantly lower RFI from age 0 to 10 than the DBP90 broilers ($P = 0.049$; Table 2-5). The EU x 708 strain fed DBP100 and DBP90 had a nearly significantly lower RFI than the NA x 708 strain fed DBP100 and DBP90 from day 25 to 35 ($P = 0.066$; Table 2-5). From 0 to 35 d of age, FCR of DBP90 broilers was 4.3% higher than in the DBP100 broilers ($P < 0.01$; Table 2-5); there was no strain effect nor strain x DBP interaction.

2.4.1.3 Yield

The DBP100 treatment increased carcass yield in the NA x 708 broilers; however, there was no significant effect of DBP100 in the EU x 708 broilers ($P = 0.021$; Table 2-6). Female broilers had 1.3% larger carcass yield that male broilers ($P < 0.001$; Table 2-6). The DBP100 treatment group had the highest *P. major* yield ($P < 0.001$; Table 2-6). *P. major* yield was lower in the male EU x 708 broilers than the female EU x 708, but sex had no effect in the NA x 708 broilers ($P = 0.016$; Table 2-6); however, no other interactions on *P. major* yield were observed. In the EU x 708 broilers, females had larger *P. minor* yield than males when fed DBP90 or DBP100; however, in the NA x 708 no sex effect was observed in the DBP90 or DBP100 fed broilers (P < 0.001; Table 2-6). In the EU x 708 broilers, males had lower breast yield than females when fed DBP90, but there was no sex effect when these broilers were fed DBP100 (P = 0.045; Table 2-6). Conversely, in the NA x 708 broilers, DBP90 reduced breast yield in both males and females compared to DBP 100 (P = 0.045; Table 2-6).

The DBP90 treatment resulted in a 3.1% larger drum yield than the DBP100 treatment (P < 0.001; Table 2-6). Drum yield in the EU x 708 was 8.7% larger in males compared to the females but only 5.6% larger for the males vs the females in the NA x 708 strain (P = 0.002; Table 2-6). There was a two-way interaction on thigh yield in which the EU x 708 broilers fed DBP90 had 7.0% larger thighs than the DBP100 treatment; there was no effect of DBP in the NA X 708 broilers (P = 0.007; Table 2-6). Male broilers had 3.1% higher thigh yield than females (P = 0.021; Table 2-6). Wing yield was 4.7% larger in the EU x 708 strain when compared to the NA x 708 strain (P <0.001) and 3.7% larger in the DBP90 compared to the DBP100 treatment (P < 0.001; Table 2-6).

2.4.2 Wheat Experiment

2.4.2.1 Live Weight

Although they were on average 1.0 gram smaller at placement on day 0 (P=0.001), the NA x 708 broilers were 8.4% heavier at day 10, 15.9% at day 25, and 14.8% larger than the EU x 708 broilers at day 35 (P < 0.001; Table 2-7). The BW of DBP100-fed broilers was 14.4% greater than the DBP90 broilers at 10 d, 29.7% greater at day 25, and 28.5% greater by day 35 (P < 0.001; Table 2-7). Both strains showed a similar decrease in BW when fed the low protein compared to the high protein diet (Table 2-7).

Neither strain nor DBP level affected FI from 0 to 10 d, nor from 25 to 35 d (Table 2-8). Feed intake of the NA x 708 strain from 10 to 25 d was 17.1% higher than the EU x 708 strain

(P=0.045); intake was 20.0% higher for the DBP100 than the DBP90 treatment (P < 0.001; Table 2-8).

2.4.2.2 Efficiency

There were no strain by DBP interactions on RFI for broilers at 0 to 10, 10 to 25, or 25 to 35 d of age; however, EU x 708 broilers had a nearly significant lower RFI than NA x 708 from 10 to 25 d (P = 0.057; Table 2-9). Feeding DBP90 significantly increased RFI at 0 to 10 and 25 to 35 d (P = 0.014, 0.001; Table 2-9). Feeding reduced DBP caused a 19.4% increase in FCR of EU x 708 broilers, but a 10.8% increase in NA x 708 broilers (P = 0.025; Table 2-9).

2.4.2.3 Yield

Carcass yield was not affected by strain, DBP, sex, nor their interactions (Table 2-10). The reduction in DBP reduced breast meat yield in both strains, but the effect was greater for the NA x 708 broilers. The EU x 708 broilers fed DBP90 had a lower *P. major* (13.8%), *P. minor* (7.2%), and breast yield (12.3%) than those fed DBP100 (P = 0.005, 0.042, 0.003; Table 2-10). The NA x 708 broilers also saw a reduction in yield for *P. major* (20.3%), *P. minor* (11.8%), total breast (19.0%) in the DBP90 broilers (P = 0.005, 0.042, 0.003; Table 2-10). Female broilers had larger *P. major* (7.4%), *P. minor* (8.5%) and total breast (7.1%) than males (P < 0.001, < 0.001, < 0.001; Table 2-10).

Increased DBP reduced drum yield by 13.3 % for the NA x 708 broilers, but had no effect on the EU x 708 broilers. (P = 0.005; Table 2-10). Male broilers had 7.8% larger drums than female broilers (P < 0.001; Table 2-10). The DBP90 treatment increased thigh yield by 7.7% in the NA x 708 strain compared to DBP100; however, there was no effect of DBP in the EU x 708 strain (P = 0.009; Table 2-10). Male broilers had 4.7% larger thighs than female broilers (P < 0.001; Table 2-10).

DBP had no effect on wing yield in the EU x 708 broilers; however, DBP90 increased wing yield by 11.1% in the NA x 708 broilers (P = 0.031; Table 2-10). Wing yield was 4.2% greater in male than in female broilers (Table 2-10; P = 0.012).

2.5 Discussion

2.5.1 Body Weight

A lower BW at age 10, 25, and 35 d was observed for broilers fed DB90 vs DBP100, ranging from 8.4% to 9.1% for the Corn Experiment and 12.6 % to 22.9 in the Wheat Experiment (Tables 2-3, 2-7). Birds received less total lysine (1.09% vs. 1.24%) and elevated total TSAA (0.91% vs. 0.82%) relative to the formulated values in the starter wheat DBP90 diet. Birds on the DBP90 treatment in the Wheat Experiment would have consumed less digestible lysine than those fed DBP90 in the Corn Experiment. The ratio of lysine to other essential AA was lower than breeder recommendations (Aviagen, 2007a) due to the lower overall lysine content. In wheat-based broiler diets, methionine and lysine are usually the first two limiting AA (Ravindran and Bryden, 1999). Broilers fed substantially more protein than required, or an unbalanced AA profile have reduced body weight, and higher FCR due to the energetic costs of excreting excess nitrogen (Roy et al., 2010). The NA x 708 broilers grew larger than the EU x 708 broilers when fed wheat-based diets. In contrast, a Ross x Ross cross (European broiler line) had a significantly larger carcass weight than a Peterson x Arbor Acres cross (North American strain) when fed wheat-based diets (Moran et al., 1993). Another study determined that increasing lysine in finisher feeds had a variable effect on weight gain, depending on the strain (Bilgili et al., 1992).

As broilers which have been selected to be lean are less tolerant to low dietary protein than those for growth (Leclercq, 1983), many of the differences observed may be due to EU strains traditionally having been primarily selected for increased efficiency and yield on wheat-based diets, whereas NA strains have been selected on corn-based diets (Moran et al., 1993). The EU strain selection criteria have had a lower focus on performance traits compared to the NA strain (Derek Emmerson, Aviagen, Huntsville, AL, personal communication). In the Corn Experiment, the EU x 708 strain fed DBP90 had a 12.4% reduction in BW (2,260 g vs 1,979 g) compared to DBP100; conversely, there was a 6.2% reduction in BW in the NA x 708 strain (2,347 g to 2,210 g; P = 0.004; Table 2-3). This suggests that the NA strain is less susceptible to the effects of reduced DBP than the EU strain. Diverse genetic selection criteria have led to genetic strains that differ in either being early or late-developing (Dozier and Moran, 2001). Similar results were observed when comparing early- and late-maturing broilers fed diets either adequate or restricted in AA (Dozier and Moran, 2001), and response to four dietary lysine levels in a line selected for higher breast meat yield or a control line (Tesseraud et al., 1999). Dietary requirements of the higher-yield chicks were lower as they were less sensitive to the deficient lysine levels provided compared to the control (Tesseraud et al., 1999). Similarly, the requirements for AA in the NA x 708 strain may be higher than that of the EU x 708; however, the current breeder management guides do not show differences in recommendations signifying that further research may be required (Aviagen, 2019b). This could be in part due to the timing of developmental stages where higher AA are required. In the Wheat Experiment the NA x 708 broilers had a higher % BW daily gain than the EU x 708 broilers between 0 to 10 d (42.78%, 37.52%, respectively), 10 to 25 d (25.38%, 23.32% respectively); in contrast the EU x 708 broilers had higher gain from 25 to 35 d (8.09%, 8.26%, respectively; Table 2-7). These periods of higher growth will have a higher nutrient demand. The EU x 708 strain begins developing frame early and develop weight rapidly later in development (Table 2-7). In contrast, the NA x 708 birds in the Wheat Experiment followed a more consistent growth pattern increasing breast yield throughout development (Table 2-7).

Nutrient requirements of EU x 708 broilers will therefore change with age as the bird shifts from carcass development to breast meat yield.

Within DBP treatments, the diets were formulated to meet the same nutritional specifications. The corn DBP90 and wheat DBP90 diets were similar in formulated nutrient composition, as were the corn DBP100 and wheat DBP100 diets; however the wheat diets were on average 7.85% lower in total lysine than the corn diets upon analysis. Within each DBP level, broilers performed relatively similar within each experiment (Table 2-3, 2-7) Our study showed significant interactions between genotype and DBP on BW in corn diets after 25 days of age when DBP and lysine were decreased simultaneously; however, similar findings between genotype and only lysine have also been observed (Sterling et al., 2006). Our findings imply the EU x 708 strain is less sensitive to reductions in dietary CP and lysine levels compared to the NA x 708 strain. This may be due to the higher genetic potential of the NA x 708 for breast meat yield, leaving it more responsive to changes in AA and lysine levels. Since our study examined DBP levels, we were unable to discern the influence of lysine compared to other AA directly; however, it does indicate an increased AA requirement for the NA x 708 compared to the EU x 708 strains. Other studies have observed a larger increase in yield in an EU strain (Ross x Ross) when compared to a North American strain (Peterson x Arbor Acres) in response to increased lysine levels (Acar et al., 1991). A meta-analysis determined that the Cobb genotype was more susceptible to dietary CP changes than Ross broilers (Faridi et al., 2015).

It is thought that older broiler strains eat to meet energy requirements (Leeson et al., 1996); however, more recent research has suggested that FI is positively influenced by dietary lysine and AA levels (Farkhoy et al., 2012). We observed a higher FI in the DBP100 treatment compared to DBP90 in both the corn and wheat experiments (4.3% and 20.0% respectively), however this effect was only present between days 10 and 25 (P < 0.001; Table 2-4, 2-8). This suggests that FI is increased with higher AA levels in young broilers, when the intestinal tract is relatively underdeveloped, and less so in later developmental stages (Tables 2-4, 2-8). This is not supported by early research in this area (Nakhata and Anderson, 1982; Pesti and Smith, 1984), with some studies determining a negative relationship on FI as AA levels are increased (Smith and Pesti, 1998). However, more recent research has found a positive relationship between dietary AA levels and FI during early developmental stages (Sterling et al., 2006; Razuki and Rawi, 2007; Kumar et al., 2016).

The nutritional profile of wheat and corn varies with growing conditions, post-harvest storage, seasonal variation, cultivars, and between geographical regions (Cowieson, 2005; Gutiérrez-Alamo et al., 2008). Since the AME of wheat can be highly variable, and the individual ingredients were not tested before formulation, the wheat may have had a lower actual AME than was anticipated during diet formulation. The differences in ME between corn and wheat could help to explain the observed changes in response between cereal source. Wheat contains 96% and 29% more soluble and total non-starch polysaccharides (NSP), respectively than corn and can reduce the passage rate of digesta through the gut (Wu et al., 2004). However, NSP-degrading enzymes can reverse the reduction in ME (Wu et al., 2004; Choct, 2006; Hashemi et al., 2017). Although wheat-based diets contain higher levels of NSP than corn-based diets (Bach Knudsen, 2014), an NSP-degrading enzyme was included in this study and therefore, this effect should have been negligible (Hashemi et al., 2017).

2.5.2 Efficiency

In the Corn Experiment, EU x 708 broilers had a significantly lower RFI than NA x 708 from days 10 to 25 (P < 0.001) and 25 to 35 (P < 0.009; Table 2-5). In contrast, there was no significant difference in RFI between strains in the Wheat Experiment (Table 2-9). It is important to note that the EU x 708 birds had lower 0 d BW than the NA x 708 birds in the Wheat Experiment (P = 0.001; Table 2-7). The net energy of production (NEp) of wheat (8.03 MJ/kg) is estimated to be slightly lower than corn (8.59 MJ/kg) when fed to poultry in conjunction with xylanase (Nian et al., 2011a; b). The ratio of apparent metabolizable energy to net energy of production (AME:NEp) is larger in corn than in wheat (66.6%, 64.6%, respectively; Nian et al., 2011a; b). Since most broiler diets are currently formulated on an ME basis, birds fed the wheat diets may have had a lower NEp intake than the corresponding corn diets (National Research Council, 1994; Barzegar et al., 2020).

The difference in RFI between strains in the Corn Experiment may be explained by further examining how energy associated with RFI may be utilized. Romero et al. (2009) hypothesized that rapidly growing animals are penalized during RFI selection due to the energetic cost of diet-induced thermogenesis in high FI birds. Due to diet-induced thermogenesis, high producing birds will lose more energy as heat than birds with a lower FI. Excess loss of heat will be associated with larger birds due to higher FI to support continued growth, which may lead to an increase in RFI differences between the EU x 708 and NA x 708 broiler cross birds, since the NA x 708 broiler is a higher carcass yield producer, leading to a higher FI. The lower RFI of DBP100 birds relative to DBP90 broilers may have been further influenced by the heat increment associated with feeding more nutrient-dense feedstuffs (Barzegar et al., 2019, 2020; Van der Klis and Jansman, 2019).

In the Wheat Experiment, the EU x 708 and NA x 708 broilers fed DBP100 had the lowest FCR from 0 to 35 d, followed by the NA x 708 DBP90 and the EU x 708 DBP90 ($P < 0.001$; Table 2-9). There was a larger increase in the FCR of EU x 708 (19.4%) than the NA x 708 (10.8%) when the birds were fed the DBP90 treatment compared to DBP100 (P = 0.025; Table 2-9). In contrast there was no strain by DBP interaction in the Corn Experiment (Table 2-5). This relationship could be due to the lower than calculated total lysine level in the wheat DBP90 diet. In some studies, up to a 20% reduction in FCR has been demonstrated with total lysine in finishing rations increasing from 0.77 to 1.26% (Belloir et al., 2019). The wheat DBP90 diet may have been deficient in digestible lysine for efficiency, therefore reducing BW and overall performance in this treatment. Although previous studies have shown a decrease in FCR with higher Arg:Lys ratios, no increased benefit on FCR was observed in ratios from 1.17 to 2.10; (Fouad et al., 2013) and arginine levels to either meet (100%) or exceed (105% to 110%) NRC recommendations (Laika and Jahanian, 2017). Recent studies have shown a linear increase in body weight gain and a decrease in FCR when increasing the Arg:Lys ratio from 0.85 to 1.26 (Sirathonpong et al., 2019). The analyzed Arg:Lys ratios in the Corn Experiment ranged from 1.02 and 1.14, but in the Wheat Experiment, the ratio in the DBP90 diets ranged from 1.11 to 1.26. Historically ideal Arg:Lys ratios in the literature have ranged between 0.90 to 1.18 (Mack et al., 1999; Balnave and Brake, 2002); however recent studies have proposed an ideal Arg:Lys ratio range of 1.15 to 1.17 (Zampiga et al., 2018). The interaction between arginine and lysine is further confounded by the lower analyzed total lysine content than formulated, leading to a further decrease in dietary lysine. The larger negative effect of the wheat DBP90 diet on performance in the NA x 708 broilers may indicate a higher lysine demand than the EU x 708 broilers; however, this is not currently well defined in current breeder management guides (Aviagen, 2019b).

2.5.3 Yield

The dietary AA requirements are different for each of these responses in increasing order: 1) maximum BW; 2) minimum FCR; 3) maximum lean mass 4) minimum carcass fat (Pesti, 2009). Optimal lysine levels for breast meat yield are higher than for growth; and are highly strain-dependent (Acar et al., 1991). Therefore, we must distinguish which requirements we are optimizing. Protein synthesis is enhanced through increasing lysine supplementation up to the optimal yield requirement; increasing muscle deposition in the skeletal muscles, especially the *P. major* to a plateau, however further supplementation becomes energetically expensive (Tesseraud et al., 2001). When dietary lysine is not provided at sufficient levels, protein synthesis is limited, and other AA in relative excess are oxidized for energy (Grisoni et al., 1991; Nasr and Kheiri, 2011). An increase in protein turnover and breast yield is consistent with an increase in dietary CP and lysine levels relative to ME levels (Tesseraud et al., 1996b; Urdaneta-Rincon and Leeson, 2004).

Unlike the Corn Experiment, there was no significant effect of strain or DBP on carcass yield in the Wheat Experiment (Table 2-10). Similar to the Corn Experiment, the DBP100 treatment resulted in the largest *P. major* and *P. minor* and overall breast meat (P = <0.001, Table 2-10). Between 9 and 23 d, broilers showed a reduction in total and muscle weight gain when dietary total lysine was reduced from 1.22 to 0.86%, regardless of CP level (Urdaneta-Rincon and Leeson, 2004). Increasing lysine dietary content increased fillet yield, tender yield and reduced abdominal fat (Acar et al., 1991), and increased overall breast meat yield by 1.31% (Hickling et al., 1990). In the same study, increasing methionine from 100% to 112% of NRC recommendations (National Research Council, 1984) increased BW at 6 weeks by 1.22%, breast meat by 3.58%, and decreased FCR by 0.02 (Hickling et al., 1990). In the Wheat Experiment, the reduction in DBP caused a larger reduction in breast in the NA x 708 (19.0%) compared to the EU x 708 (12.3%) broilers (P = 0.042; Table 2-10). Tesseraud et al., (1999) observed a greater reduction in breast yield in a commercial strain compared to a high-yield selected strain when fed 1.01% lysine compared to 1.13%. This may demonstrate that strains selected for high yield may be less susceptible to reductions in dietary lysine levels.

In the Corn Experiment, DBP100 treatments resulted in 3.1% larger drum yield than DBP90 treatments ($P < 0.001$; Table 2-6). Thigh yield from the EU x 708 broilers fed DBP90 was 7.0% larger than the EU x 708 broilers fed DBP100 ($P = 0.007$; Table 2-6). Interestingly, DBP only affected the thigh yield in the EU x 708 broilers and not the NA x 708 broilers in the Corn Experiment. In the Wheat Experiment, thigh yield was 7.7% larger in the NA x 708 strain on the DBP90 treatment compared to DBP100, with no difference between DBP treatments in the EU x 708 strain ($P= 0.009$; Table 2-10). This indicates that the NA x 708 strain prioritizes thigh muscle whereas the EU x 708 prioritizes breast muscle during periods of lower dietary lysine intake. Wing yield was 4.7% and 10.2% lower in the NA x 708 broilers compared to the EU x 708 broilers in Experiments 1 and 2, respectively ($P < 0.001$; Tables 2-6 and 2-10). Generally, a decrease in DBP led to a shift in protein deposition from the breast to the drums, thighs and wings.

At increasing dietary AA levels approaching the requirement for optimal yield, abdominal fat pad deposition is reduced and carcass weight and breast muscle deposition are increased (Bilgili et al., 1992; Holsheimer and Veerkamp, 1992; Scheuermann et al., 2003; Kidd et al., 2005; Sterling et al., 2006). In the Wheat Experiment, we found a 7.1% reduction in thigh yield when NA x 708 broilers were fed DBP100 vs. DBP90; however, no difference was observed in the EU x 708 broilers ($P = 0.009$; Table 2-10). The influence of CP and lysine on lean growth, including breast and carcass yield, is highly dependent on strain (Bilgili et al., 1992; Holsheimer and Veerkamp, 1992; Hancock et al., 1995; Scheuermann et al., 2003). Early studies failed to find a significant difference in lysine requirement between Hubbard x Hubbard and New Hampshire x Columbian chicks (Han and Baker, 1993). A study examining the effect of feeding a low and high AA density feed on high yield and conventional broiler strains found a significant strain and AA density interaction on FCR and breast yield similar to our findings, with high-yield genotypes being most affected by increases in AA density (Corzo et al., 2005b).

Performance and carcass traits were highly dependent on DBP and sex. The interaction of strain and DBP level on carcass characteristics were more pronounced in broilers fed the wheat-based diets compared to corn-based diets. When evaluating the cost savings of reducing DBP below the primary breeder recommendations, it is vital to keep in mind the effect on performance and yield parameters. Effects on yield are not directly apparent until processing, therefore, making it too late for these differences to be addressed, leaving potential marketing benefits for the producer untouched.

The results of the present and other studies indicate that the lysine requirement to optimize broiler yield is highly dependent on strain cross and should be accounted for when determining feeding programs for the cutup market. Nutritionists must consider the nutrient requirements of each strain and feed at optimal levels. Due to the differences in how genotypes respond to changes in DBP levels, nutritionists should strive to achieve optimal economic efficiency.

The objective of these findings were to enable decisions surrounding the suitability of the NA x 708 and the EU x 708 in different broiler markets. It was hypothesized that DBP100 would increase BW growth and lean yield relative to DBP90 diets in corn-and wheat-based diets. We accepted this hypothesis as BW and lean yield increased in the DBP100 relative to the DBP90 treatment. We also found the NA x 708 strain less susceptible to reduced DBP compared to the EU x 708 strain.

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2.8 Tables & Figures

Table 2-1. Composition of corn-based broiler diets in the Corn Experiment fed from 0 to 35 days of age (% as-fed)

		Starter (0-10 days)		Grower (10-25 days)		Finisher (25-35 days)	
		DBP100	DBP90	DBP100	DBP90	DBP100	DBP90
Ingredient (% as-fed)							
Corn		56.92	58.37	59.57	59.37	64.51	64.33
Canola Meal		7.50	7.50	7.50	7.50	7.50	7.50
Soybean Meal		29.93	27.67	25.41	25.84	20.67	21.05
Calcium Carbonate		0.82	1.23	0.97	0.97	0.93	0.93
Dicalcium Phosphate		1.24	1.26	1.01	1.00	0.88	0.87
Salt, (NaCl)		0.25	0.25	0.25	0.25	0.25	0.25
Lysine		0.22	0.14	0.16	0.01	0.16	0.02
Methionine		0.30	0.23	0.25	0.16	0.21	0.13
Threonine		--	--	--	--	--	--
Tryptophan		--	--	--	--	--	--
HyD Premix[1]		0.05	0.05	0.05	0.05	0.05	0.05
Vitamin E 5,000 IU/kg[2]		0.50	0.50	0.50	0.50	0.50	0.50
Avizyme® 1302[3]		0.05	0.05	0.05	0.05	0.05	0.05
Vitamin Premix[4]		0.50	0.50	0.50	0.50	0.50	0.50
Choline Cl Premix[5]		0.50	0.50	0.50	0.50	0.50	0.50
Quantum Blue Phytase[6]		0.01	0.01	0.01	0.01	0.01	0.01
Canola Oil		1.61	1.66	3.17	3.20	3.17	3.19
Coccidiostat[7]		0.05	0.05	0.05	0.05	0.05	0.05
Antibiotic Growth Promoter[8]		0.05	0.05	0.05	0.05	0.05	0.05
Calculated Nutrients							
Total Phosphorus	(%)	0.65	0.63	0.59	0.59	0.54	0.55
Available Phosphorus	(%)	0.50	0.50	0.45	0.45	0.42	0.42
Met + Cys digestible	(%)	0.94	0.85	0.84	0.76	0.76	0.68
Methionine digestible	(%)	0.64	0.55	0.56	0.47	0.51	0.43
Lysine digestible	(%)	1.27	1.14	1.10	0.99	0.97	0.87
Threonine digestible	(%)	0.83	0.80	0.77	0.77	0.70	0.70
Arginine digestible	(%)	1.31	1.24	1.18	1.19	1.04	1.05
Analyzed Nutrients[9]							
Crude Protein	(%)	20.33	20.28	19.09	19.93	18.18	17.92
Crude Fat	(%)	3.82	3.73	5.15	5.19	5.31	5.44
Calcium	(%)	0.95	1.06	0.96	0.87	0.82	0.88
Total Phosphorous (%)		0.67	0.64	0.61	0.65	0.61	0.59
AME[10]	(Kcal/Kg)	3,030	3,025	3,150	3,150	3,200	3,200
Total AA (Analyzed)							
TSAA[11]	(%)	0.93	0.82	0.79	0.74	0.77	0.69
Methionine	(%)	0.60	0.50	0.49	0.43	0.47	0.40
Lysine	(%)	1.35	1.24	1.14	1.11	1.06	0.95
Threonine	(%)	0.79	0.76	0.69	0.72	0.69	0.64
Arginine	(%)	1.39	1.36	1.21	1.27	1.16	1.08

[1] HyD Premix: Provided 69 µg of 25-OH vitamin D_3 per kg of diet.

[2] Vitamin E: provided 50 IU/kg of diet.

[3] Provided per kilogram of diet: Xylanase, 250 U g^{-1}; Protease, 80 U g^{-1}.

[4] Vitamin premix provided per kilogram of diet: iron, 80 mg; zinc, 100 mg; manganese, 120 mg; copper, 20 mg; iodine, 1.65 mg; selenium, 0.3 mg; vitamin A, 10,000 IU; vitamin D_3, 4,000 IU; vitamin E, 50 IU; vitamin K, 4 mg; vitamin B_{12}, 0.02 mg; niacin, 65 mg; D-pantothenic acid, 15 mg; riboflavin, 10 mg; pyridoxine, 5 mg; thiamine, 4 mg; folic acid, 2 mg; biotin, 0.2 mg.

[5] Choline Cl premix contained 100 mg of choline per kilogram of diet.

[6] Quantum Blue Phytase 5,000 FTU/g added at 100g/tonne of diet.

[7] Coban® Premix (Monensin sodium at 200 g/kg) to provide 100 mg/kg in the complete feed (Elanco, Guelph, ON Canada).

[8] BMD 110 G (Bacitracin methylene disalicylate at 110 g/kg) to provide 55 mg/kg in the complete feed (Zoetis Canada, Kirkland, Quebec, Canada).

[9] All feed analysis were performed by the University of Missouri Experimental Station Chemical Laboratories, Columbia, MO.

[10] Apparent metabolizable energy.

[11] Total sulfur amino acids.

Table 2-2. Composition of wheat-based broiler diets in the Wheat Experiment fed from 0 to 35 days of age (% as-fed)

		Starter (0-10 days)		Grower (10-25 days)		Finisher (25-35 days)	
Item		DBP100	DBP90	DBP100	DBP90	DBP100	DBP90
Ingredient (% as-fed)							
Wheat		58.32	58.30	61.78	65.14	64.98	67.20
Canola Meal		7.50	7.50	7.50	7.50	7.50	7.50
Soybean Meal		27.05	26.16	21.71	18.82	18.50	15.93
Calcium Carbonate		0.82	1.23	0.98	0.99	0.94	1.42
Dicalcium Phosphate		1.14	1.15	0.91	0.92	0.76	0.77
Salt, (NaCl)		0.19	0.19	0.19	0.19	0.19	0.19
Lysine		0.15	0.02	0.11	0.05	0.04	
Methionine		0.30	0.21	0.25	0.19	0.20	0.15
Threonine		0.05	--	0.03	--	--	--
Tryptophan		0.01	--	--	--	--	--
HyD Premix[1]		0.05	0.05	0.05	0.05	0.05	0.05
Vitamin E 5,000 IU/kg[2]		0.50	0.50	0.50	0.50	0.50	0.50
Avizyme® 1302[3]		0.05	0.05	0.05	0.05	0.05	0.05
Vitamin Premix[4]		0.50	0.50	0.50	0.50	0.50	0.50
Choline Cl Premix[5]		0.50	0.50	0.50	0.50	0.50	0.50
Quantum Blue Phytase[6]		0.01	0.01	0.01	0.01	0.01	0.01
Canola Oil		3.26	3.53	4.84	4.49	5.18	5.13
Coccidiostat[7]		0.05	0.05	0.05	0.05	0.05	0.05
Antibiotic Growth Promoter[8]		0.05	0.05	0.05	0.05	0.05	0.05
Calculated Nutrients							
Total Phosphorus	(%)	0.65	0.65	0.59	0.58	0.55	0.54
Available Phosphorus	(%)	0.50	0.50	0.45	0.45	0.42	0.42
Met + Cys digestible	(%)	0.94	0.85	0.84	0.76	0.76	0.68
Methionine digestible	(%)	0.61	0.52	0.53	0.46	0.47	0.40
Lysine digestible	(%)	1.27	1.14	1.10	0.99	0.97	0.87
Threonine digestible	(%)	0.83	0.77	0.73	0.66	0.66	0.62
Arginine digestible	(%)	1.35	1.32	1.20	1.12	1.11	1.04
Analyzed Nutrients[9]							
Crude Protein	(%)	23.10	21.71	21.68	21.57	21.00	19.04
Crude Fat	(%)	4.50	4.25	5.39	6.24	6.49	6.01
Calcium	(%)	0.99	0.94	1.08	0.81	0.76	0.79
Total Phosphorous (%)		0.74	0.71	0.69	0.58	0.60	0.64
AME[10]	(Kcal/Kg)	3,030	3,025	3,150	3,150	3,200	3,200
Total AA (Analyzed)							
TSAA[11]	(%)	1.02	0.91	0.87	0.86	0.76	0.76
Methionine	(%)	0.64	0.53	0.50	0.49	0.42	0.42
Lysine	(%)	1.25	1.09	1.11	1.00	0.99	0.87
Threonine	(%)	0.80	0.77	0.75	0.71	0.67	0.62
Arginine	(%)	1.39	1.34	1.31	1.26	1.21	1.07

[1] HyD Premix: Provided 69 µg of 25-OH vitamin D_3 per kg of diet.

[2] Vitamin E: provided 50 IU/kg of diet.

[3] Provided per kilogram of diet: Xylanase, 250 U g^{-1}; Protease, 80 U g^{-1}.

[4] Vitamin premix provided per kilogram of diet: iron, 80 mg; zinc, 100 mg; manganese, 120 mg; copper, 20 mg; iodine, 1.65 mg; selenium, 0.3 mg; vitamin A, 10,000 IU; vitamin D_3, 4,000 IU; vitamin E, 50 IU; vitamin K, 4 mg; vitamin B_{12}, 0.02 mg; niacin, 65 mg; D-pantothenic acid, 15 mg; riboflavin, 10 mg; pyridoxine, 5 mg; thiamine, 4 mg; folic acid, 2 mg; biotin, 0.2 mg.

[5] Choline Cl premix contained 100 mg of choline per kilogram of diet.

[6] Quantum Blue Phytase 5,000 FTU/g added at 100g/tonne of diet.

[7] Coban® Premix (Monensin sodium at 200 g/kg) to provide 100 mg/kg in the complete feed (Elanco, Guelph, ON Canada).

[8] BMD 110 G (Bacitracin methylene disalicylate at 110 g/kg) to provide 55 mg/kg in the complete feed (Zoetis Canada, Kirkland, Quebec, Canada).

[9] All feed analysis were performed by the University of Missouri Experimental Station Chemical Laboratories, Columbia, MO.

[10] Apparent metabolizable energy.

[11] Total sulfur amino acids.

Table 2-3. Effect of male line strain and dietary balanced protein (DBP) on BW of broilers fed corn-based diets (Corn Experiment)

			Age (d)			
Effect	Strain	DBP	0	10	25	35
			BW (g)			
Strain[1]	EU x 708		41.8	240^{b}	$1{,}162^{b}$	$2{,}120^{b}$
	NA x 708		41.6	256^{a}	$1{,}254^{a}$	$2{,}278^{a}$
SEM			0.1	4	18	15
P-Value			0.299	0.006	0.002	<0.001
Dietary Balanced Protein[2]		DBP100	41.7	254^{a}	$1{,}266^{a}$	$2{,}304^{a}$
		DBP90	41.7	241^{b}	$1{,}151^{b}$	$2{,}095^{b}$
SEM			0.1	3	18	15
P-Value			0.858	0.021	<0.001	<0.001
Strain * DBP	EU x 708	DBP100	41.7	249	$1{,}249^{a}$	$2{,}260^{b}$
		DBP90	41.9	231	$1{,}075^{b}$	$1{,}979^{c}$
	NA x 708	DBP100	41.8	260	$1{,}282^{a}$	$2{,}347^{a}$
		DBP90	41.5	252	$1{,}226^{a}$	$2{,}210^{b}$
SEM			0.2	5	25	21
P-Value			0.181	0.312	0.034	0.004

[a-d]Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1] Chicks from a European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[2] DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

Table 2-4. Effect of male line strain and dietary balanced protein (DBP) on feed intake (FI; g/bird/day) of broilers fed corn-based diets (Corn Experiment)

			Age (d)		
Effect	Strain	DBP	0-10	10-25	25-35
			FI (g/bird/day)		
Strain[1]	EU x 708		26	91^{b}	165
	NA x 708		28	99^{a}	178
SEM			1	1	3
P-Value			0.966	0.041	0.620
Dietary Balanced Protein[2]		DBP100	27	97^{a}	178
		DBP90	27	93^{b}	166
SEM			1	1	3
P-Value			0.622	<0.001	0.697
Strain * DBP	EU x 708	DBP100	27	93	174
		DBP90	25	89	156
	NA x 708	DBP100	28	100	181
		DBP90	28	99	176
SEM			1	2	4
P-Value			0.842	0.668	0.129

[a-b]Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1]Chicks from a European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[2]DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

Table 2-5. Effect of male line strain and dietary balanced protein (DBP) on residual feed intake (RFI)[1] (kcal/bird/day) and feed conversion ratio (FCR) of broilers fed corn-based diets (Corn Experiment)

			Age (d)			FCR (g feed:g gain)
Effect	Strain	DBP	0-10	10-25	25-35	0 to 35
Strain[2]	EU x 708		-0.43	-7.09^{b}	-6.40^{b}	1.42
	NA x 708		0.44	5.75^{a}	5.39^{a}	1.43
SEM			1.04	2.07	2.94	0.01
P-Value			0.559	<0.001	0.009	0.226
Dietary Balanced Protein[3]		DBP100	-1.52^{b}	-3.26	-0.83	1.39^{b}
		DBP90	1.53^{a}	1.91	-0.17	1.45^{a}
SEM			1.04	2.07	2.94	0.01
P-Value			0.049	0.089	0.875	<0.001
Strain * DBP	EU x 708	DBP100	-1.30	-10.10	-2.71	1.39
		DBP90	0.43	-4.08	-10.08	1.45
	NA x 708	DBP100	-1.74	3.59	1.04	1.40
		DBP90	2.62	7.91	9.74	1.46
SEM			1.48	2.92	4.15	0.01
P-Value			0.380	0.774	0.066	0.872

$^{a\text{-}b}$Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1] RFI: Expected average daily metabolizable energy intake for each age, were estimated with the following model:

$$MEI = aBW^{0.75} + bG + \varepsilon$$

Where MEI is metabolic energy intake (kcal/day), $BW^{0.75}$ is metabolic BW ($kg^{0.75}$), G is gain (g/d), $a = 365.59 \pm 51.20$, and $b = 0.3075 \pm 0.7576$.

[2] Chicks from a European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[3] DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

Table 2-6. Effect of male line strain and dietary balanced protein (DBP) on yield (g/g body weight) of carcass, *Pectoralis major (P. major), Pectoralis minor (P. minor),* total breast, drums, thighs and wings at day 35 of broilers fed corn-based diets (Corn Experiment)

				Carcass	*P. major*	*P. minor*	Breast	Drums	Thighs	Wings
Effect	Strain[1]	DBP[2]	Sex	----------	----------	----------	(% Yield)	----------	----------	----------
Strain	EU x 708			68.6^{b}	24.9	5.59^{a}	30.5^{a}	13.2^{a}	16.2	11.1^{a}
	NA x 708			70.2^{a}	25.6	5.46^{b}	31.0^{a}	12.9^{b}	16.4	10.6^{b}
SEM				0.2	0.2	0.05	0.2	0.1	0.2	0.1
P-Value				<0.001	0.154	0.036	0.046	0.047	0.620	<0.001
Dietary Balanced Protein		DBP100		70.0^{a}	26.5^{a}	5.66^{a}	32.1^{a}	12.9^{b}	16.0^{b}	10.7^{b}
		DBP90		68.8^{b}	24.1^{b}	5.38^{b}	29.4^{b}	13.3^{a}	16.6^{a}	11.1^{a}
SEM				0.2	0.2	0.05	0.2	0.1	0.2	0.1
P-Value				<0.001	<0.001	0.003	<0.001	<0.001	0.011	<0.001
Sex			Female	69.8^{a}	25.7^{a}	5.72^{a}	31.4^{a}	12.7^{b}	16.1^{b}	10.8
			Male	68.9^{b}	24.8^{b}	5.33^{b}	30.1^{b}	13.5^{a}	16.6^{a}	10.9
SEM				0.2	0.2	0.05	0.2	0.1	0.2	0.1
P-Value				0.007	<0.001	<0.001	0.003	<0.001	0.021	0.493
Strain * DBP	EU x 708	DBP100		68.8^{b}	26.2	5.70	31.9	13.1	15.7^{b}	11.0
		DBP90		68.4^{b}	23.7	5.48	29.1	13.3	16.8^{a}	11.3
	NA x 708	DBP100		71.1^{a}	26.7	5.62	32.3	12.6	16.4^{ab}	10.3
		DBP90		69.2^{b}	24.4	5.29	29.7	13.3	16.3^{ab}	11.0
SEM				0.3	0.3	0.07	0.3	0.1	0.2	0.1
P-Value				0.021	0.725	0.106	0.577	0.435	0.007	0.292
Strain * Sex	EU x 708		Female	69.2	25.7^{a}	5.88	31.6^{a}	12.7^{b}	15.9	11.0
			Male	68.0	24.2^{b}	5.29	29.5^{b}	13.8^{a}	16.6	11.3
	NA x 708		Female	70.5	25.7^{a}	5.55	31.3^{a}	12.6^{b}	16.2	10.7
			Male	69.9	25.4^{a}	5.37	30.8^{a}	13.3^{a}	16.5	10.6
SEM				0.3	0.3	0.07	0.3	0.1	0.2	0.1
P-Value				0.311	0.016	0.233	0.046	0.002	0.500	0.117
DBP * Sex		DBP100	Female	70.2	26.7	5.86	32.6	12.6	15.7	10.7
			Male	69.8	26.2	5.47	31.6	13.2	16.3	10.6
		DBP90	Female	69.5	24.7	5.57	30.3	12.7	16.4	11.0
			Male	68.1	23.4	5.19	28.6	13.9	16.8	11.3
SEM				0.3	0.3	0.07	0.3	0.1	0.2	0.1
P-Value				0.175	0.304	0.057	0.254	0.966	0.562	0.112

(continued)

Effect	Strain[1]	DBP[2]	Sex	Carcass	*P. major*	*P. minor*	Breast	Drums	Thighs	Wings
				(% Yield)						
Strain * DBP * Sex	EU x 708	DBP100	Female	69.0	26.5	6.00^{a}	32.5^{a}	13.0	15.4	11.0
			Male	68.7	25.9	5.41^{bc}	31.4^{ab}	13.3	15.9	11.0
		DBP90	Female	69.5	24.9	5.77^{ab}	30.7^{ab}	12.5	16.4	11.0
			Male	67.3	22.4	5.18^{c}	27.6^{c}	14.2	17.2	11.6
	NA x 708	DBP100	Female	71.5	27.0	5.71^{ab}	32.7^{a}	12.2	16.0	10.5
			Male	70.8	26.4	5.53^{bc}	31.9^{a}	13.0	16.7	10.2
		DBP90	Female	69.4	24.5	5.38^{bc}	29.8^{b}	13.0	16.4	10.9
			Male	68.9	24.4	5.20^{c}	29.6^{b}	13.5	16.3	11.0
SEM				0.5	0.4	0.09	0.5	0.2	0.3	0.2
P-Value				0.132	0.068	0.001	0.045	0.990	0.240	0.575

[a-e] Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1] Chicks from a European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[2] DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

Table 2-7. Effect of male line strain and dietary balanced protein (DBP) on BW of broilers fed wheat-based diets (Wheat Experiment)

			Age (d)			
Effect	Strain	DBP	0	10	25	35
			BW (g)			
Strain[1]	EU x 708		42.3^{a}	201^{b}	904^{b}	1,651^{b}
	NA x 708		41.3^{b}	218^{a}	1,048^{a}	1,896^{a}
SEM			0.2	3	12	23
P-Value			0.001	<0.001	<0.001	<0.001
Dietary Balanced Protein[2]		DBP100	41.7	223^{a}	1,102^{a}	1,995^{a}
		DBP90	41.8	195^{b}	850^{b}	1,553^{b}
SEM			0.2	3	12	23
P-Value			0.876	<0.001	<0.001	<0.001
Strain * DBP	EU x 708	DBP100	42.1	217	1,043	1,896
		DBP90	42.4	185	764	1,406
	NA x 708	DBP100	41.3	229	1,160	2,093
		DBP90	41.2	206	936	1,699
SEM			0.3	4	16	32
P-Value			0.435	0.264	0.111	0.159

$^{a\text{-}d}$Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1] Chicks from a European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[2] DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

Table 2-8. Effect of male line strain and dietary balanced protein (DBP) on feed intake (FI) (g/bird/day) of broilers fed wheat-based diets (Wheat Experiment)

				Age (d)	
Effect	Strain	DBP	0-10	10-25	25-35
				FI (g/bird/day)	
Strain[1]	EU x 708		27	76^{b}	143
	NA x 708		29	89^{a}	159
SEM			1	1	3
P-Value			0.899	0.045	0.662
Dietary Balanced Protein[2]		DBP100	28	90^{a}	155
		DBP90	28	75^{b}	146
SEM			1	1	3
P-Value			0.728	<0.001	0.679
Strain * DBP	EU x 708	DBP100	27	84	147
		DBP90	27	68	139
	NA x 708	DBP100	29	96	164
		DBP90	30	82	153
SEM			1	2	4
P-Value			0.724	0.623	0.145

$^{a-b}$Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1] Chicks from a European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[2] DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

Table 2-9. Effect of male line strain and dietary balanced protein (DBP) on residual feed intake (RFI)[1] (kcal/bird/day) and feed conversion ratio (FCR) of broilers fed wheat-based diets (Wheat Experiment)

			Age (d)			FCR (g feed:g gain)
Effect	Strain	DBP	0-10	10-25	25-35	0 to 35
Strain[2]	EU x 708		-1.67	-5.23	-2.81	1.58
	NA x 708		1.69	5.08	5.37	1.56
SEM			1.47	3.65	9.42	0.02
P-Value			0.117	0.057	0.544	0.367
Dietary Balanced Protein[3]		DBP100	-2.72^{b}	-1.30	-23.35^{b}	1.46^{b}
		DBP90	2.74^{a}	1.15	25.91^{a}	1.68^{a}
SEM			1.47	3.65	9.42	0.02
P-Value			0.014	0.639	0.001	<0.001
Strain * DBP	EU x 708	DBP100	-3.49	-7.56	-36.24	1.44^{c}
		DBP90	0.14	-2.90	30.62	1.72^{a}
	NA x 708	DBP100	-1.96	4.95	-10.46	1.48^{c}
		DBP90	5.34	5.20	21.21	1.64^{b}
SEM			2.08	5.17	13.32	0.01
P-Value			0.384	0.673	0.198	0.025

$^{a-b}$Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1] RFI: Expected average daily metabolizable energy intake for each age, were estimated with the following model:

$$MEI = aBW^{0.75} + bG + \varepsilon$$

Where MEI is metabolic energy intake (kcal/day), $BW^{0.75}$ is metabolic BW ($kg^{0.75}$), G is gain (g/d), $a = 365.59 \pm 51.20$, and $b = 0.3075 \pm 0.7576$.

[2] Chicks from a European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[3] DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

Table 2-10. Effect of male line strain and dietary balanced protein (DBP) on yield (g/g body weight) of carcass of *Pectoralis major (P. major), Pectoralis minor (P. minor),* total breast, drums, thighs and wings at day 35 of broilers fed wheat-based diets (Wheat Experiment)

Effect	Strain[1]	DBP[2]	Sex	Carcass	*P. major*	*P. minor*	Breast	Drums	Thighs	Wings
				------------------------------			(% Yield)	------------------------------		
Strain	EU x 708			66.5	20.3^{b}	4.97	25.2^{b}	14.9^{a}	17.3	12.7^{a}
	NA x 708			67.6	21.6^{a}	5.09	26.7^{a}	14.4^{b}	17.7	11.4^{b}
SEM				1.3	0.2	0.05	0.3	0.1	0.1	0.1
P-Value				0.555	<0.001	0.075	<0.001	0.004	0.073	<0.001
Dietary Balanced Protein		DBP100		67.9	22.9^{a}	5.28^{a}	28.2^{a}	14.0^{b}	17.1^{b}	11.6^{b}
		DBP90		66.2	19.0^{b}	4.77^{b}	23.7^{b}	15.3^{a}	17.9^{a}	12.4^{a}
SEM				1.3	0.2	0.05	0.3	0.1	0.1	0.1
P-Value				0.342	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sex			Female	66.9	21.7^{a}	5.23^{a}	26.9^{a}	14.1^{b}	17.1^{b}	11.8^{b}
			Male	67.2	20.2^{b}	4.82^{b}	25.1^{b}	15.2^{a}	17.9^{a}	12.3^{a}
SEM				1.3	0.2	0.05	0.3	0.1	0.1	0.1
P-Value				0.870	<0.001	<0.001	<0.001	<0.001	<0.001	0.012
Strain * DBP	EU x 708	DBP100		66.4	21.8^{b}	5.15^{b}	26.9^{b}	14.6^{a}	17.2^{b}	12.5^{ab}
		DBP90		66.6	18.8^{c}	4.78^{c}	23.6^{c}	15.3^{a}	17.4^{b}	12.9^{a}
	NA x 708	DBP100		69.3	24.1^{a}	5.41^{a}	29.5^{a}	13.5^{b}	17.0^{b}	10.8^{c}
		DBP90		65.8	19.2^{c}	4.77^{c}	23.9^{c}	15.3^{a}	18.3^{a}	12.0^{b}
SEM				1.8	0.3	0.07	0.4	0.2	0.2	0.2
P-Value				0.304	0.005	0.042	0.003	0.005	0.009	0.031
Strain * Sex	EU x 708		Female	65.3	20.8	5.17	26.0	14.5	17.1	12.4
			Male	67.7	19.8	4.76	24.5	15.4	17.6	12.9
	NA x 708		Female	68.4	22.5	5.30	27.8	13.7	17.2	11.2
			Male	66.7	20.7	4.88	25.6	15.1	18.2	11.7
SEM				1.8	0.3	0.07	0.4	0.2	0.2	0.2
P-Value				0.257	0.306	0.949	0.348	0.319	0.179	0.940
DBP * Sex		DBP100	Female	68.6	23.8	5.53	29.3	13.4	16.8	11.2
			Male	67.1	22.1	5.03	27.1	14.7	17.4	12.1
		DBP90	Female	65.1	19.5	4.94	24.4	14.8	17.5	12.4
			Male	67.2	18.4	4.61	23.1	15.8	18.3	12.5
SEM				1.8	0.3	0.07	0.4	0.2	0.2	0.2
P-Value				0.324	0.322	0.187	0.257	0.384	0.647	0.098

(continued)

Effect	Strain[1]	DBP[2]	Sex	Carcass	*P. major*	*P. minor*	Breast	Drums	Thighs	Wings
				--			(% Yield)	--		
Strain * DBP * Sex	EU x 708	DBP100	Female	66.9	22.4	5.40	27.8	14.1	17.1	12.0
			Male	65.9	21.2	4.90	26.1	15.1	17.2	13.0
		DBP90	Female	63.7	19.2	4.95	24.2	14.8	17.0	12.9
			Male	69.4	18.4	4.62	23.0	15.7	17.9	12.9
	NA x 708	DBP100	Female	70.3	25.2	5.66	30.9	12.7	16.4	10.5
			Male	68.4	23.0	5.15	28.1	14.3	17.6	11.1
		DBP90	Female	66.5	19.8	4.93	24.7	14.8	17.9	11.9
			Male	65.0	18.5	4.60	23.1	15.8	18.7	12.2
SEM				2.5	0.5	0.09	0.5	0.3	0.3	0.3
P-Value				0.381	0.628	0.977	0.657	0.414	0.154	0.346

[a-e] Means within an effect and row with different superscript letters differ significantly ($P \leq 0.05$).

[1] A European (EU x 708) male line or a North American (NA x 708) male line crossed with a Ross 708 maternal line (Aviagen, Inc., Huntsville, AL).

[2] DBP100 was dietary balanced protein at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids. DBP90 treatment was lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at a similar lysine:AA ratio as the DBP100 treatment.

3. Effect of dietary balanced protein on allometric relationships between carcass portions in offspring of two broiler male-lines

3.1 Abstract

Two experiments were conducted to determine the response of two broiler strains to varying levels of dietary balanced protein (DBP) fed corn- (Corn Experiment) or wheat- (Wheat Experiment) based diets. A North American (NA) male-line or a European (EU) male-line each crossed with Ross 708 hens were fed dietary balanced protein (DBP; first 7 limiting amino acids) at either 100% of Aviagen recommendations (DBP100) or 90% (DBP90). Diets were fed as starter (0 to 10 d of age), grower (11 to 25 d of age), and finisher (26 to 35 d of age). Feed was provided *ad libitum* throughout the study. Dissections were conducted on 4 birds per treatment every 7 d from 0 to 35 d to determine allometric growth of the pectoralis muscles, drum + thigh, fat-pad, heart, liver, and small intestines. Allometric yield curve coefficients were estimated for each treatment using a non-linear growth model. Females had a larger proportion of total breast than males ($P<0.001$); however, there was no effect of strain on breast yield allometry in either experiment. In each experiment, the DBP100 total breast yield curve was shifted higher than DBP90 ($P<0.001$). Fat pad yield curves were higher in females compared to males, and in EU x 708 compared to NA x 708 birds in each experiment. The liver yield curve was shifted upward in the DBP90 treatment compared to DBP100 and in females compared to males. There was no significant strain effect on liver allometry in either experiment. DBP100 broilers in each experiment had the drum + thigh yield curve shifted higher than DBP90 ($P = 0.018$ and 0.010, respectively). Total intestine weight was not affected by DBP level; however, DBP90 shifted the total intestine yield curve upward ($P = 0.010$) in the Corn Experiment. Broilers fed DBP100 vs DBP90 diets produced a higher proportion of breast muscle and had a smaller fat-pad with body weight (BW).

Key Words: broiler chicken, strain, allometry, carcass composition, dietary balanced protein

3.2 Introduction

Allometric relationships between individual carcass portions and overall body weight may be used to describe changes in carcass composition throughout broiler development. These relationships are crucial when optimizing carcass portions at a particular market age for a given strain. Since feed costs are upwards of 70% of total production costs, many producers reduce dietary amino acid (AA) levels in order to decrease live bird production costs; however this can reduce live growth and overall carcass yield (Corzo et al., 2005b; Donohue and Cunningham, 2009; Willems et al., 2018; Zhang et al., 2019).

Historically, US broiler strains (e. g. Peterson x Arbor Acres) have been selected for growth and performance on corn-based diets, whereas EU strains (e. g. Ross x Ross) have been selected on wheat-based diets (Derek Emmerson, Aviagen, Huntsville, AL, personal communication). Increased breast muscle yield and a greater lysine requirement were observed in an EU broiler strain compared to a US strain (Acar et al., 1991). Moran et al. (1993) observed a 1.2% reduction of broiler performance in US strains fed wheat diets compared to EU strains. This suggests a relationship between the broiler strain and protein source utilized during selection and primary protein source used in production.

Relationships have been reported between dietary protein level and genotype on nutrient utilization efficiency (Leclercq and Guy, 1991), and overall feed conversion ratio (FCR; Korver et al., 2004). The North American line (NA x 708) is a high-performance yield line, and the European line (EU x 708) is a fast-growth, feed efficiency line.

Differences in growth performance and yield response to ideal protein levels among commercial genetic strains have been observed, suggesting strain-specific studies are required to evaluate optimal AA density for growing broilers (Kemp et al., 2005; Johnson et al., 2019). A positive relationship exists between dietary protein and growth rate regardless of genetic differences, up to a plateau (Liu et al., 2019). However, maximum weight gain is achieved at a lower dietary protein level in genetically lean vs genetically fat broilers, signifying genetic selection has altered requirements (Leclercq and Guy, 1991). The dietary level of AA required for minimizing carcass fat pad is highest, followed by that for maximum lean mass, minimum FCR, and body weight gain; therefore, depending on the response criteria, the AA requirement will change (Leclercq, 1998; Pesti, 2009) Fast-growing birds require fewer kcal per kg BW gain (Rosa et al., 2007), higher dietary lysine per kg diet (Han and Baker, 1991; Belloir et al., 2019), and methionine per kg diet (Wen et al., 2017) than slow-growing birds.

Responses to lysine supplementation above the requirement for growth can lead to decreased abdominal fat deposition and is highly dependent on strain (Acar et al., 1991; Belloir et al., 2019). In current commercial strains, the lysine requirement for feed conversion ratio (FCR) is up to 8.85% higher than for growth performance (Liu et al., 2019). Therefore, to optimize economic returns, amino acids should be fed in accordance with the genotype (Smith and Pesti, 1998). Genetic selection has significantly changed broiler growth rate since 1957, as broilers with 1957 genetics weighed 0.59 kg at 42 d with an FCR of 2.8 (Schmidt et al., 2009); whereas a 42-d-old modern Ross 308 broiler can weigh up to 2.84 kg with an FCR of under 1.60 (Castro et al., 2019).

Broiler body composition is influenced by genotype and dietary protein levels (Corzo et al., 2004). Broilers fed low protein diets have reduced growth (Swennen et al., 2010); however diets with high crude protein (CP) and amino acid levels above NRC (1994) recommendations for growth lead to increased growth and breast meat yield (Kemp et al., 2005). These factors are highly influenced by broiler genotype and ensuring the ideal amino acid balance can be a major challenge for producers (Corzo et al., 2004). In commercial production, there has recently been a trend towards lower dietary nutrient densities and protein levels to reduce nutrient oversupply, nitrogen excretion, and increase overall profitability (Alagawany et al., 2014; Rehman et al., 2018). Feeding reduced CP diets has a potential benefit by reducing feed costs; however this reduction may not directly relate to increased profitability due to reduced lean yield (Corzo et al., 2005b; Rehman et al., 2018). Therefore, it is important to examine the response of modern broiler genetics to high and low DBP levels in wheat- vs. corn-based diets. When dietary CP levels are reduced by 1%, nitrogen excretion is reduced by about 10% (Bregendahl et al., 2002; Gomide et al., 2011)

Allometry is the relationship between overall body size to the shape of individual parts. Allometric relationships are presented to enable prediction of the weight of *pectoralis major* (*P. major*), *pectoralis minor* (*P. minor*), total breast, drum + thigh, fat-pad, heart, liver, and total intestine of different broiler genotypes. The ability to understand allometric relationships allows for the understanding of the final growth, carcass characteristics, developmental patterns, and profitability of broilers.

This study aimed to determine the allometric relationships for the *pectoralis major* (*P. major*), *pectoralis minor* (*P. minor*), total breast muscle, drum + thigh, fat-pad, heart, liver, and total intestine parts of the broiler as influenced by genetic strain and DBP level. This information can be used to estimate yield curves dynamically throughout the lifespan of the broiler, helping optimize genetics, nutrition, and age combinations by predicting production levels from DBP levels. We hypothesized that a NA x 708 broiler would have an increased breast muscle allometric curve compared to the EU x 708 broiler crossed with the same Ross 708 maternal line. Since primary breeder nutritional recommendations reflect the effect on yield characteristics, we expected that DBP90 would lead to a decrease in lean tissue growth and an increase in lipid deposition with BW when compared to the DBP100 treatment.

3.3 Materials and Methods

3.3.1 Experimental Design

These experiments were conducted concurrently with the experiment presented in Chapter 2. Two experiments were conducted simultaneously to determine the relationship between genetic strain and DBP level on broiler growth and development. The Corn Experiment was conducted using corn-based diets and the Wheat Experiment using wheat-based diets. Within each experiment, treatments were arranged as a 2 x 2 factorial examining the relationship between two genetic lines, and two levels of DBP. The broiler strains were the offspring of a European (EU x 708) male-line crossed with Ross 708 hens, and the offspring of a North American (NA x 708) male-line crossed with the same Ross 708 hens.

3.3.2 Stocks and management

Within each experiment, a total of 1,600 mixed-sex broilers were raised in floor pens in a light-tight facility (0.069 m^2/bird, 32 pens with four replicate pens of 50 birds per pen). Birds received 23 h of light/d at approximately 20 lux for the first 7 days. From day 7, the lighting program was 20L:4D at approximately 8 lux.

A total of five broilers in each of the 32 pens were randomly selected and wing banded individually at placement; individual BW of tagged birds was recorded twice weekly, and dissections of 1 bird per pen (4 per treatment) were performed every 7 d to 56 d of age. Whole BW and weights of *P. major*, supracoracoideus muscle (*P. minor*), total breast, drum + thigh, fat-pad (including fat adhering to the gizzard and proventriculus), heart, liver, and total intestine weights were recorded. Allometric growth of the liver and heart was determined to give an understanding of the effect of DBP level on each strain. Allometric coefficients were determined for individual parts as a proportion of the whole BW. Overall mortality-corrected feed intake and feed conversion ratio were recorded and presented previously (Chapter 2).

3.3.3 Diets

A three-phase feeding program was used: starter (0 to 10 d of age), grower (11 to 25 d of age), and finisher (26 to 56 d of age). All diets contained an exogenous enzyme (Avizyme® 1302; xylanase, 5,000 U g^{-1}; protease, 1600 U g^{-1}, supplied by Danisco Animal Nutrition, Canada). Feed was provided *ad libitum* throughout the study. Within each experiment, the DBP100 diet was formulated to contain at least 100% of Aviagen's recommendations (Aviagen, 2007a) for lysine, methionine, total sulfur amino acids (TSAA), threonine, valine, isoleucine, arginine, and tryptophan for each dietary phase. The DBP90 diet was formulated to contain lysine at 90% of Aviagen recommendations, with each of the first 7 limiting amino acids fed at an ideal digestible lysine: AA ratio across the diets within a phase, based on the Aviagen recommendations (Chapter 2, Tables 2-1, 2-2). Although diets were formulated to the same digestible AA specifications in each experiment, analyzed levels of lysine were on average 7.85% lower than expected in the Wheat Experiment (Chapter 2, Tables 2-1, 2-2). Compositional analysis of each diet was outlined in Chapter 2.

3.3.4 Statistical Analysis

Carcass data were collected twice weekly to determine the relationship between broiler genetic strain and DBP level on allometry (yield dynamics). Non-linear models were used to provide treatment-specific analysis of carcass dynamics. Data were analyzed using the Proc NLIN procedure of SAS (Version 9.2 Copyright 2002-2008 by SAS Institute Inc., Cary, NC, USA). Data were fit to Huxley's allometric function (Huxley, 1932):

$$PW = \mathrm{a} * BW^{b} + \varepsilon$$

where PW was the weight of the carcass portion (g), BW was whole BW (g), a and b were coefficients determined utilizing least-squares approximation, and ε was the random variation not accounted for by the model.

The allometric curves were evaluated, in pairwise comparisons, using a least-squares procedure and an F-test outlined by Motulsky and Ransnas (1987). Curves were estimated for each comparison separately utilizing the NLIN procedure of SAS. The sum of squares (*SS*) and degrees of freedom (*df*) were calculated for each treatment.

$$SS_{sep} = SS_1 + SS_2 \qquad df_{sep} = df_1 + df_2$$

The pooled data were fitted with a single allometric curve. The pooled analysis yields values for SS_{pool} and df_{pool}; to determine significance, F ratios were calculated:

$$F = \frac{\left(SS_{pool} - SS_{sep}\right) \big/ \left(df_{pool} - df_{sep}\right)}{SS_{sep} \big/ df_{sep}}$$

Therefore, the null hypothesis was equality - that the allometric curves for each treatment were the same, i.e. a single curve best fit the data. The alternate hypothesis was that the allometric curves were not equal, i.e. individual curves fit the data significantly better than a single curve. Curves were reported as shifted when $P < 0.05$. Nearly significant differences are presented when $P \leq 0.07$. The yield curve in this discussion relates to the allometric relationship of individual part weight in relation to a given BW.

3.4 Results

The performance results of these trials were reported in Chapter 2. Coefficients for allometric equations in Experiments 1 and 2 are reported in Tables 3-1 and 3-2, respectively. In the Wheat Experiment, the analyzed total lysine levels of the DBP90 diet were on average 7.85% lower than the formulated values in all phases (Chapter 2, Table 2-2). Graphical representation of the allometric relationships are given in the supplementary data (Appendix A).

3.4.1 Muscles and Fat-pad

3.4.1.1 Corn Experiment

Females had a higher constant term 'a' and allometric growth curve of *P. major*, *P. minor* and total breast (*P. major* + *P. minor*) than males (P < 0.0001; Table 3-1); however, there was no effect of strain on *P. major*, *P. minor,* and total breast allometric growth. The DBP100 treatment birds had larger *P. major*, *P. minor,* and total breast allometry than the DBP90 treatment birds (P < 0.0001; Table 3-1). The downward shift of the total breast allometry curve in the DBP90 treatment was larger in males than in females (P=0.003, data not shown).

There was no strain effect on drum + thigh weight relative to BW (P=0.677). The male drum + thigh curve was shifted upwards compared to the female curve (P<0.001; Table 3-1). The drum + thigh allometric curve was shifted higher in the DBP90 birds than the DBP100 birds; DBP100 also shifted thigh growth to later developing (P=0.018; Table 3-1).

Overall, there was no strain effect on fat-pad weight in relation to BW (P=0.840). Females had a larger fat-pad relative to BW than the males (P<0.001; Table 3-1). Fat-pad weight relative to BW was greater in the DBP90 treatment versus the DBP100 treatment birds (P<0.001; Table 3-1).

3.4.1.2 Wheat Experiment

Similar to the Corn Experiment, females had a larger proportion of *P. major*, *P. minor,* and total breast than males (P<0.001; Table 3-2) in the Wheat Experiment. There was a nearly significant strain effect on *P. major* (P=0.056) and total breast (P=0.065), with the NA x 708 strain having higher yield curve than the EU x 708 (Table 3-2). The DBP100 birds had a larger yield curve of *P. major*, *P. minor* and total breast muscle than the DBP90 birds (P<0.001; Table 3-2).

The NA x 708 birds had a larger drum + thigh yield curve than the EU x 708 strain at BW over ~2 kg (P<0.001; Table 3-2). Broilers fed the DBP90 diet had higher drum + thigh weight in proportion to BW than those fed the DBP100 diet (P=0.010; Table 3-2). There was a nearly significant sex effect (P=0.070; Table 3-2), with males having a higher drum + thigh yield curve than females.

The fat-pad yield curve was greater in the NA x 708 strain than the EU x 708 strain (P<0.001; Table 3-2). Fat-pad weight relative to BW was greater in the DBP90 versus the DBP100 treatment birds (P<0.001; Table 3-2). The fat pad yield curve was shifted upward in female broilers compared to the males (P<0.001; Table 3-2).

3.4.2 Internal Organs

3.4.2.1 Corn Experiment

Heart size relative to BW was larger at younger ages in the EU x 708 strain than the NA x 708 strain (P=0.007, Table 3-1), and was shifted upward in male broilers compared to females (P<0.001; Table 3-1). The DBP90 broilers had a lower heart yield curve at higher BW (P=0.002; Table 3-1).

The liver weights as a proportion of BW of the EU x 708 broilers were nearly significantly larger than the NA x 708 broilers (P=0.065, Table 3-1). The DBP100 diet resulted in heavier liver weight early in life, but high protein led to smaller weight at higher BW (P=0.001; Table 3-1). Liver weights at a given BW were significantly lower in male broilers than in female broilers (P<0.001; Table 3-1). Total intestine weight as a proportion of BW was not influenced significantly by strain, diet, or sex (Table 3-1).

3.4.2.2 Wheat Experiment

The heart yield curve was shifted upwards in the females compared to the males ($P<0.001$; Table 3-2). There was no significant strain or protein effect on heart yield curves ($P=0.271$; $P=0.598$).

Liver yield curves were shifted upward in the DBP90 treatment compared to the DBP100 ($P<0.001$; Table 3-2), and in the females when compared to the males ($P=<0.001$; Table 3-2). There was no significant strain effect on liver yield curves ($P=0.278$; Table 3-2).

Total intestine yield curves were shifted downward in the DBP100 treatment compared to DBP90 ($P=0.006$; Table 3-2). There was no significant strain or sex effects on total intestine ($P=0.249$, $P=0.116$, respectively).

3.5 Discussion

Several key production indicators such as FCR are based on live BW, however many broilers are produced for the cutup market in regions where breast meat is the most valuable portion of the carcass (Stevens, 1991; Kuttappan et al., 2016). The relationship between live BW growth and the growth of a particular part of the body was examined through allometric relationships. The value of allometric growth predictions in genetic selection criterion are important in further evaluating the development of high yield strains (Hancock et al., 1995; Danisman and Gous, 2013).

An allometric function follows some variation of a power law equation with the general form $y=ax^b$, where ‘y’ is a biological variable (such as breast size), ‘a’ is the proportionality coefficient, ‘x’ is the measure of body size or body mass, and ‘b’ is the scaling exponent (Huxley, 1932). The allometric equation describes how each body part grows in relation to overall BW (Huxley, 1932). For example, if the exponent *b* is greater than 1, as observed with breast meat and fat pad in both experiments, the part is later maturing (Govaerts et al., 2000; Table 3-1, Table 3-2). If *b* is less than 1, the part is early maturing, which is the case with intestine development (Govaerts et al., 2000; Table 3-1, Table 3-2). This allows for examination of how broilers partition energy, nutrients, and how their body develops throughout life.

The EU strain selection criteria have had a lower focus on performance traits than the NA strain (Derek Emmerson, Aviagen, Huntsville, AL, personal communication). Since the broilers produced in North America are primarily used for the cutup market, it was thought that the NA x 708 broilers would have a higher allometric growth of muscle and lower fat-pad deposition than the EU x 708 broilers; which traditionally would have serviced primarily a whole bird market (Barbut, 2001). There was no significant strain effect on *P. major* or fat-pad yield curves in birds fed the corn-based diets in the Corn Experiment (P=0.394, P=0.840; respectively). In the Wheat Experiment (wheat-based diets), the allometric growth yield curves for *P. major* were nearly significantly different with the EU x 708 curve exhibiting more of a compensatory growth yield curve than the NA x 708 (P=0.056; Table 3-2). The DBP100 treatment allometric curve for fat pad in relation to BW was shifted upwards compared to the DBP90 (P<0.001). The NA x 708 fat pad yield curve was higher than the EU x 708 in the wheat-based diets (P<0.001; Wheat Experiment) but no effect was found in the corn-based diets (P=0.677; Corn Experiment). Therefore, although there was no difference in morphology between strains raised on the corn-based diets, there was a pronounced change in morphology between strains on wheat-based diets. The differences observed may be due to the lower lysine levels than formulated for in the wheat diets. A similar response was observed among fast-growing and slow-growing strains, where strain differences in carcass traits were only present when methionine was provided at a low level and all other AA in excess (Wen et al., 2017). In wheat-based broiler diets, methionine and lysine are typically the first two limiting AA (Ravindran and Bryden, 1999). This indicates that lysine was limiting in our wheat-based diets as discussed in Chapter 2. Although this change in *P. major* allometry was not significant, the effect on total yield at day 35 was significant (Chapter 2; Table 2-6).

The DBP100 diet total breast yield curve diverged upward from the DBP90 curve (Table 3-1), suggesting that dietary DBP differences have greater influence on the rate of protein synthesis as the bird ages (Tesseraud et al., 1996b), leaving more energy for the production of adipose tissue (Table 3-1). Increases in adipose tissue deposition were observed in the DBP90 treatment in both experiments as broilers reacted to low DBP to energy ratio by increasing lipid deposition (Fraps, 1943; Aletor et al., 2000; Srilatha et al., 2018). This has also been confirmed by other studies (Jackson et al., 1982; Gous et al., 1990; Bregendahl et al., 2002) as amino acids must be provided in balance with each other to optimize development of muscle tissues (D'Mello, 2003; Hilliar et al., 2020).

When protein levels were increased in the correct balance with AME, fat levels in the body decreased (Nakhata and Anderson, 1982; Jackson et al., 1982; Summers et al., 1992; Faria Filho et al., 2006; Mohiti-Asli et al., 2012a). However, three specific amino acids (methionine, lysine, and arginine) have been shown to affect fat deposition simultaneously. Supplementation of lysine and methionine at levels of 0, 10, 20, 30, or 40% higher than the NRC (1994) recommendations increased breast meat yield and decreased abdominal fat pad weight (Bouyeh and Gevorgyan, 2011). Methionine is the first limiting amino acid in many wheat-based commercial poultry diets (Dozier et al., 2009; Da-Hye et al., 2019). Supplementing methionine to a deficient basal diet increased breast muscle and decreased abdominal fat deposition; however supplementation beyond the requirement for growth continued to increased breast yield with no effect on abdominal fat levels. (Yao et al., 2006; Zhan et al., 2006). Ross 308 boilers fed methionine at 0.58% vs 0.48% of the starter diet had lower overall fat pad deposition (Andi, 2012).

Another study determined that adding methionine to a methionine-deficient diet, increased the amount of hormone-sensitive lipase (HSL; lipolysis) compared to fatty acid synthase (FAS; lipogenesis) (Takahashi and Akiba, 2011); therefore higher methionine inclusion shifts the balance between lipolysis and lipogenesis leading to lower overall carcass fat. Increasing lysine concentration in a lysine-deficient basal diet increased broiler muscle deposition and reduced overall carcass fat (Grisoni et al., 1991; Attia, 2003). However, further increases in a sufficient lysine diet did not cause a further reduction in fat deposition (Grisoni et al., 1991; Tian et al., 2019). This relationship is not completely linear as lysine, when supplemented at 120% of NRC (1994) recommendations, increased fat deposition (Nasr and Kheiri, 2011). This supports the concept that dietary amino acids must be included in an ideal ratio to lysine (Wu, 2014).

In meat-type ducks, increased dietary arginine reduced adipose deposition and adipose cell diameter and volume (Wu et al., 2011). Ross 308 broilers had reduced abdominal fat yield when dietary arginine was increased from 0.80 % to 1.25% (Corzo et al., 2003). A similar response was observed in Cobb 500 broilers when arginine levels were increased from 1.25% to 1.49% (Fouad et al., 2013). Methionine, arginine, and lysine are important in ideal ratios to satisfy the needs of protein synthesis and limit excessive fat deposition. If one amino acid is provided in a less than the ideal ratio, this can lead to deamination of excess amino acids and breakdown of the ketoacid as an energy source (Pesti, 2009). When energy-containing nutrients such as amino acids are provided in excess of requirements, they will undergo lipogenesis and be deposited as fat (Pesti, 2009).

The aforementioned relationship was first proposed in the form of an ideal protein to energy ratio by Fraps (1943); several studies followed further refining ideal ratios (Baker and Han, 1994; Emmert and Baker, 1997; Corzo et al., 2003; Wu, 2014). Ideal ratios are not consistent throughout life and change according to the phase of development, genetics, and age (Gous et al., 1990).

Fat-pad allometric curve was highly influenced by strain in the Wheat Experiment however, no effect was found in the Corn Experiment ($P<0.001$, $P=0.840$; respectively). Wheat starch content can range from 402 to 712 g/kg and therefore the wheat used in the present study may have been higher in AME than accounted for during formulation (Amerah, 2015). Excess AME in relation to AA requirements increases fat pad deposition and may also upregulate Na^{2+}-dependent glucose transporters (Barekatain et al., 2019). Since the NA x 708 broilers have a larger fat-pad in relation to BW than the EU x 708; the NA x 708 may have higher AA requirements than the EU x 708 broilers (Table 3-2).

At higher BW, females tended to have a larger fat-pad than males (Table 3-1). This is in agreement with other studies (Gous et al., 1999; Zuidhof, 2005). This is important as breast meat has the highest market value per kg from the chicken carcass; however, fat-pad is not valued in the marketplace but is energetically expensive to deposit (Zuidhof, 2005). In many global markets, breast meat is highest in demand, other parts of the carcass including the fat, non-recovered meat, and bone, are sent to rendering for manufacture of a low-cost by-product (Marx et al., 2016).

At smaller BW, the liver had larger size-dependent allometric relationship to BW in the DBP100 birds than the DBP90 birds; however, the DBP90 birds had a larger size-dependent weight at later stages in life. The liver yield curve was shifted upward in the females vs the males, and DBP90 vs DBP100 treatments in both the corn ($P<0.001$ and $P=0.001$, respectively) and wheat experiments ($P=0.003$ and $P<0.001$, respectively). The liver yield curve in this study followed the same response by sex as the fat-pad. The upward shift of liver allometry in the females is consistent with the larger proportion of fat reserves in females than in males at a given BW (Chapter 2), and could indicate higher activity of fatty acid synthase and metabolic activity in females (De Souza Khatlab et al., 2018). In early development, the heavier liver size presumably enables birds to metabolize nutrients more effectively due to endogenous enzyme secretions (Zaefarian et al., 2019). One of the functions of the liver is fat metabolism and lipogenesis; the liver is the main site for converting excess carbohydrates into fatty acids and triglycerides (Hermier, 1997). The increased liver weight at BW may be an indicator of increased hepatic activity but could also be confounded by hepatic lipid content.

Drum + thigh weights increased in a highly isometric fashion to overall BW in both experiments. DBP90 shifted the development of drum + thigh to earlier development in the Corn Experiment and to later developing in the Wheat Experiment (Tables 3-1, 3-2). A strain effect was only observed in the Wheat Experiment with NA x 708 broilers having a larger proportion of drum + thigh yield than the EU x 708 (Table 3-2). Broiler chicken strains have developed through selection for various performance, efficiency, and carcass characteristics. Muscle is energetically expensive to maintain (Zuidhof, 2005) and since the EU x 708 broiler has been selected for feed efficiency and breast yield, the EU x 708 may have later development of breast muscle (Table 3-2). Differences in drum + thigh allometry were relatively smaller in response to dietary protein when compared to the differences observed in breast muscle and fat-pad. Although there were significant DBP effects found in each experiment, the differences in the allometry curve in the Corn Experiment were smaller than in the Wheat Experiment. In the Wheat Experiment, DBP90 resulted in a larger proportion of drum + thigh at larger BW (P=0.010). The analyzed total lysine levels were lower than formulated in the wheat DBP90 treatment; therefore, the effects on yield curves may be due to lower overall lysine levels. An increase of drum + thigh yield due to an increase in lysine concentration is in agreement with other studies (Kheiri and Alibeyghi, 2017;

Liu et al., 2019). Drums + thigh weight relative to BW were larger and shifted to later developing in male broilers compared to females in the Corn Experiment; which has been identified in previous studies (Nogueira et al., 2019).

Other studies have examined the allometric responses to DBP in several genetic strains. Danisman and Gous (2011) found no significant effects of strain (Ross 708, Ross 308, Cobb 500) nor sex; however, the allometric relationship in their study was based on broiler protein deposition throughout the body. Comparing our results to Danisman and Gous (2011; 2013) indicates the differences observed in this study may be due to increased lipid deposition in breast muscle tissues. This study used BW as an allometric basis to allow the coefficients to be easily interpreted for a broiler at any given BW. Examining allometric relationships on overall protein deposition may provide insight into protein synthesis in various parts of the body of broilers, as it may reduce errors associated with fat inter-dispersed within muscle or white striping, however when examining carcass composition from a further processing perspective basing yield on overall BW provides more applicable insights.

Fast-growing broilers (2001 genetics) had a smaller heart weight to body weight ratio than slow-growing (1957 genetics) broilers (Havenstein et al., 2003). Average heart weight decreased by 0.08 g (0.004% yield) per year due to genetic progress in meat yield in commercial broilers (Gaya et al., 2007). Genetic selection for increased breast muscle and high meat yield broilers has led to an imbalance between oxygen-providing organs (i.e. lungs and heart) and oxygen-demanding organs (i.e. muscle tissue; Khajali and Wideman, 2016). The heart yield curve was shifted upward in the EU x 708 broilers vs the NA x 708 on corn diets (Table 3-1) and was shifted to later developing in NA x 708 compared to EU x 708 on corn-based diets (Table 3-1). Early development of the heart is vital to ensure a healthy broiler with a low incidence of metabolic disorders such as pulmonary arterial hypertension (ascites). A smaller heart in relation to overall BW puts excess strain on the cardiopulmonary system leading to an increased incidence in ascites (Wideman, 2001). Since the EU x 708 had a larger heart in relation to BW we would expect they would be less susceptible to ascites due to increased pulmonary vascular capacity; however the ratio of right:total ventricle is a more accurate indicator (Wideman, 2001; Wideman et al., 2013). Our findings agree with the findings that a heritage broiler line developed heart size earlier than Ross broilers; which is important to note as ascites is a major cause of mortality and economic loss in the modern broiler industry (Aftab and Khan, 2005; Schmidt et al., 2009; Özkan et al., 2010). DBP90 shifted the heart yield curve to earlier developing in only the Corn Experiment (Table 3-1). As it is difficult to influence growth of larger frame and heart size, the increase in the EU x 708 and DBP90 allometry is likely due to the overall smaller size of the broilers. Low protein diets have shown mixed results on the prevalence of ascites in broiler flocks; with the negative effect linked to the reduction of uric acid production and therefore the ability to withstand oxidative stress (Maxwell and Robertson, 1998; Behrooj et al., 2012; Sharifi et al., 2016; Khajali and Sharifi, 2018).

There was no effect of strain, DBP, or sex on intestine allometry in the Corn Experiment (Table 3-1). In the Wheat Experiment, the total intestine yield curve was shifted to be earlier maturing in DBP100 birds than DBP90 birds (Table 3-2); higher dietary AA levels allow the bird to increase early growth and development of the intestinal tract (Lilburn and Loeffler, 2015; Cardinal et al., 2019); in turn allowing for faster recovery from subclinical necrotic enteritis (Keerqin et al., 2017). There was no significant sex or strain effect on the total intestine allometry; indicating the different selection criterion between NA x 708 and EU x 708 has had minimal impact on the progression of intestinal development.

Deterministic models have been developed to assess the economic differences between supply chains (Groen et al., 1998). The use of models can aid the supply chain and producer to evaluate the risks associated with changes in biological production systems (Gous and Berhe, 2006). The first step to developing simulation models is to predict the effects of different feeding programs on the performance and carcass development of different genotypes (Hancock et al., 1995; Gous et al., 1999). By estimating coefficient relationships that are accurate for use, these models can subsequently become predictive tools to increase profitability. Overall, we observed that there were no significant differences between the NA x 708 and the EU x 708 on broiler allometric yield curves when the birds were fed corn-based diets and only a nearly significant difference when fed wheat-based diets. Given the increased yield of breast meat with feeding the DBP100 diet, allometric models can be developed to optimize saleable breast meat at market prices by finding the ideal slaughter weight and DBP level.

Without properly defined specifications to meet the requirements for overall efficiency and yield of broilers, least-cost diet formulation may lead to reduced profitability (Guevara, 2004). Chickens fed a low protein to energy ratio will reduce muscle deposition and increase fat deposition (Bregendahl et al., 2002; Faria Filho et al., 2006; Mohiti-Asli et al., 2012a; Srilatha et al., 2018). This may be due to excess intake of energy per unit intake of CP as broilers fed diets with adequate energy will adjust intakes dependent on AA requirements (Srilatha et al., 2018). A reduction in yield will cost significantly if the decrease in feed costs fail to outweigh the reduction in yield (Holsheimer and Ruesink, 1993). In order to extract maximum efficiency, the allometric effects of dietary protein on breast size and current meat prices need to be accounted for while performing diet formulation. Models that take performance and yield into account in addition to feed cost are available. However, they are not commonly used, largely because although the relationships between nutrition and performance are understood in principle, they are difficult to predict and understand quantitatively.

By utilizing coefficients such as those estimated in the current study, processors may be able to make production decisions surrounding supplemental amino acid use and the suitability of the NA x 708 and EU x 708 for use in the desired market. Published allometric growth coefficients estimating modern high yield genetics are scarce and the data can be used in further bioeconomic models to predict scenarios that would produce the highest profit when considering input and production costs. Our study found that by reducing DBP lean allometric growth was reduced and adipose tissue was increased. Furthermore, there was no differences between strains on allometric growth of muscle and fat-pad. Ideally further studies could include further variations of protein content that would enable users to predict how precise allometric relationships change in relation to protein content.

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3.8 Tables & Figures

Table 3-1. Coefficients for allometric curve comparisons[1] for the Corn Experiment (Corn-based diets).

	Coefficients		
Part	*a*	*b*	P-Value[2]
P-Major			
NAx708[3]	0.0260	1.2422	
EUx708	0.0219	1.2651	0.394
DBP90[4]	0.0310	1.2153	
DBP100	0.0265	1.2451	< 0.001
Female	0.0262	1.2472	
Male	0.0180	1.2852	< 0.001
P-Minor			
NAx708	0.0100	1.1698	
EUx708	0.0108	1.1605	0.861
DBP90	0.0117	1.1475	
DBP100	0.0107	1.1638	< 0.001
Female	0.0089	1.1912	
Male	0.0080	1.1937	< 0.001
Total Breast			
NAx708	0.0352	1.2288	
EUx708	0.0311	1.2456	0.495
DBP90	0.0419	1.2023	
DBP100	0.0361	1.2306	< 0.001
Female	0.0347	1.2365	
Male	0.0250	1.2686	< 0.001
Drum + Thigh			
NAx708	0.1346	1.0412	
EUx708	0.1410	1.0345	0.677
DBP90	0.1782	1.0058	
DBP100	0.1074	1.0686	0.018
Female	0.1715	1.0058	
Male	0.1431	1.0357	< 0.001
Fat-pad			
NAx708	0.0036	1.2100	
EUx708	0.0026	1.2483	0.840
DBP90	0.0020	1.2918	
DBP100	0.0030	1.2254	< 0.001
Female	0.0005	1.4714	
Male	0.0022	1.2544	< 0.001
Heart			
NAx708	0.0123	0.8867	
EUx708	0.0233	0.8017	0.007
DBP90	0.0275	0.7820	
DBP100	0.0100	0.9122	0.002
Female	0.0169	0.8373	
Male	0.0197	0.8301	< 0.001
Liver			
NAx708	0.1694	0.7531	
EUx708	0.1100	0.8112	0.065
DBP90	0.0844	0.8447	
DBP100	0.2084	0.7271	0.001
Female	0.0853	0.8458	
Male	0.1755	0.7481	< 0.001

(continued)

Part	Coefficients *a*	*b*	P-Value[2]
Total Intestine (Duodenum Jejunum Ileum)			
NAx708	0.3520	0.6461	
EUx708	0.3727	0.6380	0.902
DBP90	0.3021	0.6651	
DBP100	0.4177	0.6241	0.502
Female	0.2520	0.6885	
Male	0.4638	0.6112	0.098

[1] Data were fit to the Huxley's allometric function (Huxley, 1932): $PW = \mathrm{a} + BW^{b} + \varepsilon$, where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least-squares approximation, and ε is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS.

[2] The allometric curve coefficients were compared using a least-squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons.

[3] Strain: Offspring of either a European (EU) male-line or a North American (NA) male-line, each crossed with a Ross 708 maternal line from Aviagen.

[4] Protein level: The DBP100 protein diet was formulated at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids on a digestible basis. The DBP90 protein diet was formulated with digestible lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at an ideal digestible lysine: AA ratio.

Table 3-2. Coefficients for allometric curve comparisons[1] for the Wheat Experiment (Wheat-based diets).

Part	Coefficients *a*	Coefficients *b*	P-Value[2]
P-Major			
NAx708[3]	0.0244	1.2406	
EUx708	0.0113	1.3330	0.056
DBP90[4]	0.0189	1.2566	
DBP100	0.0290	1.2257	< 0.001
Female	0.0103	1.3557	
Male	0.0102	1.3402	< 0.001
P-Minor			
NAx708	0.0115	1.1457	
EUx708	0.0070	1.2078	0.265
DBP90	0.0062	1.2191	
DBP100	0.0140	1.1236	0.002
Female	0.0055	1.2463	
Male	0.0069	1.2028	< 0.001
Total Breast			
NAx708	0.0343	1.2230	
EUx708	0.0169	1.3082	0.065
DBP90	0.0250	1.2492	
DBP100	0.0408	1.2072	< 0.001
Female	0.0149	1.3348	
Male	0.0154	1.3137	< 0.001
Drum + Thigh			
NAx708	0.1359	1.0451	
EUx708	0.3146	0.9321	< 0.001
DBP90	0.1305	1.0516	
DBP100	0.2181	0.9808	0.010
Female	0.1882	0.9985	
Male	0.2258	0.9813	0.070
Fat-pad			
NAx708	0.0031	1.2336	
EUx708	0.0022	1.2503	< 0.001
DBP90	0.0003	1.5400	
DBP100	0.0030	1.2117	< 0.001
Female	0.0003	1.5400	
Male	0.0010	1.3416	< 0.001
Heart			
NAx708	0.0193	0.8271	
EUx708	0.0194	0.8306	0.271
DBP90	0.0237	0.8016	
DBP100	0.0176	0.8404	0.598
Female	0.0244	0.7923	
Male	0.0225	0.8144	< 0.001
Liver			
NAx708	0.0739	0.8602	
EUx708	0.0458	0.9226	0.278
DBP90	0.0332	0.9679	
DBP100	0.0791	0.8489	< 0.001
Female	0.0429	0.9350	
Male	0.0588	0.8851	< 0.001

(continued)

Part	Coefficients		P-Value[2]
	a	*b*	
Total Intestine (Duodenum Jejunum Ileum)			
NAx708	0.3139	0.6682	
EUx708	0.3597	0.6472	0.249
DBP90	0.2577	0.6961	
DBP100	0.3663	0.6445	0.006
Female	0.2754	0.6820	
Male	0.3976	0.6384	0.116

[1] Data were fit to the Huxley's allometric function (Huxley, 1932): $PW = \mathrm{a} + BW^{b} + \varepsilon$, where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least-squares approximation, and ε is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS.

[2] The allometric curve coefficients were compared using a least-squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons.

[3] Strain: Offspring of either a European (EU) male-line or a North American (NA) male-line, each crossed with a Ross 708 maternal line from Aviagen.

[4] Protein level: The DBP100 protein diet was formulated at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids on a digestible basis. The DBP90 protein diet was formulated with digestible lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at an ideal digestible lysine: AA ratio.

4. Metabolizable Energy Partitioning in Broiler Breeders

4.1 Abstract

Selection for increased meat yield, rapid growth, and feed efficiency in broiler chickens has resulted in an increased *ad libitum* feed intake relative to maintenance requirements, but this selection has led to a decrease of reproductive capacity in broiler breeders. Feed restriction is a standard tool utilized in broiler breeder production. The period of most severe feed restriction is during the rearing phase. In order to feed breeder hens at the ideal level for reproductive efficiency, the maintenance requirements of the flock must be estimated. Biometric models have been previously developed; however, these estimates may lose accuracy due to rapid changes in genetics over time. Industry data were collected from two commercial broiler breeder operations in order to estimate the metabolizable energy of maintenance (ME_m) of Ross 308 broiler breeders reared in floor housing. A total of 8,558 broiler breeders were included in this study. ME_m requirements per metabolic body weight ($BW/kg^{0.67}$) were lowest during periods of high feed restriction. This was consistent with previous studies in the literature as breeders will become more efficient when energy is limited. The study also examined the effect of environmental temperature on the maintenance requirements of commercial broiler breeders. Although the effect of temperature was inconclusive, the estimates of maintenance requirements were consistent with other experimental findings in the literature.

4.2 Introduction

Broiler chickens have been highly selected for meat production and growth; it is estimated that 19.1% and 25.4% of apparent metabolizable energy (AME) is utilized for protein and lipid deposition, respectively (Carré and Juin, 2015). Since broilers are the offspring from broiler breeders, breeders must be feed restricted to ensure settable egg production, prevent developing health issues like erratic oviposition and defective egg syndrome (EODES), sudden death, lameness, and prolapsed cloaca (Yu et al., 1992; Renema et al., 1999; Heck et al., 2004; Renema and Robinson, 2004; Mohiti-Asli et al., 2012b). A significant concern for producers is managing broiler breeder body weight (BW) during the rearing and reproduction phase; between approximately 7 to 16 weeks is the period of most intense feed restriction during which the birds are provided only 25 to 33% of *ad libitum* intake (Hocking, 1993; Savory and Kostal, 1996; De Jong et al., 2002). Broiler breeders are fed only slightly above maintenance requirements to maintain egg production levels; it has been suggested that energy intake between 20 to 30 weeks of age does not meet maintenance requirements (Rabello et al., 2006). When breeders partition energy, maintenance requirements are met first, leaving the remainder for growth and production (Boekholt et al., 1994). How energy is partitioned changes with bird age; broiler breeders before 50 weeks of age will catabolize protein in order to maintain egg production; however, after 50 weeks, they catabolize more energy from lipid stores (Caldas et al., 2018). Excess feed intake will lead to surplus growth and adipose deposition, leading to decreased reproduction and formation of multiple hierarchies of large yellow follicles; therefore, broiler breeders are fed close to maintenance requirements to regulate flock BW (Yu et al., 1992; Renema et al., 1999; Rabello et al., 2006; Wei et al., 2019). Pullet BW between 7 and 15 weeks of age is crucial for the future reproductive success of the broiler breeder (Bruggeman et al., 1999). During the rearing stage feed allocation is commonly reduced to approximately one-third of *ad libitum* consumption although, with recent genetic changes, the gap between growth potential and breeder target BW is increasing (De Beer and Coon, 2007; Renema et al., 2007; Richards et al., 2010; Zuidhof et al., 2014).

As a proportion of total metabolizable energy (ME) intake, maintenance energy functions utilize up to 79% of total energy usage at 21°C (Rabello et al., 2006; Caldas et al., 2018).

Environmental temperature outside the thermoneutral zone of the broiler breeder requires energy expenditure for thermogenesis or cooling (Rabello et al., 2006; Pishnamazi et al., 2015). Environmental temperature profoundly influences maintenance energy requirements of poultry linearly when within a narrow range and close to the thermoneutral zone and quadratically as temperatures vary further above or below the thermoneutral range (Peguri and Coon, 1993; National Research Council, 1994; Sakomura, 2004; Pishnamazi et al., 2015). At temperatures below the thermoneutral zone, broilers increase feed intake for heat production; at high temperatures, birds decrease intake to minimize heat increment (Sakomura et al., 2005). The effect of temperature in laying hens has been studied extensively; however, fewer studies have been performed specifically with broiler breeders (Peguri and Coon, 1993; Rabello et al., 2006; Nonis and Gous, 2018). Ross broiler breeders have up to 320% lower diet-induced thermogenesis (DIT) per metabolic BW than a layer (ISA brown) breed (Swennen et al., 2006). Therefore, breeder-specific studies are necessary. Due to the tightly regulated energy intake for broiler breeders, relatively small changes in environmental temperature outside the thermoneutral zone have the potential to significantly impact maintenance requirements. Although internal barn temperature can be highly regulated, control is not perfect and external factors will impact internal barn temperature. As total energy intake by broiler breeders is only slightly above the requirements for growth, reproduction, and maintenance, changes in the weather can result in large swings in metabolizable energy requirements, leading to changes in energy balance (Pishnamazi et al., 2015). Since broiler breeders are feed restricted to their minimum required level to prevent excess growth, it is vital to understand maintenance requirements for feed allocation decision making. These decisions will impact later growth and production of broiler breeders. Mathematical models can be used to demonstrate the effect a production decision has on subsequent growth.

Bioeconomic models have been developed using empirical parameters; however, there is a growing interest in the development of mechanistic biometric models. Empirical models describe correlations between variables with no indication of the underlying biological mechanisms (Zoons et al., 1991). Since their derivation is determined in a particular set of experimental constraints, extrapolation can be limited. Mechanistic biometric models predict relationships between independent and dependent variables representing biological processes, allowing for a robust model under broad conditions. Biometrical models are of interest as economic models are dependent on biometric parameters. Biometrical models have been developed for broiler breeders (Gous and Nonis, 2010), and broilers (Aggrey, 2002; Reddish and Lilburn, 2004). Rapid changes in broiler genetics have caused older biometric models to become out-dated. A broiler breeder model has been developed using animals raised in an intensively-monitored research facility (Gous and Nonis, 2010). In order for biometric models to be accurate enough to use in the industry, mathematical models must be validated. Metabolizable energy of maintenance (ME_m) requirements fluctuate significantly depending on the degree of feed restriction (Sakomura et al., 2003), feed intake (Romero et al., 2009a), and environmental temperature (Pishnamazi et al., 2015). Variation among studies estimating ME_m show significant variation dependent upon feed intake (Liu et al., 2017), environmental temperature (Rabello et al., 2006; Pishnamazi et al., 2015), feed restriction (Plavnik and Hurwitz, 1985; Pinchasov and Galili, 1990; Brainer et al., 2012; Liu et al., 2017), and diet composition (Carré et al., 2014; Barzegar et al., 2019; Table 4-1). One of the purposes of this study was to validate the coefficients of ME_m obtained in previous studies. Validating models developed in research settings with industry data will allow for a more robust model that can be utilized in a variety of conditions.

Historically, ME_m has been expressed as a function of metabolic body weight ($BW^{0.75}$). However, ME_m is more accurately represented by exponents lower than 0.75 in modern broilers due to genetic changes to a faster-growing and leaner bird (Romero et al., 2009a; Noblet et al., 2015). The use of a 0.75 exponent will bias the value for fasting heat production and conversely, the estimated ME_m coefficients; therefore, in this study, ME_m is reported as a function of $BW^{0.67}$ (Noblet et al., 2015).

4.3 Materials and Methods

4.3.1 Birds and Management

Industry data were collected to estimate the maintenance requirements of commercially-reared broiler breeders from 0 to 20 weeks of age in two flocks from separate locations in Alberta, Canada. To maintain confidentiality, they are referred to as Farm A and Farm B. Barn dimensions and configurations were recorded prior to chick placement. Each flock was housed in a conventional light-tight floor housing facility and were raised according to breeder recommendations (Aviagen, 2014a). The flocks were fed *ad libitum* for the first 4 weeks and then placed on a skip-a-day feeding program.

All research protocols were approved by the University of Alberta Animal Care and Use Committee for Livestock and followed the principles established by the Canadian Council on Animal Care (Canadian Council on Animal Care, 2009).

4.3.1.1 Farm A

At hatch, a total of 4,490 Ross 308 female broiler breeders were placed in a 631.7 m^2 light-tight facility (0.141 m^2/bird). A total of 683 Ross 308 males were placed in a separate 111.5 m^2 section of the barn (0.163 m^2/bird) for the first 2 weeks then transferred to a separate facility for rearing. At 2 weeks of age, the Ross 308 females were provided full access to the 743.2 m^2 area. At 10 weeks, the males and females were cohabitated.

4.3.1.2 Farm B

At hatch, a total of 4,068 Ross 308 female broiler breeders were placed in a 634.7 m^2 light-tight facility (0.156 m^2/bird), with 475 males raised in a 102.0 m^2 separate portion of the barn (0.215 m^2/bird). At 10 weeks, the males and females cohabitated in the 736.7 m^2 facility.

4.3.2 Data Collection

The data utilized in this study were collected from pullets from 0 to 20 weeks of age. Flock BW was estimated through a random selection of 100 target birds identified and weighed at placement. Subsequent weighing occurred at 3 to 4 weeks of age, and 9 to 11 weeks of age. Additional weekly weighings were performed by the producer and were also included in the analysis. The estimates for Farm B from 0 to 4 weeks were removed from the study due to collection error. Feed intake data were collected from barn scales. Barn temperatures were recorded every 30 minutes, using automated data loggers positioned evenly throughout the barn at bird head height. Temperature averages were calculated among the loggers for each 30 min increment. External temperature data were obtained from Environment Canada (Government of Canada, 2020). Using the physical location of the farms, the closest possible weather station was utilized (Farm A = 7.83 km; Farm B = 11.67 km).

4.3.3 Analysis

Data were analyzed in a least-squares linear model using the MIXED procedure of SAS (SAS Institute, 2009) to estimate the metabolizable energy (ME) requirement for maintenance for age in

4-week blocks: 0 to 4 weeks, 5 to 8 weeks, 9 to 12 weeks, 13 to 16 weeks, and 17 to 20 weeks with the following linear model:

$$mei = a(BW^{0.67}) + b(BW^{0.67})(T_e - 21) + c(G)$$

Where *mei* is ME intake (kcal/day) was determined from feed disappearance and the formulated ME value; BW is live BW (kg); $T_e - 21$ is internal barn temperature relative to 21°C; and G is gain (g/day); a is the coefficient representing the relationship between metabolic body weight and base ME maintenance requirements (ME_m); b is the coefficient of the effect of temperature on the maintenance ME energy; c is the coefficient representing the ME cost for one gram of BW gain. The model was considered significant, where $P < 0.05$. The estimate for 'a', age-specific ME requirements were considered significantly different than 0 at $P < 0.05$. A regression analysis was performed to examine the correlation between barn temperature and external temperature.

4.4 Results and Discussion

4.4.1 Maintenance requirements

The model for age-specific base ME maintenance requirements were found to adequately fit data at Farm A and Farm B ($P < 0.001$, 0.001, respectively).

Birds on Farm A showed the lowest estimated value for 'a' (ME_m requirements) from weeks 9 to 12 and then an increase in ME_m in the period 17 to 20 weeks ($P = 0.040$, <0.001; Table 4-2). The estimates for ME_m requirements at Farm A were not significant at 0 to 4 weeks and 13 to 16 weeks and therefore are not considered to accurately represent the data ($P = 0.220$, 0.069; Table 4-2).

ME_m of birds on Farm B showed a decrease in the 9 to 12 week period compared to 5 to 8 weeks, and then a slight increase during the 13 to 16 week period, and a further increase through to 20 weeks ($P = 0.002$, 0.001, <0.001; Table 4-2). For both farms, the ME_m requirements were highest during the 5 to 8 week period and the 17 to 20 week period (P = 0.018, <0.001, <0.001, <0.001; Table 4-2).

The coefficient for b, the effect of barn temperature on maintenance, was 4.83 and 4.01 for Farm A and Farm B respectively; however, it was not significant for either farm (P = 0.776, 0.475). The coefficient for c, the ME requirement per gram of growth, was 0.701 and 1.328 for Farms A and B, respectively, but the coefficient was not significant (P = 0.469, 0.157).

Studies in laying hens and broiler breeders show that higher levels of feed restriction reduce the amount of energy utilized for maintenance (Plavnik and Hurwitz, 1985; Pinchasov and Galili, 1990; Brainer et al., 2012; Liu et al., 2017). Although feed efficiency increases during restriction, this does not carry into periods immediately following re-alimentation (Zubair and Leeson, 1994; Swennen et al., 2006). Since ME_m includes the energy released as heat increment (Luiting, 1990), high feed intake results in larger DIT, with the animals consequently losing more energy as heat to their environment. Following the breeder recommendations, the period between 5 to 15 weeks has the largest feed restriction relative to *ad libitum* feed intakes (Renema and Robinson, 2004; Aviagen, 2014b; a). A study estimated that from 9 to 20 weeks of age, 95 to 96% of total broiler breeder ME intake is used for maintenance, whereas from 5 to 8 weeks, only 72.5% is utilized for maintenance (Sakomura et al., 2003). On each farm, the lowest ME_m requirements were between 9 to 12 weeks of age (Table 4-2; P = 0.040; 0.001). Although the ME_m value is numerally lower at 13-16 weeks the coefficient for Farm A was only nearly significant (Table 4-2; P = 0.069). The reduction in required ME_m observed between 8 to 16 weeks of age was due to the increase in the severity of feed restriction relative to *ad libitum* during this period. Decreases in flock efficiency were seen during the 17 to 20 week period compared to the previous periods as the degree of feed restriction lessened on both Farm A and Farm B (P < 0.001, 0.001; Table 4-2). From 17 to 20 weeks of age, the degree of feed restriction was lessened, causing an increase in feed intake relative to metabolic BW and therefore, a higher degree of DIT. It has been proposed that ME_m requirements fluctuate significantly with feed intake (Liu et al., 2017), environmental temperature (Rabello et al., 2006; Pishnamazi et al., 2015), feed restriction (Plavnik and Hurwitz, 1985; Pinchasov and Galili, 1990; Brainer et al., 2012; Liu et al., 2017), and diet composition (Carré et al., 2014; Barzegar et al., 2019); therefore there is significant variation in ME_m values reported in the literature (Table 4-1). Furthermore, the observed differences in estimated base ME maintenance requirements between farms can be attributed to many factors such as: activity levels, feathering, immune status, and diet composition. The proportion of NE/AME varies significantly between nutritional components in the feed such as proteins, lipids, and non-cell wall carbohydrates 0.69 to 0.68; 0.849 to 0.90; 0.75 to 0.779; respectively, with these differences being attributed to heat production in the animal (Carré et al., 2014; Barzegar et al., 2019). Nutrients and ME were formulated to the same specifications for both farms; however, the specific ingredients used varied and therefore, if the feed were to contain higher lipid to protein content, this would lower the heat increment of feeding and subsequently lower the estimation of ME_m. Estimates of ME_m are impacted further by the dietary components in each phase. The 4-stage rearing program used in this study starts breeders on a 21% dietary CP and steps down to 14% CP by the developer stage (Aviagen, 2007b). By moving to a lower protein diet, we would expect a reduction in heat increment; as the level of crude protein is negatively related the NE to AME ratio of the overall diet (Carré et al., 2014; Wu et al., 2019); therefore, impacting ME_m. We observed a significant difference between Farm A and B for estimations in ME_m. As this study was dependent on feed allocations by the producer this may also be due to inaccuracy feeding scales. For future studies, the factors discussed previously affecting ME_m should be measured and included in the estimation for ME_m.

As total heat production is included in any estimate of ME_m, the results from this study support the concept that the true maintenance requirements of broiler breeder pullets may be lower than what is currently reported in the literature. Feed intake is positively correlated to ME_m; therefore, when feed intake is reduced, ME_m is decreased (Pishnamazi et al., 2008). This theory supports that the reduction in ME_m during the 8 to 16 week period is due to the severity of feed restriction relative to *ad libitum* (Liu et al., 2017).

4.4.2 Environmental temperatures

The correlation between outdoor environmental temperature and internal barn temperature was strongest when outdoor temperatures were higher than the set point of the barn. In the first two weeks, when the barn temperatures were above ~25°C, high external temperature was not significantly correlated to internal barn temperature (Figures 4-1 and 4-2). Excluding the first 2 weeks of rearing, the relationship between outdoor daily maximum temperature and the indoor daily average temperature was highly correlated for each farm (Farm A $R^2 = 0.765$, Farm B $R^2 = 0.758$, $P < 0.001$, < 0.001; Figures 4-1 and 4-2).

That the relationship between environmental temperature and metabolic BW was not significant it is likely due to the small variation in external temperature throughout the trials. Although our study did not show an effect of barn temperature on maintenance requirements, barn temperatures above or below 24.3°C increase ME_m of adult broiler breeders (Pishnamazi et al., 2015). Due to the severity of feed restriction, the total consumed energy of broiler breeders is very close to maintenance requirements, and any change in ME_m requirement must be accounted for as it will affect energy available for growth and production. Since broiler breeders are homeothermic, increasing temperature from 15°C to 17°C may require up to a 5% decrease in feed allocation to account for the decrease in requirements (Pishnamazi et al., 2015). Higher outdoor temperatures have more of an influence on indoor barn temperatures except during the first few weeks of rearing where indoor barn temperatures are increased using supplemental heat (Figures 4-1 and 4-2). In order to adjust for these fluctuations, the influence of weather should be taken into consideration prior to making weekly feed allocation decisions for broiler breeders.

Interestingly, the data obtained from industry sources were similar to other studies in Ross 708 (Pishnamazi et al., 2015) and Hubbard-Hi-Yield broiler breeders (Sakomura et al., 2003). However, previous research has determined slightly higher coefficients for ME_m than this study (Table 4-1). In this study, temperatures were controlled as per the primary breeder recommendations (Aviagen, 2014a), and the flock were not subjected to different experimental temperature treatments. Anecdotally, it was observed during researcher weighings that birds from Farm A had higher fleshing, an indication of how much muscle is developed on the breast, than Farm B. The inconsistencies may also be due to the differences in proportional adipose and muscle tissue weights relative to BW that were maintained by breeders at Farm A vs Farm B, as muscle tissues are more energetically expensive to maintain than adipose tissue (Zuidhof, 2005). Further composition of body tissues could be examined to explore the effects of fleshing.

The sources of error in this study may be related to variation in our estimate of flock BW. It is interesting to note that, after a researcher weighing, the daily gain of the flock decreased. The decrease may have been caused through inconsistency in BW obtained between the producer and the researcher leading to the underestimation of BW by the producer and subsequently a decrease in feed allocation by the producer, leading to an increase in the degree of feed restriction.

Overall our estimates in Farm A of ME_m align with recently published studies and support the concept that the true maintenance requirements of modern broiler breeder pullets may be lower than previously reported in literature (Table 4-1). Our industry study lacked some controls compared to intensive research studies; however, our results show that current estimates for ME_m match closely to requirements in free-run rearing situations. The significance of this study is to validate research models in a commercial setting. The understanding of how breeders partition energy in commercial systems is extremely important for further breed development. Through the continued development and improvement of mathematical models, these decisions can be accurately tailored to increase overall efficiency.

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4.6 Tables & Figures

Table 4-1. Summary of metabolizable energy of maintenance (ME_m) requirements reported in the literature.

Source	Bird type[1]	Reported ME_m	Standardized ME_m[2]
Current Study[3]	BP	107 $kcal/kg^{0.67}$	107 $kcal/kg^{0.67}$
Current Study[4]	BP	55 $kcal/kg^{0.67}$	55 $kcal/kg^{0.67}$
Caldas et al., 2018	BB	106 $kcal/kg^{0.75}$	112 $kcal/kg^{0.67}$
Darmani Kuhi et al., 2011	BB	103 kcal/kg	129 $kcal/kg^{0.67}$
Darmani Kuhi et al., 2012	L	88 kcal/kg	111 $kcal/kg^{0.67}$
Hadinia et al., 2019	BB	142 $kcal/kg^{0.67}$	142 $kcal/kg^{0.67}$
Nonis and Gous, 2018	BB	133 $kcal/kg^{0.75}$	140 $kcal/kg^{0.67}$
Pishnamazi et al., 2015	BB	104 $kcal/kg^{0.84}$	98 $kcal/kg^{0.67}$
Rabello et al., 2006	BB	112 $kcal/kg^{0.75}$	118 $kcal/kg^{0.67}$
Reyes et al., 2011	BB	98 $kcal/kg^{0.75}$	104 $kcal/kg^{0.67}$
Romero et al., 2009a	BB	141 $kcal/kg^{0.54}$	128 $kcal/kg^{0.67}$
Romero et al., 2009b	BB	104 $kcal/kg^{0.75}$	110 $kcal/kg^{0.67}$
Sakomura et al., 2003	BB	144 $kcal/kg^{0.75}$	152 $kcal/kg^{0.67}$
Sakomura et al., 2003	AL	192 $kcal/kg^{0.75}$	203 $kcal/kg^{0.67}$
Sakomura et al., 2003	54% AL	179 $kcal/kg^{0.75}$	189 $kcal/kg^{0.67}$
Sakomura et al., 2003	34% AL	159 $kcal/kg^{0.75}$	168 $kcal/kg^{0.67}$
Sakomura et al., 2003	19% AL	134 $kcal/kg^{0.75}$	141 $kcal/kg^{0.67}$
Spratt et al., 1990	BB	70 $kcal/kg^{0.75}$	74 $kcal/kg^{0.67}$
Valencia et al., 1980	L	104 $kcal/kg^{0.75}$	110 $kcal/kg^{0.67}$
Zuidhof et al., 2017	BB	122 $kcal/kg^{0.67}$	122 $kcal/kg^{0.67}$
Zuidhof et al., 2017	BP	86 $kcal/kg^{0.67}$	86 $kcal/kg^{0.67}$

[1] BP = Broiler breeder pullet; BB = broiler breeder hen; L = laying hen; AL = ad-libitum

[2] Data were standardized for a 2 kg pullet (metabolic BW = 1.591 $kg^{0.67}$)

[3] 2 kg female pullets at Farm A

[4] 2 kg female pullets at Farm B

Table 4-2. Estimated coefficient[1] values of a for Farm A and B; the coefficient representing the relationship between age-specific base ME maintenance requirements.

	Farm A			Farm B[2]		
Weeks	a	Standard error	P-Value	a	Standard error	P-Value
0-4	97.66	74.15	0.220	-	-	-
5-8	128.91	44.69	0.018	88.32	9.86	<0.001
9-12	107.13	44.67	0.040	55.77	11.63	0.002
13-16	76.91	37.20	0.069	63.51	8.33	0.001
17-20	132.83	16.16	<0.001	72.92	9.17	<0.001

Data were analyzed in a least-squares linear model using the mixed procedure of SAS to estimate the metabolizable energy (ME) requirement for maintenance.

[1] Data were fit to the equation $mei = a(BW^{0.67}) + b(BW^{0.67})(T_e - 21) + c(G)$ Where mei is ME intake (kcal/day); BW is whole BW (kg); $T_e - 21$ is internal barn temperature corrected to 21°C; and G is gain (g/day); a is the coefficient representing the relationship between age specific base ME maintenance requirements (ME_m); b is the coefficient of the effect of temperature on the maintenance ME energy; c is the coefficient representing the ME cost for one gram of BW gain.

[2] Data missing from Farm B from 0-4 weeks as accurate feed intake could not be determined as birds were fed ad libitum till 4 weeks.

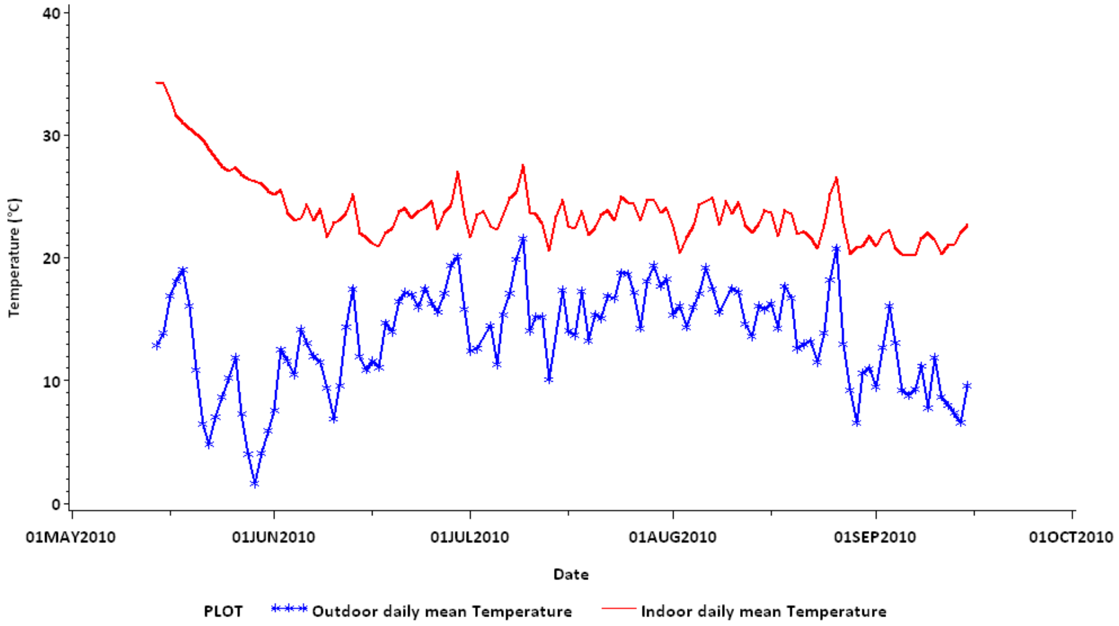

Figure 4-1. Relationship between indoor and outdoor barn temperature at Farm A.
Indoor temperature averages were calculated for each 30 min increment. External temperature data were obtained from Environment Canada (Government of Canada, 2020). Using the physical location of the farms, the closest possible weather station was utilized ~7.83 km away.

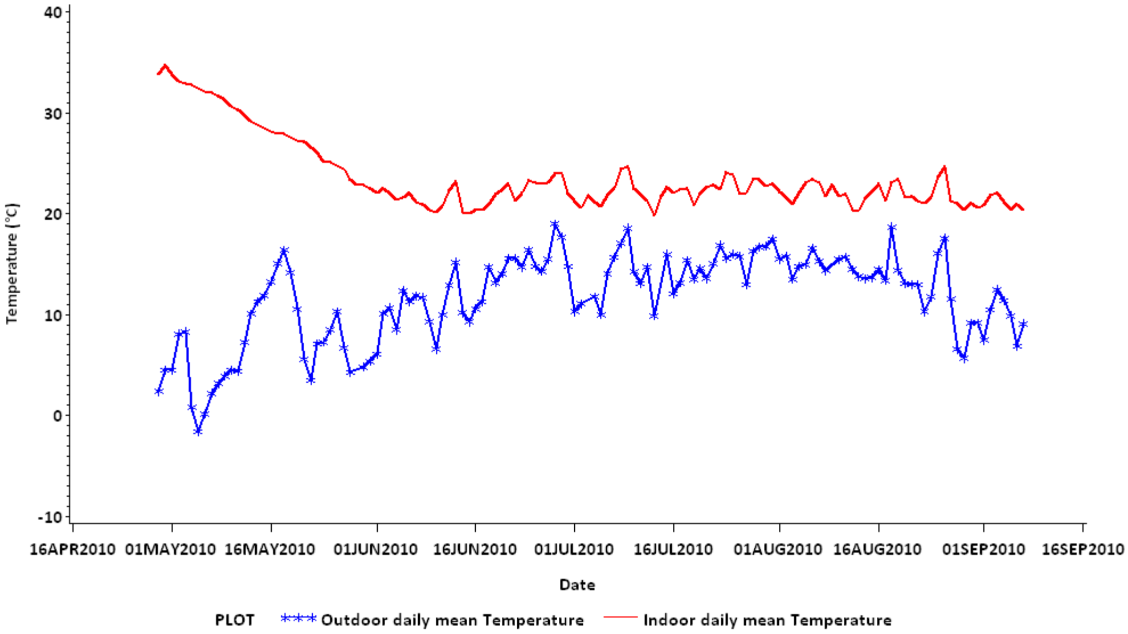

Figure 4-2. Relationship between indoor and outdoor barn temperature at Farm B.
Indoor temperature averages were calculated for each 30 min increment. External temperature data were obtained from Environment Canada (Government of Canada, 2020). Using the physical location of the farms, the closest possible weather station was utilized ~11.67 km away.

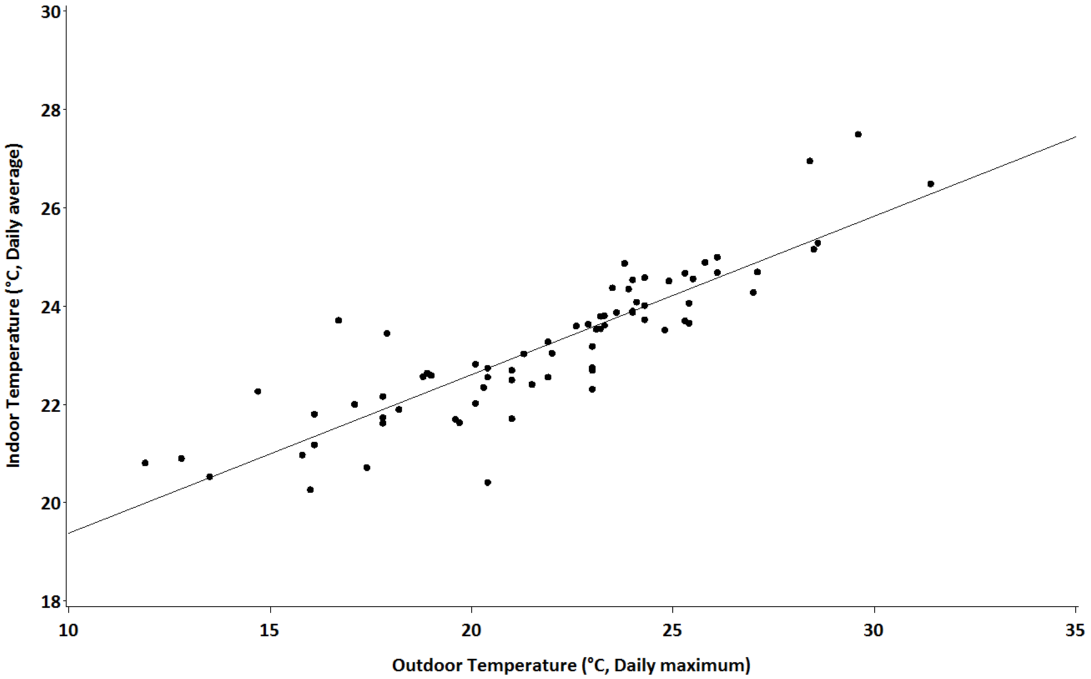

Figure 4-3. Regression between indoor and outdoor temperature at Farm A.

Indoor temperature averages were calculated for each 30 min increment. External temperature data were obtained from Environment Canada (Government of Canada, 2020). Using the physical location of the farms, the closest possible weather station was utilized ~7.83 km away. (R^2= 0.765; $P < 0.001$)

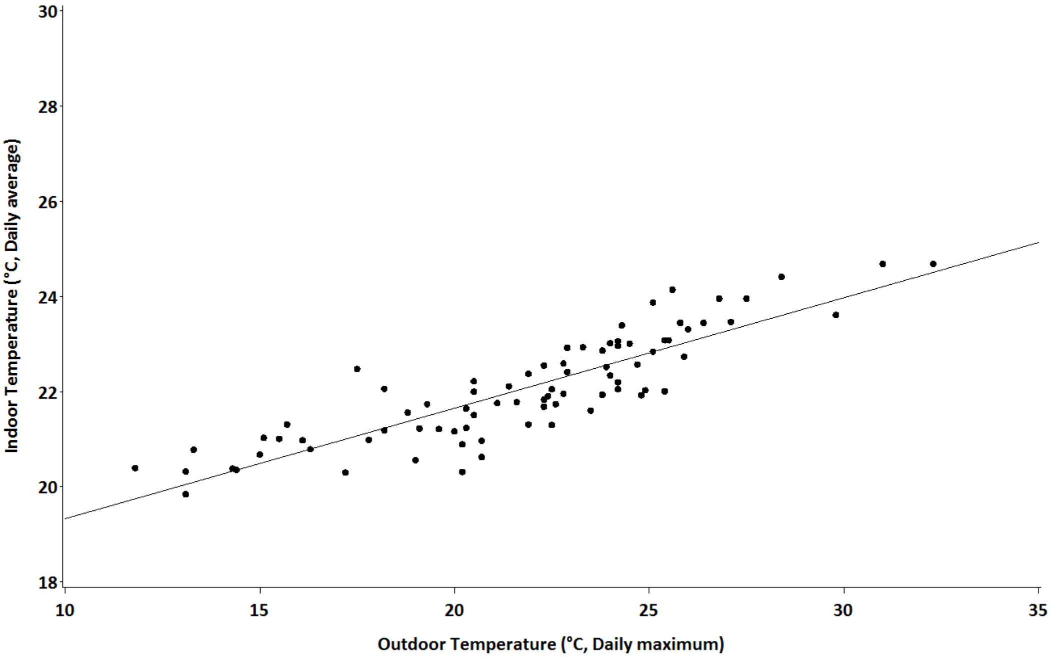

Figure 4-4. Regression between indoor and outdoor temperature at Farm B.
Indoor temperature averages were calculated for each 30 min increment. External temperature data were obtained from Environment Canada (Government of Canada, 2020). Using the physical location of the farms, the closest possible weather station was utilized ~11.67 km away. (R^2= 0.758; $P < 0.001$)

5. General Discussion and Conclusions

5.1 Review of Hypotheses and Conclusions

Chapters 2 and 3 examined performance, yield, and allometric relationships in broiler offspring from North American or European male lines crossed with the same Ross 708 breeder females (NA x 708; EU x 708, respectively), and fed diets of differing dietary balanced protein (DBP) levels. Diets contained DBP at 100% (DBP100) or 90% (DBP90) of Ross 708 recommendations. Growth and performance were examined on birds fed either corn- (Corn Experiment) or wheat- (Wheat Experiment) based diets. It was expected that the EU x 708 broilers would have higher growth and yield performance on wheat-based diets relative to NA x 708 broilers due to the primary grain used during breed genetic selection.

Chapter 4 studied the maintenance energy requirements of commercially-reared broiler breeder pullets from 0 to 20 weeks of age. Data was collected from a total of 8,558 Ross 308 broiler breeders reared at two breeder operations; the metabolizable energy of maintenance (ME_m) was estimated for each of the flocks in 4-week intervals.

Hypothesis 1. It was hypothesized that DBP100 would increase growth and yield relative to DBP90 diets in corn- (Corn Experiment) and wheat-based (Wheat Experiment) diets. Increased amino acid density would, therefore, increase the yield of salable meat and influence overall carcass composition. We failed to reject this hypothesis as yield and growth increased in the DBP100 relative to the DBP90 treatment. We found the NA x 708 strain less susceptible to reduced DBP compared to the EU x 708 strain. Yields of individual portions were also affected with lower DBP content; in general, we observed a reduction in breast meat and an increase in other portions, specifically the thighs and wings.

Hypothesis 2. It was hypothesized that the NA x 708 would have an overall higher yield than the EU x 708. We also hypothesized that the EU x 708 would be less susceptible to lower DBP levels than the NA x 708. We failed to reject these hypotheses. We observed a more significant reduction in the breast meat and overall yield when fed the DBP90 diet in the NA x 708 broilers compared to the EU x 708 broilers.

Hypothesis 3. Allometric yield curve coefficients were estimated for each treatment using a non-linear growth model. It was hypothesized that DBP90 would reduce the allometric growth of lean tissue and increase lipid deposition compared to DBP100. We failed to reject this hypothesis. In both experiments, the DBP100 total breast curve yield curve was higher than DBP90. DBP100 broilers had larger drum + thigh allometric growth than DBP90

Hypothesis 4. Allometric yield curve coefficients were estimated for each treatment using a non-linear growth model. We hypothesized that a NA x 708 broilers would have a breast muscle allometric curve shifted upward compared to the EU x 708 broilers crossed with the same Ross 708 maternal line. We rejected this hypothesis as there was no difference breast muscle allometric between the NA x 708 and the EU x 708 broilers.

Hypothesis 5. Chapter 4 focused on the development and estimation of ME_m requirements of Ross 308 breeder pullets in commercial open floor housing systems. We hypothesized that our estimate for the ME_m requirement would match closely to current published research performed in controlled settings. Although current estimates vary significantly, our estimates of requirements were found to be 107 kcal/kg$^{0.67}$, and 70 kcal/kg$^{0.67}$ for Farms A and B, respectively which is lower than the many currently published studies; however, several recent studies support our conclusion that current estimates for ME_m are lower than what is currently reflected in historical literature.

5.2 Discussion and Conclusions

Broiler chickens have undergone significant genetic selection for growth rate and carcass composition over time. Due to genetic selection, requirements have significantly changed from previous years. Understanding nutrient requirements, and the influence on body conformation is important to optimize broiler nutrition for a given market. The influences of DBP on performance and carcass characteristics of two broiler male-lines were investigated in Chapter 2. The performance was examined using corn- (Corn Experiment) and wheat- (Wheat Experiment) based diets. We hypothesized that DBP100 would increase growth and yield relative to DBP90 diets.

In Chapter 2 lower BW for DBP90 fed broilers were found at age 10, 25, and 35 d in each experiment, however, there was a more significant decrease in broilers fed wheat-based diets compared to corn-based diets; however, this was confounded by the lower lysine levels than formulated in the Wheat Experiment (Table 2-2). Increased dietary lysine has been shown to increase growth, lean composition of the carcass, decrease abdominal fat content (Kidd et al., 2005; Sharma et al., 2018), increase breast yield (Tesseraud et al., 1996a, 2001; Kidd et al., 2005; Sharma et al., 2018), and reduce FCR (Kidd et al., 2005; Sterling et al., 2006). Lower BW was observed in both genetic strains when fed DBP90 compared to DBP100; however, a greater reduction was observed in the EU x 708 strain compared to the NA x 708 strain. The EU x 708 broilers were significantly more efficient in residual feed intake (RFI) than the EU x 708 broilers on corn-based diets; however, there was no difference found in FCR between strains. The results show that the NA x 708 strain was less susceptible to the effects of reduced DBP than the EU x 708 strain. Amino acid requirements to optimize broiler yield were highly dependent on strain cross. This may be due to differences in the efficiency of utilization of AA and lysine between the EU x 708 and the NA x 708 genotypes; however, since the AA digestibility was not measured, and the lysine level was lower than expected, it is not possible to isolate the effect of lysine and DBP. There were differences in amino acid requirements for the EU x 708 and the NA x 708 for optimal growth and yield; however, these differences are not accurately represented in current breeder manuals. The objectives of this study were to determine the suitability of the NA x 708 and the EU x 708 for use in broiler markets which utilized corn- or wheat-based diets. Overall, we found that the NA x 708 and the EU x 708 suitable for use; however, DBP levels must considered when determining expected yields.

Chapter 3 examined the influence of DBP on the allometric growth, development, and carcass characteristics of the progeny of two male lines crossed with Ross 708 breeder females fed corn- and wheat-based diets. Genetic selection for increased meat production has significantly influenced the relative development of organs and carcass components (Schmidt et al., 2009); furthermore, these relationships are dependent on genetic strain and nutrient level (Gous et al., 1999; Danisman and Gous, 2011, 2013). Predictive models that enable the prediction of cutup portions at a given BW must be developed for the strain being utilized. We examined the allometric growth of the *pectoralis* muscles, drum + thigh, fat-pad, heart, liver, and intestines from 0 to 35 days of age through dissections performed every 7 days. We did not observe a strain effect on breast muscle and fat pad allometry on the corn-based diets. Although there was no difference in morphology between strains raised on the corn diets, there was a more pronounced effect on morphology between strains with wheat-based diets, which may have been confounded by lysine requirements of each strain. In each experiment, DBP100 increased total breast meat deposition. DBP100 also increased the drum + thigh allometric growth curve in both experiments; however, DBP90 shifted the development of the drums + thigh to earlier developing on corn-based diets and later developing on wheat-based diets. Broilers that were fed higher levels of DBP produced a higher proportion of breast muscle and had a smaller fat pad at a given BW. With ideal DBP intake, broilers partitioned more energy towards the development of muscle tissue than adipose tissue. Given the increased yield of breast meat with feeding of a high DBP diet, allometric models can be further developed to optimize saleable breast meat by finding the ideal slaughter weight and DBP level at given meat market prices. Our study found that by reducing DBP, lean allometric growth was reduced and adipose tissue deposition was increased. Furthermore, there were no differences between strains on allometric growth of lean muscle and fat-pad. By utilizing coefficients such as those estimated in the study, producers can make production decisions to optimize profitability in current market conditions.

Chapter 4 examined energy partitioning throughout growth in broiler breeder pullets. A biometric model was developed utilizing data collected from two commercial broiler breeder operations. ME_m was estimated for Ross 308 broiler breeder pullets in floor housing. ME_m requirements were found to be 107 kcal/kg$^{0.67}$; recent studies aligned with the estimated value for ME_m requirements. On each farm, there was a reduction in the ME_m between 9 to 12 weeks of age, which coincided with the highest ratio of restricted intake to *ad libitum* intake and is the point of highest feed restriction of the flock. Estimates of ME_m vary significantly in the literature depending on the stage of development, environmental temperature (Rabello et al., 2006; Pishnamazi et al., 2015), diet composition (Carré et al., 2014; Barzegar et al., 2019); and degree of feed restriction (Plavnik and Hurwitz, 1985; Pinchasov and Galili, 1990; Brainer et al., 2012; Liu et al., 2017). The objective of our study was to validate research models developed in controlled research settings; we concluded ME_m requirements are currently overestimated in the literature. Several recent studies also support the conclusion that ME_m requirements may be lower in modern genetics than previously published literature (Romero et al., 2009a; Darmani Kuhi et al., 2011; Reyes et al., 2011; Pishnamazi et al., 2015; Caldas et al., 2018). Given the confounding effect of heat increment on estimates of $ME_{m,}$ further studies should investigate the impact of dietary nutrient components on ME_m requirements in free-run rearing situations.

The results of our studies lead us to believe differences exist between strains in the efficient use of nutrients in diets differing in primary cereal source. Further studies should examine the effect of feed composition, on growth development and allometric growth. Studies should examine the digestibility and loci of the small intestine where nutrients are absorbed between strain and primary grain source. Net availability of nutrients and the effect on allometric growth will also prove useful for further optimization of growth and carcass composition.

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Appendix A.

Allometric growth pairwise comparison supplementary data.

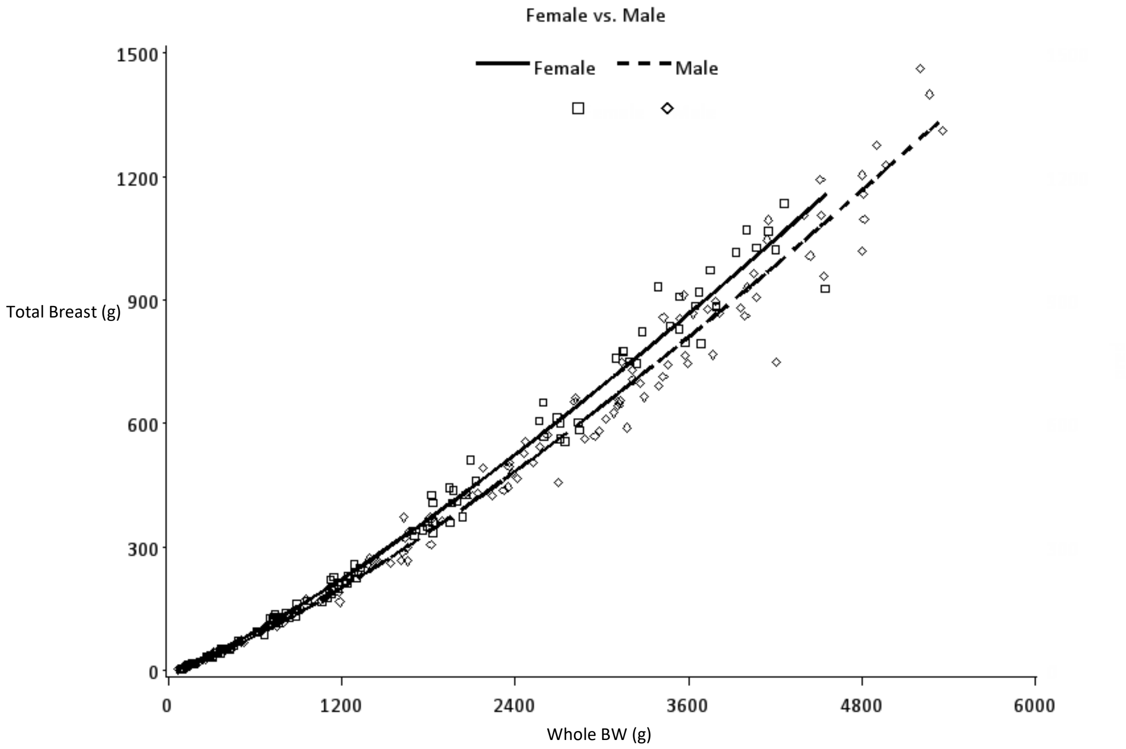

Figure A.1. Total breast meat (g), in relation to live BW. Data are from female and male broilers of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW = a + BW^{b} + \varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

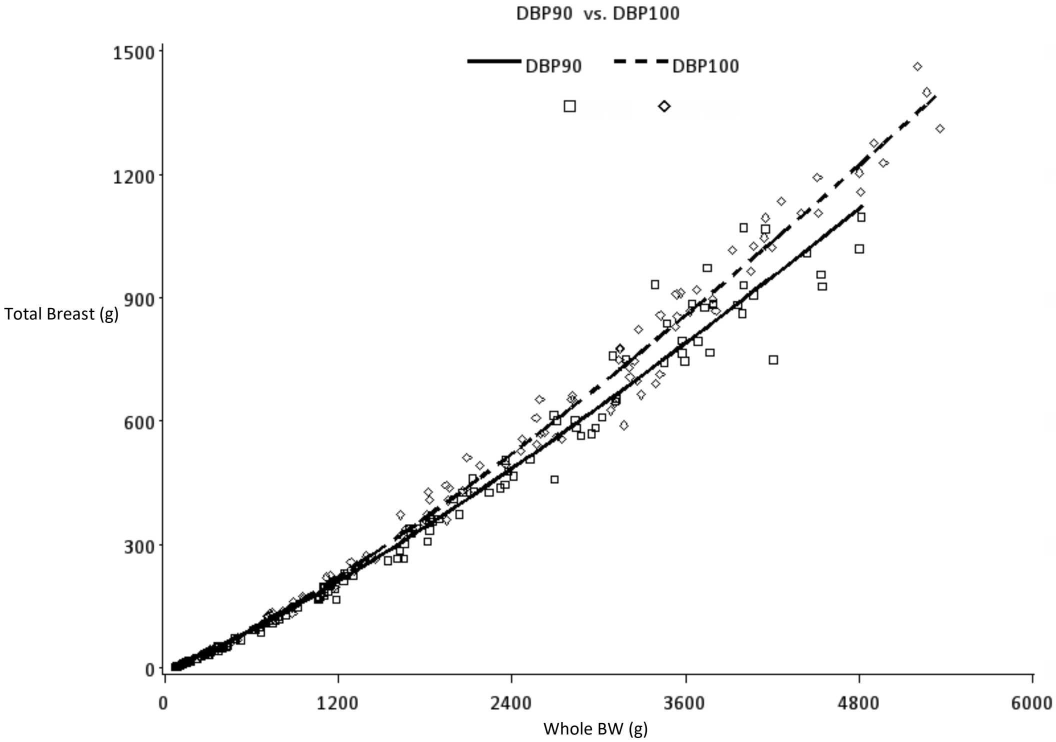

Figure A.2. Total breast meat (g), in relation to live BW. Data are from DBP90 and DBP100 broilers of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. The DBP100 protein diet was formulated at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids on a digestible basis. The DBP90 protein diet was formulated with digestible lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at an ideal digestible lysine: AA ratio. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW^{b}} + \boldsymbol{\varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

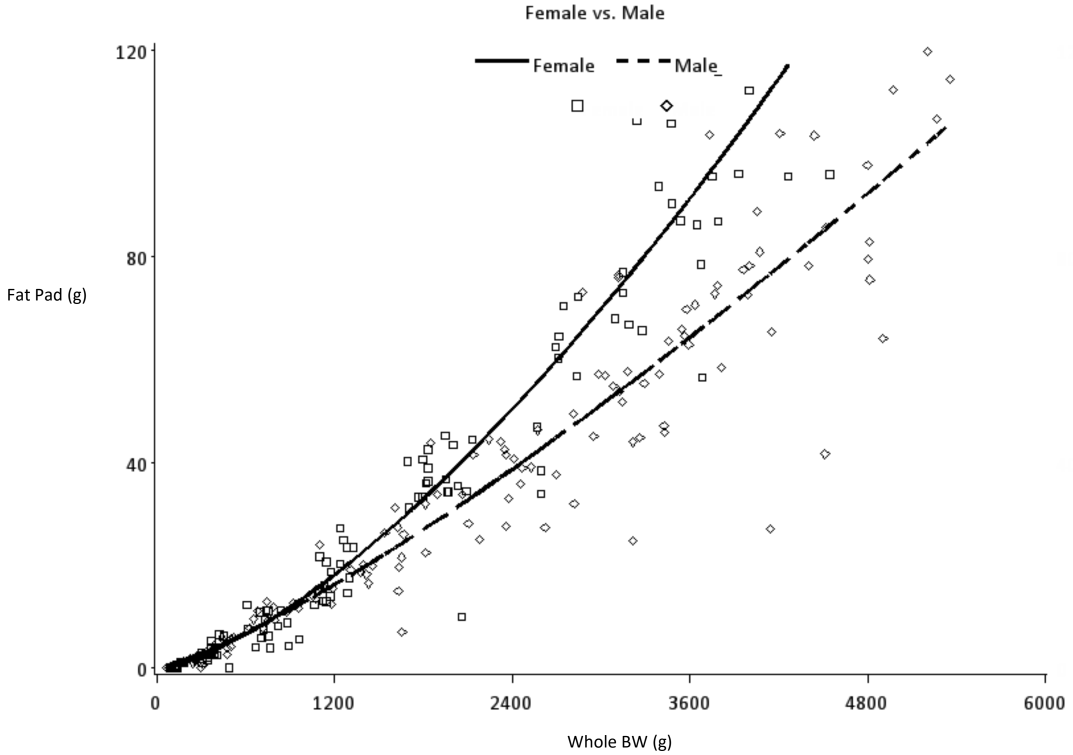

Figure A.3. Total abdominal fat pad (including gizzard and proventriculus fat) weight (g), in relation to live BW. Data are from female and males of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW^b} + \boldsymbol{\varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), *a* and *b* were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

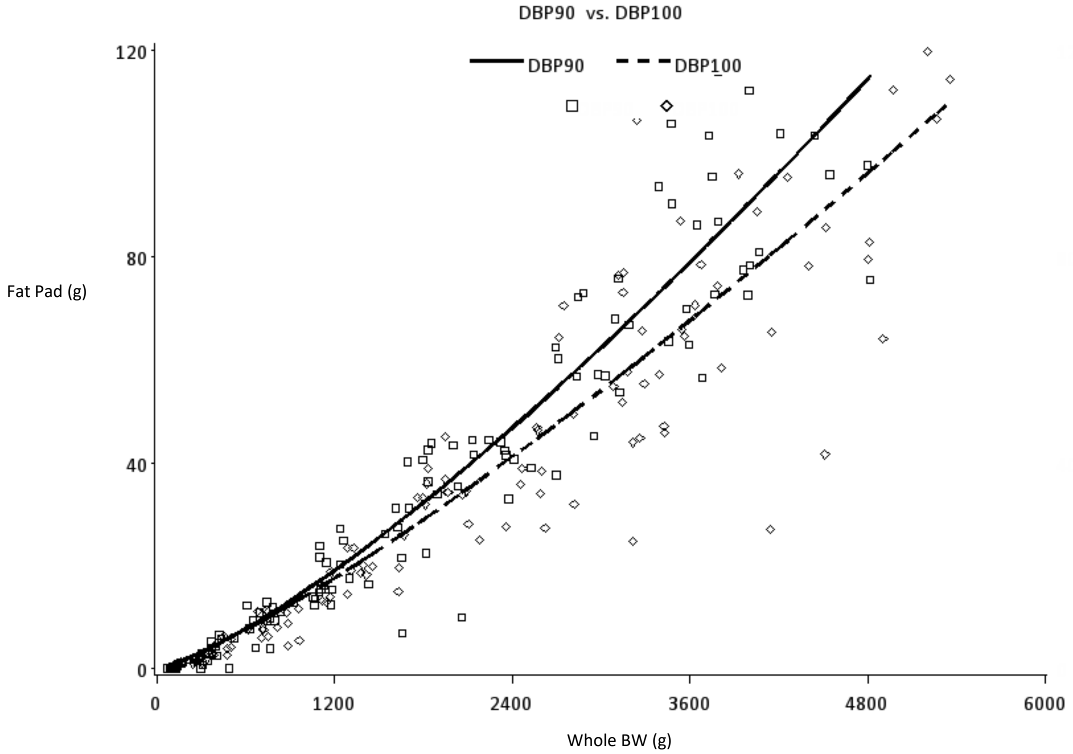

Figure A.4. Total abdominal fat pad (including gizzard and proventriculus fat) weight (g), in relation to live BW. Data are from DBP90 and DBP100 of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. The DBP100 protein diet was formulated at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids on a digestible basis. The DBP90 protein diet was formulated with digestible lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at an ideal digestible lysine: AA ratio. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW}^{\boldsymbol{b}} + \boldsymbol{\varepsilon}$ Where *PW* was: weight of the carcass part (g), *BW* is whole BW (kg), *a* and *b* were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

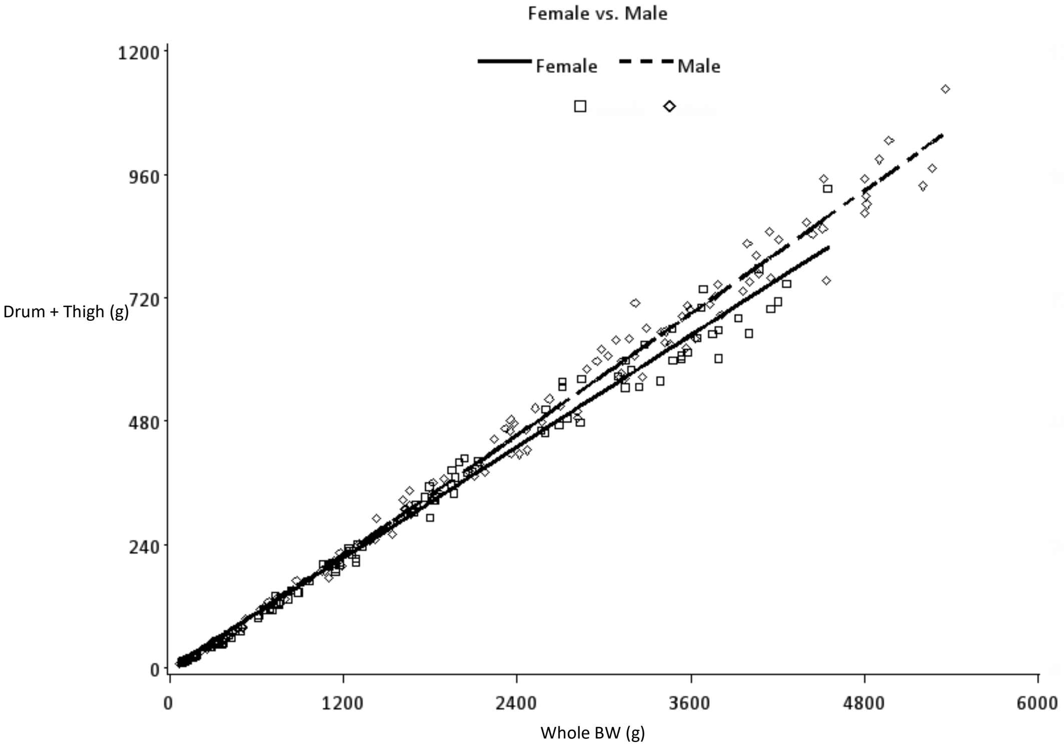

Figure A.5. Drum + thigh weight (g), in relation to live BW. Data are from females and males of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW^b} + \boldsymbol{\varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

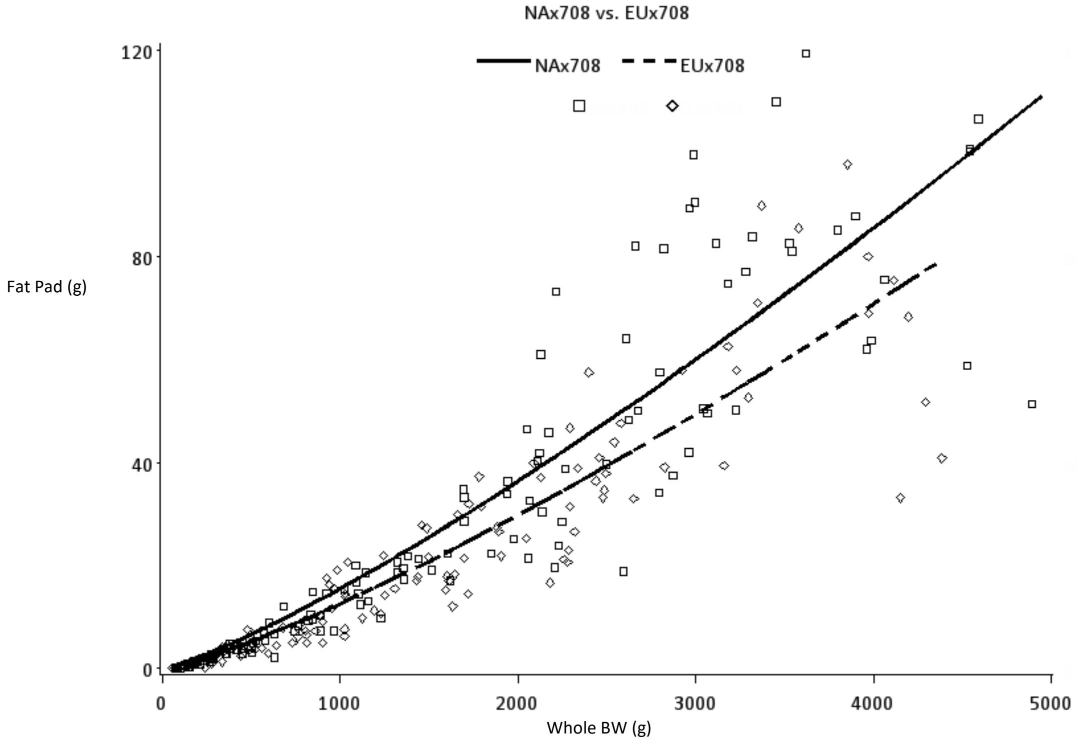

Figure A.6. Total abdominal fat pad (including gizzard and proventriculus fat) weight (g), in relation to live BW. Data are from NA x 708 and EU x 708 of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Wheat Experiment on a wheat-based diet. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW = \mathrm{a} + BW^{b} + \varepsilon}$ Where *PW* was: weight of the carcass part (g), *BW* is whole BW (kg), *a* and *b* were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

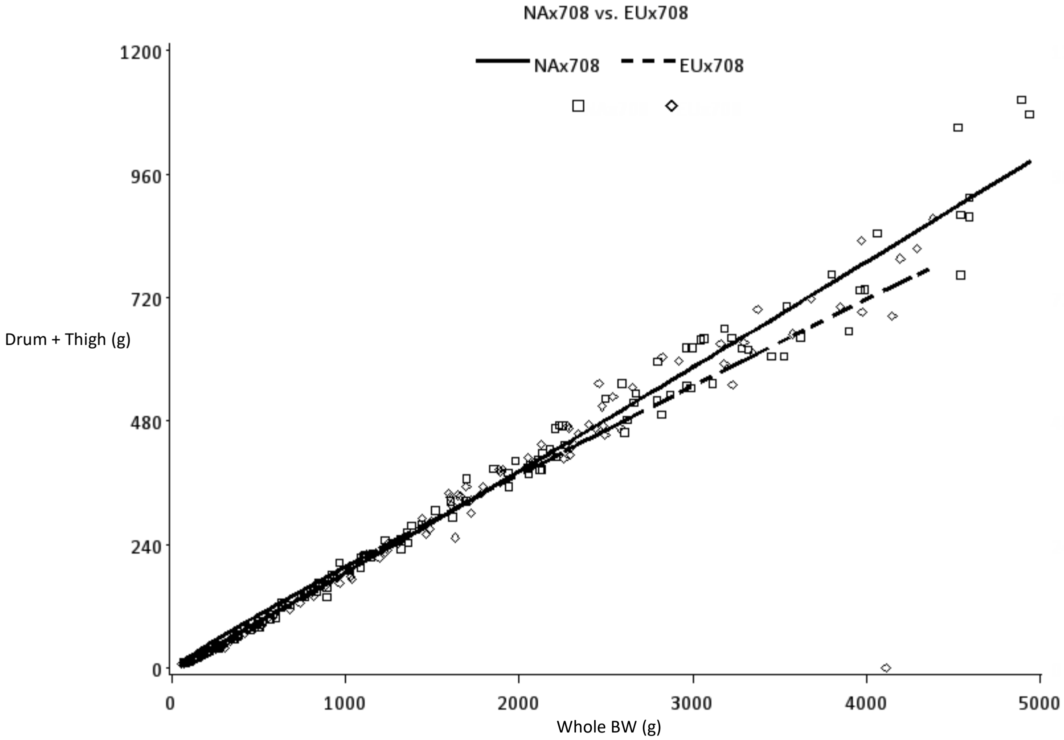

Figure A.7. Drum + thigh weight (g), in relation to live BW. Data are from NA x 708 and EU x 708 of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Wheat Experiment on a wheat-based diet. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW}^{\boldsymbol{b}} + \boldsymbol{\varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

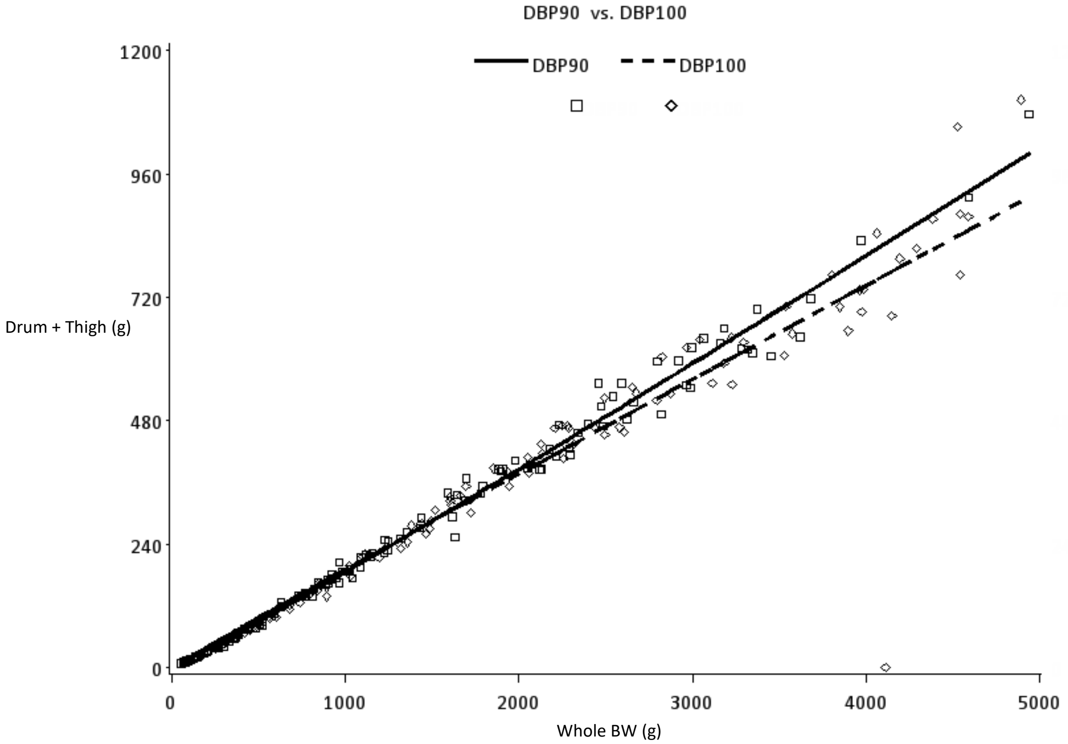

Figure A.8. Drum + thigh weight (g), in relation to live BW. Data are from DBP90 and DBP100 of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Wheat Experiment on a wheat-based diet. The DBP100 protein diet was formulated at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids on a digestible basis. The DBP90 protein diet was formulated with digestible lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at an ideal digestible lysine: AA ratio. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW}^{\boldsymbol{b}} + \boldsymbol{\varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P = 0.010**

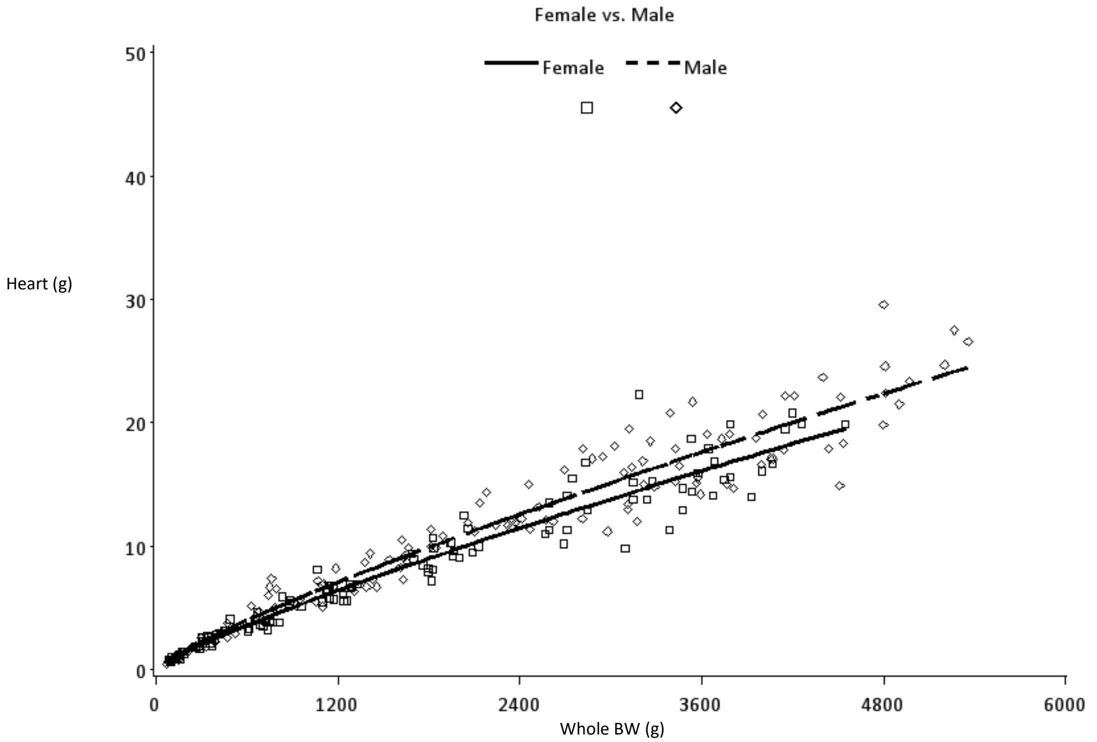

Figure A.9. Heart weight (g), in relation to live BW. Data are from females and males of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW}^{\boldsymbol{b}} + \boldsymbol{\varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P < 0.001**

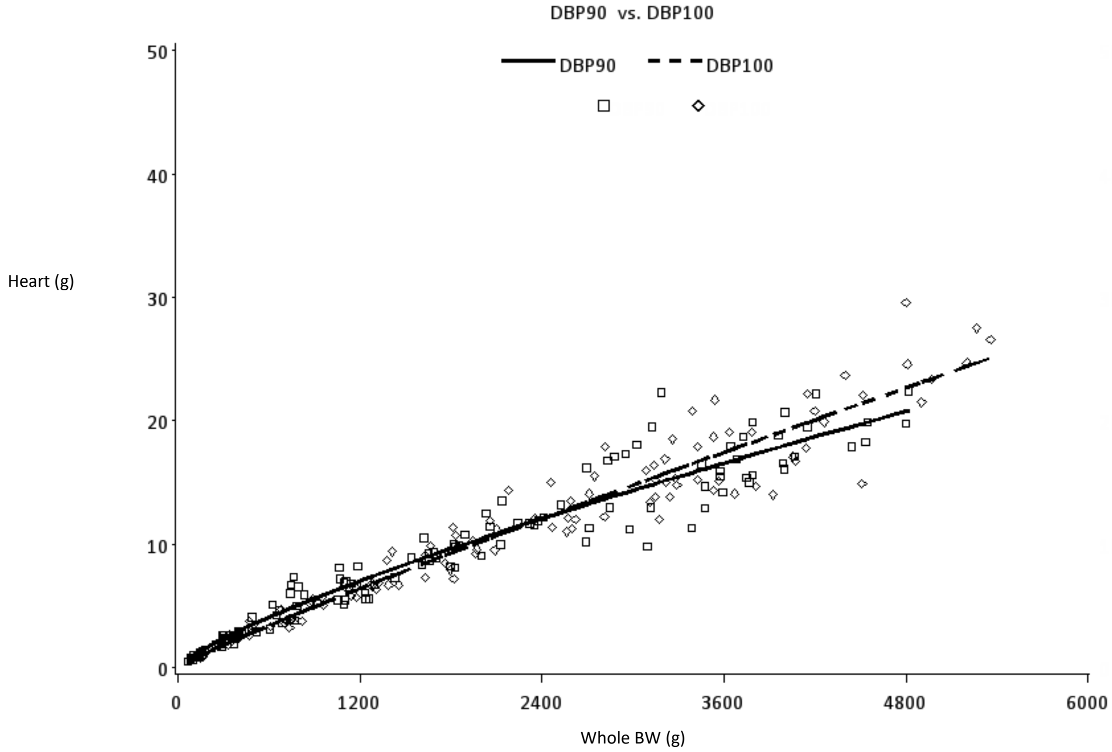

Figure A.10. Heart weight (g), in relation to live BW. Data are from DBP90 and DBP100 of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. The DBP100 protein diet was formulated at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids on a digestible basis. The DBP90 protein diet was formulated with digestible lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at an ideal digestible lysine: AA ratio. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW}^{\boldsymbol{b}} + \boldsymbol{\varepsilon}$ Where PW was: weight of the carcass part (g), BW is whole BW (kg), a and b were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P = 0.002**

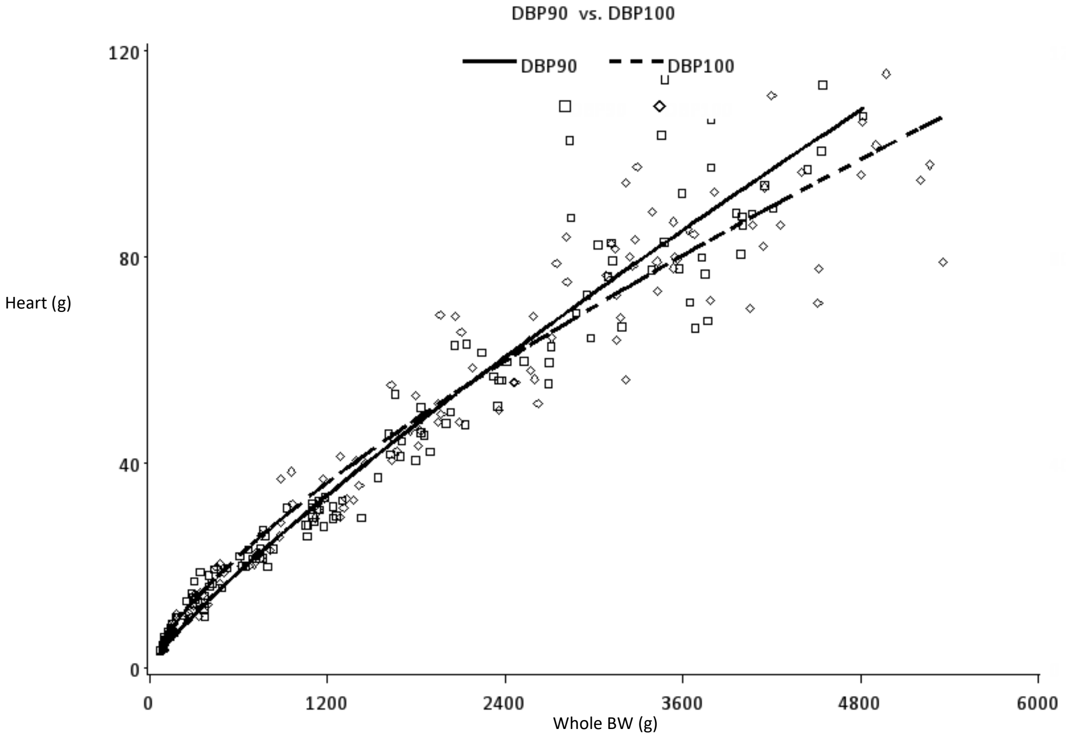

Figure A.11. Liver weight (g), in relation to live BW. Data are from DBP90 and DBP100 of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. The DBP100 protein diet was formulated at 100% of Aviagen's recommendations (Aviagen, 2007) for the first 7 limiting amino acids on a digestible basis. The DBP90 protein diet was formulated with digestible lysine at 90% of Aviagen recommendations, with the first 7 limiting amino acids held at an ideal digestible lysine: AA ratio. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW = \mathbf{a} + BW^{b} + \varepsilon}$ Where *PW* was: weight of the carcass part (g), *BW* is whole BW (kg), *a* and *b* were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P = 0.001**

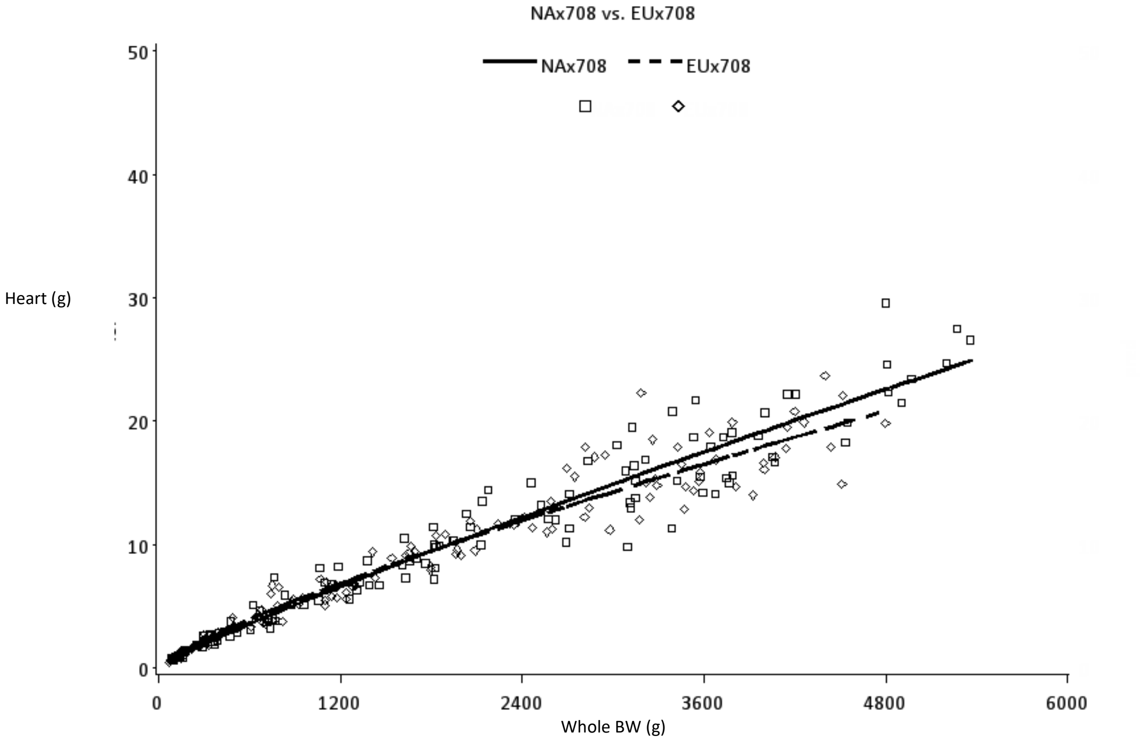

Figure A.12. Heart weight (g), in relation to live BW. Data are from NA x 708 and EU x 708 of 2 strain crosses a European (EU) male-line or a North American (NA) male-line crossed with a Ross 708 maternal line from Aviagen in the Corn Experiment on a corn-based diet. Data were fit to the Huxley's allometric function (Huxley, 1932): $\boldsymbol{PW} = \mathbf{a} + \boldsymbol{BW^{b}} + \boldsymbol{\varepsilon}$ Where *PW* was: weight of the carcass part (g), *BW* is whole BW (kg), *a* and *b* were coefficients determined utilizing least squares approximation and $\boldsymbol{\varepsilon}$ is the random variation not accounted for by the model. Data were analyzed using the NLIN procedure of SAS. The allometric curve coefficients were compared using a least squares comparison and F-test utilizing expected values from the non-linear model. Curves were separated using pairwise comparisons. P - value signifies the probability that the two non-linear curves are the same. **P = 0.007**