Evaluation of broiler breeder reproductive management on hunger, reproduction and offspring performance using a precision feeding system

by

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Abstract

Body weight (**BW**) of female broiler breeders is strictly controlled through feed restriction to optimize reproductive performance. A precision feeding (**PF**) system feeds birds individually based on live BW, which allows for precise feed allocations and BW management. To achieve good flock health and BW targets from a young age, chicks undergo training for the first 3 wk of life to learn how to successfully eat from the PF system. An automated marking system (**AMS**) prototype was installed in a PF station as a visual method to identify chicks that successfully eat from the station versus those that need additional training. The first experiment in this thesis evaluated if the dye markings from the AMS prototype promoted aggression in broiler breeder chicks. It was hypothesized that the dye markings would not promote aggressive behaviours in broiler breeder chicks. Dye markings from the AMS prototype did not increase aggression from 0 to 21 d of age. The frequency of aggressive pecking increased on d 26, however this is beyond the age at which the AMS prototype is recommended to be used as a visual identification method.

The second experiment of this thesis implemented various BW trajectories to individual broiler breeder females through the PF system. Trajectories were created using a Gompertz growth model that estimated pre-pubertal, pubertal and post-pubertal phases of growth. Each trajectory varied in 2.5% increases in pre-pubertal and pubertal BW gain from 2.5 to 22.5% above the recommended Ross 708 BW target. An additional group of unrestricted females were given access to a meal upon every station visit, meaning they were not limited to a maximum BW. The objective of the second experiment was to investigate various levels of increased BW, and concomitant levels of relaxed feed restriction, on feeding, feed seeking behaviour and reproductive performance. It was hypothesized that increased BW (lesser degree of feed

restriction) would decrease station visit frequency and meal size, and increase meal frequency and feed intake. In addition, it was hypothesized that increased BW (lesser degree of feed restriction) would reduce egg production and age at first egg, and increase egg weight. It was observed that station visit frequency decreased as BW increased during lay, however, not during the rearing period. Thus, increased BW up to 22.5% above the recommended BW target did not reduce motivation to seek feed and hunger during rearing. Two unrestricted hens came into lay prior to photostimulation (22 wk of age), and egg production was similar across BW trajectories.

A third experiment was conducted in extension of the second experiment to evaluate the intergenerational effect of increased maternal BW (relaxed feed restriction) on broiler growth performance. Two replicated broiler studies were conducted that varied in maternal age (35 and 42 wk). The main objective of the third experiment was to evaluate increased maternal BW on offspring BW, feed efficiency and carcass traits. It was hypothesized that increased maternal BW would increase offspring BW, breast muscle yield and fatness, and reduce feed efficiency. A second objective was to investigate offspring BW, feed efficiency and carcass traits in response to maternal age and broiler sex. It was hypothesized that offspring BW, fatness, breast muscle, liver, and gut weights would increase, and feed efficiency would decrease with maternal age. In addition, males would be have a greater BW and breast muscle yield, less fat, and would be more efficient than females. There were no significant effects of maternal BW on offspring BW. Broilers from high BW hens were less efficient than those from low BW hens. Proportional gut weight decreased as maternal BW increased, which may have been associated with reduced feed efficiency. The effects of maternal age and broiler sex was consistent with the hypotheses.

It was concluded that there is potential to increase female broiler breeder BW targets using a PF system to reduce the level of feed restriction without negatively affecting reproductive performance and offspring growth performance, which would in turn improve broiler breeder welfare.

Preface

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A version of Chapter 3 of this thesis has been published as Zukiwsky, N. M., T. E. Girard, and M. J. Zuidhof (2020), "Effect of an Automated Marking System in Precision-fed Broiler Breeder chicks on Aggressive Behavior" in the Journal of Applied Poultry Research. The MSc student was responsible for data collection, management and analysis, and manuscript composition. Statistical data analysis was designed with support of co-authors T. E. Girard and M. J. Zuidhof. T. E. Girard contributed to critical review of the manuscript. M. J. Zuidhof served as supervisory author and provided critical review of the manuscript.

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Dedication

This thesis is dedicated my grandfather, Walter, who has always encouraged me to pursue my education with a smile on his face.

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List of Abbreviations

ADFI	Average daily feed intake
AFE	Age at first egg
AM	Automatic marking
AMS	Automated marking system
ANOVA	Analysis of variance
BW	Body weight
Ca	Calcium
CON	Control
CP	Crude protein
CV	Coefficient of variation
d	Day
E2	Estradiol
EODES	Erratic oviposition and defective egg syndrome
ESF	Electronic sow feeder
EW	Egg weight
FCR	Feed conversion ratio
FSH	Follicle stimulating hormone
g	Gram
GnIH	Gonadotropin inhibitory hormone
GnRH	Gonadotropin releasing hormone
h	Hour
H:L	Heterophil to lymphocyte ratio

HPG	Hypothalamus-pituitary-gonadal
ID	Identification
kg	Kilogram
LED	Light emitting diode
LH	Luteinizing hormone
LSMeans	Least square means
lx	Lux
m	Meter
ME	Metabolizable energy
mL	Milliliter
MM	Manual marking
ng	Nanogram
PF	Precision feeding
PLF	Precision livestock farming
PS	Photostimulation
RFID	Radio frequency identification
RH	Relative humidity
s	Second
SAS	Statistical analysis system
SEM	Standard error of the mean
UNRES	Unrestricted
wk	Week

1.0 Chapter 1: General Introduction

This thesis evaluated broiler breeder reproductive management on welfare, performance and broiler offspring performance using a precision feeding (**PF**) system. Specifically, this thesis studied broiler breeder behaviour, hunger and reproduction in response to altered body weight (**BW**) and concomitant levels of feed restriction, and further evaluated the effect of altered maternal BW on broiler offspring growth and efficiency.

Broiler breeder management presents a challenge as it requires strict balance of managing BW and to optimize reproductive performance. In the past, feed restriction has been a crucial part of broiler breeder management to control BW and ovary morphology at sexual maturation (Hocking, 1993). Unrestricted feed intake has led to obesity-related lameness and mortality (Mench, 2002), and reproductive dysfunction such as reduced egg and chick production (Yu et al., 1992; Renema and Robinson, 2004), which strongly reinforces the importance of implementing feed restriction strategies for broiler breeders. However, broiler breeders experience chronic hunger, stress and frustration as a result of feed restriction (as reviewed by D'Eath et al., 2009). This leads to the paradox of broiler breeder management as feed restriction is necessary to control BW and prevent health and welfare issues related to unrestricted feeding, however, severe feed restriction results in poor welfare (Decuypere et al., 2010).

Broilers, or meat-type chickens, are the progeny of broiler breeders that have great genetic potential for efficient growth performance. Over the past 60 years, broiler genetic selection has heavily focused to increase growth rate, yield and feed efficiency to meet high demands and increased consumption of poultry meat. Modern broiler strains are more efficient and reach a greater BW in a shorter amount of time compared to broiler strains used in the 1950s (Zuidhof et al., 2014). While drastic changes have been made to optimize growth in broilers, there has been little change to broiler breeder management, specifically to BW targets (Renema et al., 2007). This means that broiler breeder BW targets have remained relatively similar to those which were put in place 60 years ago, while their progeny growth potential has and continues to increase.

There is recent evidence that suggests broiler breeder BW targets need to be increased. Studies using a novel PF system (Zuidhof et al., 2019) have demonstrated that egg production of precision-fed hens was less than that of hens fed conventionally (Hadinia et al., 2019; Zuidhof, 2018). The PF system is different from conventional feeding program because it allows for multiple, small meals throughout the day, and birds are fed according to their live BW to maintain strict BW trajectories. It was hypothesized that despite increased meal frequency and controlled feed allocations, precision-fed hens reared according to the current recommended BW targets did not receive a sufficient amount of nutrients to reach a body composition threshold necessary to reach sexual maturity (Zuidhof et al., 2018). In other words, precise feed allocations reduced the proportion of carcass fat, which is essential to support egg production. This suggests BW targets of precision-fed broiler breeders can be increased to allow for greater feed intake to achieve a higher BW. Not only could this optimize egg production, it would potentially reduce hunger and improve bird welfare. Thus, research is needed to evaluate various BW trajectories that are above recommended BW targets on broiler breeder reproductive performance. Increased BW targets concomitantly results in relaxed feed restriction. As such, research is required to evaluate hunger in response to relaxed feed restriction.

Broiler breeder nutrition has influence on broiler growth performance such as BW and carcass composition (Moraes et al., 2014; van der Waaij et al., 2011; van Emous et al., 2015; Humphreys, 2020). Specifically, feed restriction has been demonstrated to increase stress of broiler breeders during lay, which in turn reduced broiler growth (Bowling et al., 2018). Therefore it is not only essential to evaluate increased BW targets (lower degree of feed restriction) in broiler breeders, but the repercussions of maternal BW on broiler growth performance.

Chapter 2.1 provides an overview on current broiler breeder reproduction management and challenges, with emphasis on feed restriction and the significance of broiler breeder welfare in relation to feed restriction (Chapter 2.2). Chapter 2.3 provides an in-depth review of precision livestock farming and specific details about the PF system used in poultry production. A brief review of the current knowledge on aggression in broiler breeders is discussed in Chapter 2.4 as aggression is evaluated in Chapter 3. Chapter 2.5 summarizes growth modeling and hunger of broiler breeders relative to optimizing reproductive performance, and Chapter 2.6 discusses supply chain consequences of maternal nutrition on progeny growth performance. Chapter 3 evaluates challenges of the PF system (outlined in Chapter 2.3) and explores aggression in broiler breeder chicks. The experiments in Chapters 4 and 5 were part of a life-time study that evaluated hunger and reproductive performance of broiler breeders as a result of increase BW targets (lesser degree of feed restriction; Chapter 4). Further repercussions of increased maternal BW (relaxed feed restriction) on progeny growth performance is discussed in (Chapter 5). A synthesis and conclusions from the experiments is provided in Chapter 6.

1.1 References

Bowling, M., R. Forder, R. J. Hughes, S. Weaver, and P. I. Hynd. 2018. Effects of restricted feed intake in broiler breeder hens on their stress levels and the growth and immunology of their offspring. Transl. Anim. Sci. 2: 263-271.

D'Eath, R. B., B. J. Tolkamp, I. Kyriazakis, and A. B. Lawrence. 2009. 'Freedom from hunger' and preventing obesity: The animal welfare implications of reducing food quantity or quality. Anim. Behav. 77:275-288.

Decuypere, E., V. Bruggeman, N. Everaert, Y. Li, R. Boonen, J. de Tavernier, S. Janssens, and N. Buys. 2010. The broiler breeder paradox: ethical, genetic and physiological perspectives, and suggestions for solutions. Br. Poult. Sci. 51:569–579.

Hadinia, S. H., P. R. O. Carneiro, D. R. Korver, and M. J. Zuidhof. 2019. Energy partitioning by broiler breeder hens in conventional daily-restricted feeding and precision feeding systems. Poult. Sci. 98:6721–6732.

Humphreys, K. D. 2020. Implications of altering maternal feed availability and feeding system on offspring performance. MSc. Thesis. University of Alberta, Edmonton, Alberta, Canada.

Hocking, P. M. 1993. Roles of body weight and feed intake in ovarian follicular dynamics in broiler breeders at the onset of lay and after a forced molt. Poult. Sci. 83:2044-2050.

Mench, J. A. 2002. Broiler breeders: feed restriction and welfare. Worlds Poult. Sci. J. 58:23-29.

Moraes, T. G. V., A. Pishnamazi, E. T. Mba, I. I. Wenger, R. A. Renema, and M. J. Zuidhof. 2014. Effect of maternal dietary energy and protein on live performance and yield dynamics of broiler progeny from young breeders. Poult. Sci. 93:2818–2826.

Renema, R. A., and F. E. Robinson. 2004. Defining normal: Comparison of feed restriction and full feeding of female broiler breeders. Worlds Poult. Sci. J. 60:508-522.

Renema, R. A., M. E. Rustad, and F. E. Robinson. 2007. Implications of changes to commercial broiler and broiler breeder body weight targets over the past 30 years. Worlds Poult. Sci. J. 63:457-472.

van der Waaij, E. H., van den Brand, J. A. M. van Arendonk, and B. Kemp. 2011. Effect of match or mismatch of maternal-offspring nutritional environment on the development of offspring in broiler chickens. Anim. 5:741-748.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, H. van den Brand, and W. H. Hendriks. 2015. Effects of growth patterns and dietary protein levels during rearing of broiler breeders on fertility, hatchability, embryonic mortality, and offspring performance. Poult. Sci. 94:681-691.

Yu, M. W., F. E. Robinson, R. G. Charles, and R. Weingardt. 1992. Effect of feeding allowance during rearing and breeding on female broiler breeders. 2. Ovarian morphology and production. Poult. Sci. 71:1750-1761.

Zuidhof, M. J. 2018. Lifetime productivity of conventionally and precision-fed broiler breeders. Poult. Sci. 97:3921-3937.

Zuidhof, M. J., M. V. Fedorak, C. C. Kirchen, E. H. M. Lou, C. A. Ouellette, and I. I. Wenger. 2019. System and method for feeding animals. PrecisionZX, Inc., assignee. US Pat. No. 10,506,793.

Zuidhof, M. J., B. L. Schneider, V. L. Carney, D. R. Korver, and F. E. Robinson. 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. Poult. Sci. 93:2970-2982.

2.0 Chapter 2: Literature Review

2.1 Broiler Breeder Production and Management

The poultry industry has largely focused on optimizing broiler genetic selection to produce fast growing and feed-efficient birds. From 1957 to 2005, broiler growth rate has increased by 400% while feed efficiency has decreased by 52.4% (Zuidhof et al., 2014). Moreover, a 2005 broiler line reached a body weight (**BW**) of 1.4 kg by 28 d of age, which is 2.2 and 4.4 times greater than the BW of broiler lines used in 1957 and 1978, respectively. Broiler breeders, the parent stock of broilers, are feed restricted to control BW during rearing to optimize reproductive performance during lay. Feed restriction is important to control ovary morphology and optimize egg and chick production (Hocking, 1993). Despite rapid change in the broiler industry, broiler breeder BW targets have remained relatively constant (Renema et al., 2007). Unrestricted feeding results in over-production of large yellow follicles, which results in increased numbers of eggs unsuitable for incubation and chick production (Yu et al., 1992), and also increased incidence of lameness and mortality in broiler breeder flocks (Mench, 2002). However, feed restriction results in chronic hunger and stress (D'Eath et al., 2009), and is therefore associated with poor welfare.

This chapter will focus on the current state of broiler breeder production, management and welfare, with emphasis on challenges associated with reproductive management and the management strategies that have evolved to optimize reproductive performance. Further, this chapter will give an overview of precision livestock farming (**PLF**) with specific discussion on precision feeding (**PF**) technologies used in the poultry industry and its associated challenges. Finally, this chapter will summarize the supply chain effect of broiler breeder nutrition, specifically feed restriction, on progeny growth performance.

2.1.1 Introduction to Neuroendocrine Control of Reproduction

The reproduction cycle in a female broiler breeder is predominantly controlled by the hypothalamus. The hypothalamus interprets and responds to signaling molecules such as hormones related to the reproductive system of birds (Richards and Proszkowiec-Weglarz, 2007; van der Klein et al., 2020). The hypothalamus regulates the hypothalamic-pituitary-gonadal (**HPG**) axis by releasing gonadotropin releasing hormone (**GnRH**) that acts as a stimulatory neuropeptide, and gonadotropin inhibitory hormone (**GnIH**) that acts as an inhibitory neuropeptide (Bédécarrats, 2015; Bédécarrats et al., 2009). The HPG axis is activated when broiler breeders are photostimulated around 18 wk of age to initiate the onset of sexual maturation. At that time, light directly stimulates photoreceptors located in the hypothalamus (Dunn and Sharp, 1990) and promotes GnRH release from the hypothalamus to the anterior pituitary. In the anterior pituitary, GnRH binds to its respective receptors to stimulate the release of luteinizing hormone (**LH**) and follicle stimulating hormone (**FSH**). Luteinizing hormone and FSH target the ovary through the bloodstream, which then stimulates the ovary to produce a steroid hormone called estradiol (**E2**). In female birds, E2 acts as a GnIH inhibitor which in turn signals sexual maturation. In a sexually mature bird, high levels of E2 may also act as positive feedback to promote GnRH, and subsequent LH and FSH production (Robinson and Etches, 1986; Bédécarrats et al., 2016). Luteinizing hormone and FSH levels peak at 3 to 6 d after photostimulation indicating sexual maturation, and declined thereafter (Renema et al., 1999; Hadinia et al., 2020). As LH and FSH levels decline after the peak, it is suggested that increased E2 acts as a negative feedback signal to the brain at the hypothalamus (Renema et al., 1999; Hadinia et al., 2020) or pituitary level (Hadinia et al., 2020).

There are many factors that influence the onset of sexual maturation of broiler breeders, including but not limited to BW and body composition. In particular, broiler breeders with a greater BW and greater proportion of fat reach sexual maturity earlier than broiler breeders with a lower BW and proportion of fat (van der Klein et al., 2018a). Body weight and body composition fluctuate depending on nutrient intake, and more specifically nutrient storage and mobilization. Unrestricted feed intake has advanced the onset of lay (Renema et al., 1999) and led to reproductive dysfunction further discussed in the next section of this chapter. As such, broiler breeders are strictly feed restricted to control BW and body composition. However, there is limited knowledge of how metabolic factors, such as neuroendocrine signals associated with feed restriction (van der Klein et al., 2020), and molecular mechanisms of energy intake (Hadinia et al., 2019; Hadinia et al., 2020) influence sexual maturation, and more research is needed in these areas.

2.1.2 Challenges in Broiler Breeder Reproduction

Female broiler breeders are feed restricted to control BW leading up to sexual maturity to optimize health and reproductive success. It is important to control BW to minimize health issues such as obesity, lameness, and consequently high mortality rates that could result from unrestricted feeding (Renema and Robinson, 2004; Mench, 2002; de Jong and Guémené, 2011). Additionally, feed restriction has been reported to control ovary morphology and follicular development to reduce reproductive dysfunction and optimize egg and chick production (Katanbaf et al., 1989; Hocking, 1993; Renema et al., 2007; Renema and Robinson, 2004). Overfeeding has led to excess production of large yellow follicles as a result of multiple hierarchies and ovulations (Hocking et al., 1987; Yu et al., 1992), which is also defined as erratic oviposition and defective egg syndrome (**EODES**; van Middelkoop, 1978). Hens that are affected by EODES lay eggs are unsuitable for incubation and chick production. It was reported that ad libitum-fed broiler breeder females exhibit reduced fertility due to unrestricted feeding (Hocking et al., 2002a; Mohiti-Asil et al., 2012) and hatchability (Hocking et al., 2002a), and increased mortality rates after peak production (Hocking et al., 2002a). Thus, to date, broiler breeders have been feed restricted to increase reproductive performance. However, genetic selection and growth potential has increased since these results were reported, and there may be less of a negative impact on egg production in modern broiler breeder lines.

Animal welfare has become an important focus of livestock production and scientific research (Fraser, 2008). Although feed restriction is a common feeding strategy in broiler breeder production, it is associated with poor welfare (Mench, 2002, D'Eath et al., 2009; Tolkamp and D'Eath, 2016). As a result, broiler breeder management has evolved over time to investigate whether reproductive performance can be managed through alternative practices besides feed restriction.

2.1.3 Evolution of Reproductive Management

Broiler breeder management can be described as a paradox: severe feed restriction is required to achieve optimal reproductive performance and prevent health issues related to obesity, yet results in hunger that impairs bird welfare (Decuypere et al., 2006). As such, feed restriction is identified as a welfare issue. Feed restriction begins after 1 wk of age and is reported to be the most severe during rearing from 7 to 15 wk of age (Bruggeman, 1999; Yu et al., 1992), during which feed intake is 25 to 33% of what ad libitum birds would consume (Savory et al., 1996). Feed restriction is somewhat relaxed by 18 wk of age and throughout the laying phase to support sexual maturation and egg production (Bruggeman et al., 1999; Hocking et al., 2002b).

Conventional feeding management includes qualitative and quantitative feed restriction programs. Qualitative feed restriction involves diluting the nutrient composition of a diet to decrease nutrient intake per kg of diet consumed, and allows for longer feeding durations (Savory et al., 1996). Non-nutrient diet diluents include oat hulls, sugar beet pulp and soybean hulls (Hocking et al., 2004; Morrissey et al., 2014). In addition, some literature more broadly defines qualitative feed restriction as diet manipulation to reduce voluntary feed intake (Savory et al., 1993; Savory et al., 1996; Sandilands et al., 2006). In other words, an appetite suppressant such as calcium propionate can be added to the diet (Savory et al., 1996; Sandilands et al., 2006). Sandilands et al. (2005) assessed hunger of broiler breeders that were qualitatively feed restricted by evaluating resting and stereotypic behaviours during the rearing period. The authors reported diets with oat hulls and calcium propionate increased resting behaviours and reduced eating rate and stereotypic pecking during the rearing phase. They concluded that qualitative feed restriction reduced hunger and motivation to eat during the rearing phase. Similarly, de Jong et al. (2005) and Arrazola et al., (2020) reported nutrient diluted diets reduced stereotypical and abnormal repetitive behaviours associated with feed frustration and hunger, overall improving pullet welfare. However, qualitative feed restriction can adversely affect egg production if poor quality feedstuffs are used or diets are not properly diluted (Savory et al., 1996; Sandilands et al., 2005). In addition, it is important to control broiler breeder flock BW during rearing leading up to sexual maturation. Poor flock uniformity, or a high coefficient of variation (**CV**) in BW, results in underweight and overweight birds. Large variation of low BW birds delayed development of the reproductive tract and age at first egg, thus reduced reproductive success on a flock level (Yu et al., 1992). Zuidhof et al. (2015) reported that pullets fed a standard diet were 20% more feed efficient than pullets fed a high fibre diet containing 25% lower nutrient density. Moreover, pullets fed a high fibre diet had a CV of 15.2% at 22 wk of age compared to a CV of 12.7 and 10.9% of pullets fed on a quantitative skip-a-day and scatter feeding program, respectively. Thus, qualitative feed restriction did not increase BW uniformity leading up to and by sexual maturation in comparison to scatter feeding.

Quantitative feed restriction reduces the amount of feed available to broiler breeders at a given time. Quantitative feed restriction is achieved through, but not limited to, a skip-a-day or every-day feeding programs to reduce meal frequency and increase meal size (Mench, 2002). Skip-a-day feeding provides a meal every second day, whereas daily feeding provides a single meal each day. Quantitative feed restriction more consistently controls BW during rearing than qualitative feed restriction. Sandilands et al. (2006) reported broiler breeder pullets reared on a quantitative feed restricted schedule achieved a BW close to the target BW than highly qualitative-restricted pullets. Zuidhof et al. (2015) similarly reported that a skip-a-day feeding program increased BW and carcass trait uniformity in comparison to pullets fed a qualitatively-diluted diet. In addition to controlling BW, pullets that were quantitatively feed restricted had less bone, joint and foot lesions in comparison to unrestricted pullets which suggests quantitative feed restriction reduced lameness and increased bird welfare (Hocking and Duff, 1989). Further, Hocking and Duff (1989) suggested that feed restriction has potential to reduce feed costs through reduced feed wastage and incidence of skeletal and metabolic diseases.

In addition to feed restriction management, broiler breeder reproductive success can be influenced by age of photostimulation and lighting programs. Broiler breeders are sensitive to changes in photoperiod. During rearing, broiler breeders are exposed to 8 h of light and then gradually exposed to 12 to 16 h of light at 20 to 22 wk of age, respectively (Lewis, 2006). Commercially, it is recommended to photostimulate broiler breeders around 21 to 22 wk of age, and no earlier than 21 wk of age so that females reach a certain BW and body conformation to respond to photostimulation (Aviagen, 2018; Cobb-Vantress, 2016). A study conducted by Pishnamazi et al. (2014) photostimulated pullets at 17, 19, 21 or 23 wk of age and demonstrated that sexual maturation was accelerated as age at photostimulation increased. In addition, as age at photostimulation increased, the interval from photostimulation to first egg decreased. The study suggested that females photostimulated at 21 and 23 wk of age shift energy partitioning priorities from skeletal and muscle growth towards reproductive tract development, meaning those females are more able to respond to photostimulatory cues. Similarly, other literature reported that at 22 wk of age broiler breeder females shift their energy partitioning toward reproductive organ development rather than muscle gain when compared to 18 wk old females (Renema et al., 2007). Melnychuk et al. (2004) reported feed restricted pullets photostimulated at 21 wk of age reached sexual maturity 13.6 d later than ad libitum females photostimulated at the same age. However there were no difference in age of sexual maturity between feed restricted and ad libitum-fed females photostimulated at 24 wk of age. This suggests female broiler breeders reach an appropriate BW and body composition by 24 wk of age, and are synchronous in their response to photostimulation. Precision-fed female broiler breeders reared 22% above recommended BW came into lay 16.6 d earlier than standard BW hens (van der Klein et al., 2018a). Regardless of BW, 90% of hens photostimulated at 21 wk of age reached sexual maturity, while 17.8% of high BW hens and 31.9% standard BW hens photostimulated at 18 wk of age never came into lay by 55 wk of age. The authors emphasized that only a proportion of high BW hens reached sexual maturity below their target BW. They suggested that body composition, specifically the proportion of fat pad at sexual maturity, was reduced by increased meal frequency of the PF system and influenced the onset of lay and laying performance to 55 wk of age. van der Klein et al. (2018b) demonstrated an interaction between BW and rearing photoperiod on sexual maturity. High BW hens came into lay an average of 34 d before standard BW hens did, which is consistent with previous literature. Moreover, sexual maturity was delayed in standard BW hens as photoperiod increased from 8 to 16 h of light, and 3.3, 18.1 and 37.6% of the standard BW hens did not come into lay prior to 55 wk of age when reared on 8, 10 and 12 h of light, respectively. Similar to van der Klein (2018a), these results were attributed to the use of an automated precision-feeding system that allowed for small, multiples meals to be consumed throughout the day. As a result, the consistent, small meals may have altered metabolism and body composition, and ultimately reduced the proportion of body fat presumed to be required for the onset of lay. A recent study reported similar rates of sexual maturation that compared broiler breeder females photostimulated at 16, 18, 20 and 22 wk of age. Females photostimulated at 22 wk of age produced 21, 22 and 9% less eggs compared to females photostimulated at 16, 18 and 20 wk, respectively (Shi et al., 2020). Moreover, the study reported eggs from females photostimulated at 16 wk had reduced hatchability and egg shell quality, and increased number of broken eggs, while females photostimulated at 22 wk of age reduced egg production compared to females photostimulated at 18 and 20 wk of age. Further studies are needed to determine the effect of BW, photostimulation and photoperiod on reproductive performance, as there may be alternative management strategies to optimize reproductive performance other than conventional feed restriction regimens. Specifically, there is potential to alter BW management so that BW targets are increased to allow for relaxed feed restriction.

2.2 Broiler Breeder Welfare

Animal welfare is considered to be a conglomerate concept as it reflects elements of basic health and functioning, affective states and natural living, all of which contribute to the overall quality of life of an individual or group of animals (Fraser, 2008). There is concern regarding broiler breeder welfare as feed restriction negatively affects basic health and functioning and the affective state of broiler breeders. This is clearly described as the paradox of broiler breeder management in that good health and reproductive performance is achieved through feed restriction, however, it must be done without reaching a point of severity that leads to poor welfare (Decuypere et al., 2006).

Broiler breeders are restricted severely to reach 50 to 60% of their potential BW, and consume 25 to 50% of ad libitum feed intake (Rosales, 1994; Renema et al., 2007). Consequently, broiler breeders experience chronic hunger, lack of satiety, and feeding frustrations that are assessed through various behaviours and physiological parameters (Arrazola et al., 2019; D'Eath et al., 2009; Tolkamp and D'Eath, 2016). Prolonged hunger and feeding frustration can lead to oral-repeated behaviours such as feather pecking and feather licking which can further develop into abnormal repetitive behaviours (Arrazola et al., 2020). Abnormal repetitive behaviours can further lead to redirected behaviours such as over-drinking and pecking to the point of injury and cannibalism, and poor plumage condition due to feather loss, all of which indicate poor welfare (Savory and Maros, 1993; Mellor et al., 2018; Hocking et al., 2001; Morrissey et al., 2014). Hunger is associated with increased restless and hyperactive behaviours which can develop into problematic oral-redirected behaviours such as feeder pecking and drinker pecking, and decreased comfort behaviors such as sitting, preening, wing flapping and stretching (de Jong et al., 2003; Arrazola et al., 2020). Further, feeding frustration result from inability to forage for food, and result in stereotypic object and feather pecking (Sandilands et al., 2005; Morrissey et al., 2014). Feed restricted broiler breeder pullets have been reported to have a greater heterophil:lymphocyte (**H:L**) ratio and plasma corticosterone levels than unrestricted pullets, indicating that feed restriction is stressful (Arrazola et al., 2019; Sandilands et al., 2006; Hocking et al., 2001; Savory et al., 1996). In contrast, feed restriction is crucial to prevent certain welfare issues such as obesity-related lameness and death (Mench, 2002).

2.3 Precision Livestock Farming

Precision livestock farming is a form of livestock management with integrated technology, computers and engineering (Wathes et al., 2008). The goal of PLF is to continuously monitor animals on a group or individual basis through a network of sensor technologies then compare animal performance to a standard, and make automatic adjustments to optimize production (Werkheiser, 2018). Briefly, PLF uses sensors to record information of an individual or a group of animals which is used to monitor animal production. In other words, data recorded through PLF technology allows for real-time management decisions. As a comparison, traditional livestock farming relies heavily on manual labour, farm employees and producer experience. However, each individual working on farms can have different management techniques that may result in production variation (Frost, 2001). Precision livestock farming uses consistent measuring and recording methods and strictly organizes data to minimize variation in production. By doing so, PLF increased economic profits and output efficient. Moreover, PLF simplifies and increases reliability of animal monitoring. This provides a clear direction for the future of animal management and assists producers and farm employees as the scale of livestock production continues to increase (Banhazi et al., 2012).

Precision livestock farming was first used in the beef and swine industry to sustain increased consumer demands for protein and advances in production methods by monitoring livestock animals and providing information to make management decisions (Vranken and Berckmans, 2017). The swine industry has used PLF technologies to monitor and collect data on feed intake, growth, activity, BW and body condition, which are critical aspects to manage to achieve optimal performance. Computing technologies have also been created to monitor aspects of animal welfare such as feed and water intake, pain and injury by assessing vocalizations and behaviour on an individual pig basis (Vranken and Berckmans, 2017). Two specific examples of commercialized systems that have been implemented in swine barns are eYeScan and eYeNamic. eYeScan system software uses 3D images to predict and record estimates of BW and body condition, which are used to adjust feed allocations to reach target BW and body condition. eYeNamic is a camera-based system that records video footage in a barn to monitor activity and feeding behaviour, and aggression among penmates. Thus, producers are closely able to monitor herds and make real-time management decisions related to performance and welfare through PLF technologies. Similarly, the beef industry has implemented PLF through technologies to monitor BW and body condition, feed intake, BW gain, energy efficiency and monitor animal grazing to aid producers in making management decisions both on individual and herd basis (Fournel et al., 2017; Shao et al., 2020; Eastwood et al., 2015). Further, robotic milking, heat detection, disease and behaviour monitoring technologies are used to optimize milking and reproduction in dairy herds (Mottram, 2016; John et al., 2016; Borchers et al., 2016).

Poultry-specific PLF technologies include instruments built into barns to monitor and control feed, water lines and ventilation systems. In addition, automated recording systems are used to adjust feeding schedules to control flock BW and optimize feed efficiency by measuring and recording FI and live bird BW (Corkery et al., 2013). A study by Fontana et al. (2015) used microphone technology to determine the relationship between broiler vocalizations and their weight. The authors reported that the greatest frequency of vocalizations was recorded when birds were young. In other words, peak frequencies of vocalizations were inversely proportional with age, and by extension BW. Mortensen et al. (2016) used a 3D camera in combination with an algorithm to predict the weight of broilers. The camera was hung above a scale platform. As the bird stood on the scale, and image was taken with the camera while the BW is recorded in the scale software. The predicted BW from the image is compared to the real-time BW recorded by the scale. With BW estimates from the camera technology, producers can monitor flock BW and adjust feed allocations to achieve specific BW targets.

2.3.1 Precision Feeding Systems in Livestock Production

Precision feeding is a category of PLF in which various feeding technologies are used to allocate the proper amount of feed according to specific nutrient requirements to an individual or a group of animals at the appropriate time (Pomar et al., 2014; Andretta et al., 2016). Precision feeding techniques allow livestock producers to tailor nutrient requirements to match nutrient requirements as they change throughout a production period. In addition, livestock sectors use PF technology to reduce the environmental footprint and waste excretion associated with livestock production, and reduce feed costs without compromising performance. For example, Pomar and Remus (2019) reported PF techniques in the swine industry reduced production costs and greenhouse gas emissions by 8 and 6 %, respectively.

Precision feeding technology has been used in the swine industry to monitor feed intake, feed disappearance, and weight gain. Electronic sow feeders (**ESF**) are a common sequential feeding system used on a global scale to manage gestating sows. The system is a noncompetitive environment in which sows are isolated within the system to eat individually, protected from aggressive penmates. This allows the sows, particularly submissive sows, to eat the amount of feed they need to meet their nutrient requirements throughout their gestation period. The system is further a useful tool to manage sows on an individual basis as it can provide real-time feed intake information and further make decisions about feed allocations to control BW and body condition, both of which contribute to reproductive success (Buis, 2016).

GrowSafe is a precision feeding technology system used in the beef and dairy cattle industries. GrowSafe technology is based on a radio frequency identification (**RFID**) system that assigns a unique number to each cow. With unique cow RFIDs, GrowSafe can record feed intake and feeding activities, such as meal duration and eating patterns, for individual cows in a group-housed setting (DeVries et al., 2003; Basarab et al., 2003; Wang et al., 2006). Average daily dry matter intake and residual feed intake are used to estimate feed and production costs in the beef industry. Culbertson et al. (2015) conducted a study using GrowSafe to record average daily dry matter intake and residual feed intake 14, 28, 42, 56 and 70 d after cattle were placed in a pen. They demonstrated that average daily dry matter intake recorded on d 42 and residual feed intake recorded on d 56 better predicted feed utilization and feed costs compared to data collected on d 70, which is the industry recommended day to collect estimates for cost predictions.

As described above, PF technology has successfully been implemented in various aspects of management in the swine, dairy and beef livestock industries. Specifically, ESF and GrowSafe are two examples that use feeding behaviours to adjust feed allocation to control BW, and similar advancements in precise feeding management are being used in the poultry industry.

2.3.2 Precision Feeding Systems in Poultry

An automated PF system has been developed at the University of Alberta that feeds individual birds based on live BW measurements (Zuidhof et al., 2019; Zuidhof et al., 2017). The goal of the PF system is to provide the right amount of feed to the right bird at the right time. The PF system consists of individual feeding stations that communicate with computer software and a database system. The detailed process is described elsewhere (Zuidhof et al., 2019). Briefly, each bird must walk through two sets of automated doors and isolated stages to reach the feeder. Birds have 24 h sequential access to the PF stations, and voluntarily enter a station where its live BW is recorded by the system and compared to a pre-programmed target BW according to each bird's unique RFID transponder. If the real-time BW is below the target BW, the bird is given access to a meal over a short period of time. If the real-time BW is above the target BW, the bird is gently ejected from the station. Meal duration and the amount of feed provided during a meal bout can be adjusted through the system software and implemented instantaneously. Each station records BW, FI and the number of station visits on an individual bird basis.

It is crucial for chicks to learn how to successfully eat from the PF stations to achieve high flock uniformity and maintain good flock health from a young age. During the first 14 d of life, there is an essential training period in which chicks are taught how to successfully eat from the station feeder. The training period consists of four software modes. Each mode progressively introduces chicks to the sounds and movements of the PF stations in addition to teaching chicks how to maneuver through the station to reach the feeder (Zuidhof, 2018). Ideally, by d 14 all chicks successfully eat from the station individually. However, some chicks can be considered late adopters if they are slow to learn how to eat from the PF stations, and therefore require additional training. It is a challenge to distinguish chicks that require additional training from those that have successfully learned to eat individually from the station feeder. In a research setting, each chick is equipped with a unique RFID transponder that allows the station software to recognize individual chicks upon entry. In addition, the PF system records feed intake, BW, station visit data for each chick based on each its unique RFID. By examining recorded data from the PF database, chicks with low feed intake and few stations visits are considered late adopters that require training. Research personnel must then search the flock for these chicks to assist with training. On a commercial farm, implementing a unique wing tag and RFID for each chick would be a laborious process and would be expensive for a large flock of birds. In addition, searching for chicks that need training in a commercial barn may take a great amount of time and require many personnel. Therefore, a more suitable identification method is needed to identify chicks that have not eaten from the station and require training.

An automated marking system (**AMS**) prototype was incorporated into the PF system that marked chicks with dye as they eat from the PF feeder. As a result, chicks that had learned to eat from the feeder can be identified by dye markings. Chicks that completely lack or have minimal dye markings can be identified as chicks that have not yet learned to eat from the station feed and require additional training. Dye has been used for identification purposes in previous poultry research experiments, and has stimulated aggressive encounters and aggressive behaviours between penmates which is a welfare issue (Estevez et al., 2003; Dennis et at., 2008). However, the effect of dye marking on aggression in chicks is unknown.

2.4 Aggression in Broiler Breeders

In a broiler breeder flock, Aggression can be classified as aggressive behaviours such as pecking, or aggressive encounters such as fights and threats that are directed toward other birds. Aggressive behaviours and encounters are commonly observed in broiler breeder flocks as a mechanism to establish a dominance hierarchy of social order (Estevez, 2002; Girard et al., 2017a). Typically, a dominance hierarchy is established between 6 to 12 wk of age in domesticated poultry flocks, specifically around 7 wk of age for broiler breeders (Mench, 1988; Shea et al., 1990). Aggression can be influenced by factors such as hunger, feeding motivation and feeding frustration as a result from feed restriction (Mench, 1988; Mench 2002; Girard et al., 2017a). Further, aggression can arise within a flock from competition to mate successfully (de Jong and Guémené, 2011).

Feather pecking is broadly defined as a bird using its beak to grasp and pull feathers of another bird, and can be further classified as gentle, severe and aggressive feather pecks (Savory, 1995). Gentle feather pecking is defined as an exploratory, non-damaging behaviour, while severe feather pecking is considered a welfare concern as it can result in complete removal of feathers or skin, and can lead to cannibalism in extreme cases (Nicol et al., 2013; Dalton et al., 2018). Aggressive feather pecking occurs as a forceful motion of the beak directed at another bird's neck or head (Savory, 1995). Feather pecking can result from a lack of sulfur amino acids in the diet or from a change in environment including alterations in temperature and humidity, and also from genetic modification (Leeson and Walsh, 2004; Nicol et al., 2013). Feather pecking can develop into abnormal repetitive behaviours further causing injury to oneself or other birds in the flock (Arrazola et al., 2020).

2.4.1 Aggression in Broiler Breeder Chicks

There is little knowledge published on the development of aggression in chicks. Fights, threats and avoidances tend to occur beyond the first few weeks of age to establish social order or to compete for feed and potential mates. In contrast, feather pecking is a part of expected social behaviour of chicks. Within the first 2 wk of life, feather pecking consists of mostly gentle feather pecks and indistinguishable from severe feather pecking (Riedstra and Groothius, 2002). Arrazola et al. (2020) reported that gentle feather pecks are performed as a curious behaviour early on in the rearing phase, and can develop into abnormal repetitive behaviours and severe feather pecking later in the rearing phase and as hens begin to lay eggs. However, higher frequencies of gentle feather pecking, and more so severe feather pecking, tend to occur as pullets and hens molt and develop new feathers (Nicol et al., 2013). It is suggested that gentle feather pecking performed within the first weeks of life are redirected as foraging and eating behaviours (van Hierden et al., 2002). In addition, chicks tend to perform gentle feather pecks towards unfamiliar chicks and aspects in their environment as a mechanism to explore and familiarize themselves with their surroundings (Zajonc et al. 1975; Estevez et al., 2007). As such, further research is required to determine if broiler breeder chicks perform aggressive behaviours aside from exploratory behaviours during the first few wk of life.

2.5 Optimizing Reproduction in Broiler Breeders

2.5.1 Growth Modeling

Mathematical growth models use BW measurements over time to predict growth patterns and body composition, and estimate daily nutritional requirements and feed allocations (Wang and Zuidhof, 2004; Tompić et al., 2011). The Gompertz growth model is commonly used to predict growth of broilers and broiler breeders by fitting BW as a function of time up to maturity of a final BW target (Emmans, 1981; Gompertz, 1825). Early growth modeling studies have reported growth as a single phase represented by a sigmoidal curve that successfully predicted an allometric relationship of lean tissue and fat growth rates in broilers (Gous et al., 1999). However, Kwakkel et al. (1993, 1995) proposed growth in egg-laying birds is characterized into phases based on growth of different components of the body. Specifically, the authors suggested development of the reproductive tract and the proportion of lean tissue, fat and body size influence sexual maturation. As a result, growth can be categorized into pre-pubertal and pubertal growth phases. Pre-pubertal growth represents skeletal and muscular development during the early stage of rearing that is growth of intermuscular and functional tissues. Pubertal growth represents a shift in energy partitioning when nutrients are focused toward sexual organ development in preparation for reproduction right before sexual maturation (Kwakkel et al., 1995; Kwakkel et al., 1993). Predicted growth patterns using multi-phase models have reduced the unknown variation of breed, sex and age related growth compared to a single-phase model prediction (Grossman and Koops, 1988). Therefore, a multiphase growth model is better suited to more closely predict BW estimates and magnitude of growth of particular body components associated with specific phases of growth. In turn, this suggests a multiphase growth model better predicts nutrient requirements and feed allocations to minimize feed costs in addition to optimizing performance (Kwakkel et al., 1993; Tompić et al., 2011). Genetic potential of both broilers and broiler breeders has increased since this work was reported, but there has been little development of multiphasic growth models over the past 30 years. Zuidhof (2020) summarized broiler breeder growth is complex and particularly difficult to predict since recent research has demonstrated current feed restriction levels may be too low to provide a sufficient amount of nutrients to establish fat reserves to reach sexual maturity (Zuidhof, 2018; van der Klein et al., 2018a; van der Klein et al., 2018b; Hadinia et al., 2019). Therefore, a tri-phasic model was proposed to estimate growth in pre-pubertal, pubertal and post-pubertal growth, the goal of which being to better predict growth and development of modern lines of broiler breeders (Zuidhof, 2020).

2.5.2 Feeding Motivation and Behaviour

Feeding motivation is driven by internal factors, such as genetics and metabolism, and external factors in the environment such as the amount of available feed (Duncan, 1998). Hunger is not well defined in the literature. D'Eath et al. (2009) defines hunger as a negative subjective state experienced by an animal that is undernourished, or in other words, an animal does not receive a sufficient amount of nutrients to reach a point of satiety. Because hunger is subjective, it cannot be directly measured. Instead, hunger is measured by assessing a combination of feeding and feed seeking behaviours, activity and restlessness, oral-related stereotypies, comfort behaviours and physiological measures to provide multiple perspectives that contribute toward relationships and strong conclusions about hunger.

Internal factors such as basic physiology and physical digestive tract limitations can influence hunger experienced by an animal in the short and long term. In the short term, feed intake has been reported to be dependent on hormones and neural signals that stimulate physiological regulation in response to gut fill and nutrient present in the digestive tract (Richards et al., 2010). Crop and gizzard capacity limited feed intake (Savory and Maros, 1993) and reduced meal size (Savory et al., 1993) due to the physical restraints of how much feed each organ can hold at a given time, which led the authors to believe hunger was reduced for a short period of time when the crop and gizzard are full of feed. In addition, Lees et al. (2017) found that chronically restricted birds had approximately three times greater crop fill 4 h post-feeding compared to ad libitum fed birds. These results suggest restricted birds 'binge eat', or increase their feed intake, in an attempt to eat as much food to reach a point of satiety. In the long term, hunger is dependent on energy balance to support metabolic needs. Birds obtain nutrients and energy through their diet to support growth, maintenance and reproduction (D'Eath et al., 2009).

In general, feed intake is reported to increase as nutrient requirements to support growth, maintenance and reproduction increase. However, nutrient requirements may be unsatisfied due to reduced quality of diet, such as nutrient dilution, or a reduced amount of feed consumed, such as feed restriction. As such, feed restricted broiler breeders may experience chronic hunger due to reduced nutrient intake (D'Eath et al., 2009).

Feed restriction can influence broiler breeder behaviour, specifically feeding and feed seeking. Compared to ad libitum-fed broiler breeders, feed restricted broiler breeders are more active and spend less time resting before a meal (Savory and Maros, 1993; de Jong et al., 2003; Hocking et al., 2002b). Moreover, feed restricted broiler breeders spend a greater proportion of time performing stereotypic pecking directed toward the ground and empty feed containers, and drink more than ad libitum birds (Merlet et al., 2005; Savory and Maros, 1993; Hocking et al., 2002b; de Jong et al., 2003). Further, feed restriction alters feeding behavior. Hocking et al. (2002b) reported that restricted breeders spent less proportion of time during the day eating than ad libitum birds (0.5 and 6.1%, respectively). In addition, restricted breeders ate 83 g during a 2-minute feeding bout, while ad libitum breeders ate 35 g in the same period of time (Savory et al., 1993). Thus, feed restriction led to hunger, which motivated birds to consume larger meals and eat at a faster rate than unrestricted birds. Buckley et al. (2015) tested state-dependent learning to evaluate hunger in broiler breeder hens over three experiments. Broiler breeders were reared on a feeding program that alternated between quantitative feed restriction (to simulate high deprivation and hunger) and ad libitum feeding (to simulate low deprivation and satiety) every 2 days. In the second experiment, birds were given 5 minutes to consume a food reward. Feed intake was 9.3 g greater on days when hens were feed restricted compared to ad libitum feeding days. While the authors did not find statistical differences in the third experiment, mean feed intake during a 3-minute period on restricted feeding days was 6.1 g greater than ad libitum feeding days. Increased feed intake indicated the birds were hungrier on restricted feeding days than on ad libitum feeding days. In summary of the findings above, feed restriction led to hunger which results in increased meal size, eating rate and feed intake.

Hunger in broiler breeders can be assessed through foraging, which is a behaviour performed to search for feed by pecking and scratching (Dixon et al., 2014). Feed restricted broiler breeder hens were reported to experience greater motivation to seek for feed and spend more time foraging compared to unrestricted breeders (Savory and Maros, 1993; Dixon et al., 2014). Moreover, feed restricted breeders experienced greater motivation to forage and to reach a feed source when presented with a cost such as traveling through deep water to reach foraging sites and food sources. As such, feed seeking behaviours can be used to assess hunger of feed restricted broiler breeders.

Specific work has been conducted to compare hunger between conventionally fed skip-a-day pullets and pullets fed using a PF system. Providing broiler breeders with more frequent meals throughout the day using the PF system decreased restlessness and increased sitting and lying behaviours compared to conventionally fed broiler breeder pullets (Girard et al., 2017b). Additionally, the authors observed that PF pullets performed a greater frequency of object pecking, which is an indicator of hunger. Thus, despite increased meal frequency precision-fed pullets experienced hunger. Previous PF studies have evaluated feed seeking (station visits frequency) and feeding behaviour (meal frequency, meal size and average daily feed intake; **ADFI**) in response to various BW profiles (Zuidhof et al., 2017; Zuidhof, 2018). However, this research compared BW profiles that followed similar BW trajectories. Therefore, more research is needed to determine feeding and feed seeking behaviours of broiler breeders under a range of BW trajectories subjective to relaxed levels of feed restriction.

2.6 Supply Chain Consequences of Maternal Nutrition on Broiler Performance

Genetic selection has focused on optimizing broiler performance to produce fast and efficiently growing birds with high breast muscle yield to meet increased consumer demands for poultry meat. Specifically, broiler growth efficiency has increased 400% and feed conversion decreased by 52.4% over 35 d from 1957 to 2005 (Zuidhof et al., 2014). In addition, allometric growth of breast muscle has increased while fat deposition has decreased in 2005 broiler strains compared to strains used through the late 1900s. Broiler growth potential continues to increase while little focus is placed on implementing changes to broiler breeder BW profiles and corresponding levels of feed restriction. Renema et al. (2007) summarized that the recommended commercial broiler breeder flock BW targets and feed restriction practices have remained relatively constant since the late 1970s despite increased broiler growth potential. However, feed restriction raises welfare concerns and questions if feed restriction may limit growth performance in modern broiler strains.

2.6.1 Broiler Growth and Development

Broilers are genetically selected for fast growth rates, feed efficiency and high meat yield (Tallentire et al., 2016). Modern broilers are typically raised between 35 to 42 d to reach an approximate BW of 2.0 to 3.0 kg (Aviagen, 2019; Cobb-Vantress, 2018), and are provided with ad libitum access to feed. Since the 1950s, broiler BW targets have dramatically increased while the number of days to reach target market weight has decreased (Renema et al., 2007; Zuidhof et al., 2014). After 56 d of growth, broiler strains from 2005 achieved a BW approximately 4.6 times greater than the BW of a broiler strain used in 1957 (Zuidhof et al., 2014). Further, growth rates have increased by 400% from 1957 to 2005. Specifically, growth rate of breast muscle has doubled compared to overall growth rate of the entire body (Tallentire et al., 2016). In addition, modern broilers more efficiently convert feed to BW gain. Zuidhof et al. (2014) demonstrated that broiler strains used in 2005 required 1.208 less g of feed per g of BW compared to broiler strains used in 1957.

Fast growth rates due to genetic selection and ad libitum feeding are associated with an increased incidence and severity of metabolic diseases and skeletal disorders, which can reduce welfare. Sudden death syndrome and ascites are two common metabolic diseases as a result of fast growth rates that lead to flock mortality (Bessei, 2006; Leeson, 2007; Hutchinson and Riddell, 1990). Moreover, broilers were observed to have leg problems such as deformities, bone necrosis, and bone weakness that impaired locomotion (Zubair and Leeson, 1996; Bessei, 2006). Unrestricted feeding led to obesity and further led to cardiovascular issues, heart failure and death (Zubair and Leeson, 1996; Shariatmadari, 2012). In addition, fast growing broilers sit and lay for prolonged periods of time which can lead to hock burns, breast blisters and foot pad lesions (Bessei, 2006). By the year 2000, broiler genetic selection shifted to reduce metabolic diseases without compromising growth potential. In addition, various feeding programs were created to reduce metabolic diseases and reach optimal growth potential.

2.6.2 Mechanisms of the Effect of Maternal Nutrition on Broiler Performance

Broiler skeletal and muscle development (Saccone and Puri, 2010), BW and carcass composition (van der Waaij et al., 2011; van Emous et al., 2015; Lesuisse et al., 2017; Bowling et al., 2018; Humphreys, 2020) are affected by maternal nutrition. In addition, stress induced by maternal nutrition, for example feed restriction, is reported to reduce growth in male progeny (Bowling et al., 2018; van der Waaij et al., 2011). There are two main mechanisms by which maternal nutrition can affect broiler performance: first, through direct nutrient availability through the egg during embryo development, and second through epigenetic effects. During embryonic development in bird species, nutrients are solely accessible through the egg (Rao et al., 2009). Nutrients consumed by broiler breeders are metabolized and deposited into the egg during egg formation. Thus, nutrients can alter egg composition and size during egg formation. During the first 2 weeks of embryonic development chicks obtain their nutrients primarily located in and through a highly vascularized network throughout the yolk and albumen (Moran, 2007; Uni et al., 2012). In addition, the vascular system allows for oxygen and carbon dioxide exchange which supports fatty acid combustion and acts as the main source of energy during the last week of embryonic development. It is possible that feed restriction lowers the amount of nutrients broiler breeders can use for egg production (Wilson, 1997). Consequently, less nutrients may be deposited into the egg during egg formation, which reduces egg size and may limit embryo growth and development.

Epigenetics is defined as a heritable change in gene function without change in DNA sequence that can influence phenotype (Scholtz et al., 2014). Changes in gene function result from molecular mechanisms such as chromatic folding and DNA methylation that occur during meiotic and mitotic cellular events, and can be passed down from parent to offspring and further on to multiple generations (David et al., 2017). Epigenetic changes can be influenced by changes in the environment, such as nutrition, climate and disease presence, and are highly influential during embryonic development (Scholtz et al., 2014). In terms of poultry, epigenetic changes can be influenced by maternal nutrition (Frésard et al., 2013). Epigenetic mechanisms are beyond the scope of this thesis, however, broiler breeders experience chronic stress due to feed restriction throughout their production cycle to control BW to optimize reproductive performance (Mench, 2002). There is little knowledge of the effect of stress from maternal feed restriction on broiler performance post-hatch (Angove and Forder, 2020). However, it has been reported that broiler breeders under nutritive stress deposit corticosteroids in the yolk during egg formation which can influence progeny growth performance post-hatch. Bowling et al. (2018) recently investigated the effect of maternal feed restriction on corticosterone and progeny growth. They found that yolks from broiler breeder hens feed restricted to maintain a low BW contained more corticosterone (90.8 ng/g) than yolks from medium BW hens (74.8 ng/g). Moreover, yolks from low BW hens tended to have 3.5 ng/g more corticosterone than heavy BW hens. In addition, it was reported that male progeny from high BW hens weighed 227.4 g heavier than males from low BW hens at 42 d of age. This suggests broiler breeders restricted feed intake to achieve a low BW experience more stress than medium and heavy BW hens, and high levels of maternal stress reduce growth in male progeny.

Additional hormones such as sex steroids, glucocorticoids, thyroid hormones and leptin have been identified to be present in yolk sacs during embryo development (Groothuis et al., 2005; Hayward et al., 2005; Wilson and McNabb, 1997; Hu et al., 2008), and have further been reported to vary in concentrations depending on maternal nutrition which can affect gene expression in the brain and muscle development post-hatch (Rao et al., 2009; Welberg and Seckl, 2001). It is possible that broilers are sensitive to endocrine pathways involved with growth and metabolism during embryo development that can be influenced by an interaction of maternal nutrition and epigenetic changes.

2.6.3 Effects of Maternal Feed Restriction on Egg Traits and Offspring Growth Performance

The hatching egg industry heavily focuses on optimizing reproductive performance as there are supply chain effects seen in the broiler industry. Broiler breeder nutrition has become of particular interest as it affects egg traits such as egg weight, and progeny growth parameters such as BW, efficiency and carcass traits.

Egg weight (**EW**) is generally understood to increase as broiler breeder BW increases at sexual maturity (McDaniel et al., 1981; McDaniel, 1983). van der Klein et al. (2018a) demonstrated that heavy BW hens that were reared to be 22% above the recommended BW by 18 wk of age produced eggs that were on average 1.3 g heavier than eggs from hens reared according to the recommended BW. Moreover, a 20% increase in BW at 20 wk of age increased EW by 1.11 g from 30 to 65 wk of age (Sun and Coon, 2005). In contrast, increased BW at 20 wk of age had no effect on EW (Ekmay et al., 2012; van Emous et al., 2013). Egg weight is also dependent on broiler breeder age. Iqbal et al. (2016) conducted a study to compare EW from a broiler breeder flock at 30, 45 and 60 wk of age. The authors found that eggs from the 30 wk old flock were 8.98 and 12.87 g lighter than eggs from the flock at 45 and 60 wk of age.

Egg weight and chick weight at hatch are positively correlated (Wilson, 1991). At hatch, broiler chicks from large eggs (70 to 72.0 g) were 10.4 g greater than chicks from small eggs (54.0 to 56.0 g; Lourens et al., 2006). This may be because large eggs have a greater amount of albumen and yolk than small eggs, which provides more available nutrients to support chick development. Chick weight is similarly positively correlated with broiler breeder age as per the previous paragraph that discussed the relationship between EW and broiler breeder age. Tona et al. (2004) reported chicks from a 45 wk old breeder flock were 4.17 g heavier at hatch than those from a 35 wk old flock. Similarly, female and male chicks from a 60 wk old breeder flock had a hatch BW 7.96 and 8.81 g greater than chicks from a 30 wk old breeder flock, respectively (Iqbal et al., 2016). In contrast, van Emous et al. (2015) reported similar chick weight from broiler breeder flocks of 33 and 37 wk of age, however the study investigated the effect of maternal age in a 5 wk increment, while findings from Tona et al. (2004) and Iqbal et al. (2016) compared maternal flocks that differ in 10 and 20 wk of age, respectively. These differences in broiler BW from broiler breeders that vary in age may be due to egg size, as larger eggs from heavier BW hens contain more nutrients for growth during chick development, resulting in a heavier chicks at hatch.

Broiler BW and weight gain throughout the growth cycle is also influenced by maternal age. van Emous et al. (2015) reported broilers from high growth broiler breeders had a greater BW gain from 28 to 34 d of age, and tended to have a greater BW gain throughout the entire growth period (0 to 34 d) than broilers from standard growth pattern broiler breeders. Recently, a study by Humphreys (2020) investigated the effect of maternal nutrition on broiler BW and body composition. They reported that broilers from high BW hens (21% above the standard BW target) were 3 and 4% heavier than broilers from standard BW hens on 35 and 42 d of age, respectively. Body weight is influenced and can be manipulated by maternal feeding programs. Specifically, feed restriction and ad libitum feeding influence broiler growth performance. A particular study by Mohiti-Asli et al., (2012) reported hatch weight of chicks from ad libitum-fed broiler breeders were 2 g lighter than chicks from feed restricted hens. Moreover, Bowling et al. (2018) that demonstrated males from high BW broiler breeders (that experienced a lower degree of feed restriction) were 227.4 g heavier than males from low BW broiler breeders. The authors further suggested that maternal stress induced by feed restriction reduced progeny BW, however more research is needed to determine the link between maternal BW and the concomitant degree of feed restriction on progeny BW.

Recent literature has demonstrated that carcass composition is affected by maternal BW and nutrition, specifically feed restriction to achieve BW targets. van der Waaij et al. (2011) investigated the effect of ad libitum versus restricted broiler breeder feeding regimens on progeny growth, and further fed the broilers ad libitum or 70% ad libitum. It was reported that female progeny from ad libitum hens were 8% fatter than those from restricted breeders which suggested maternal nutrition has a long term effect on progeny growth for up to 6 wks. Humphreys et al. (2020) reported broilers from high BW hens had a heavier fat pad (27.6 g) and gut weight (111.3 g) compared to broilers from standard BW hens (23.8 and 104.6 g, respectively). It is suggested that body composition is influenced by egg composition and nutrient availability during embryo development. Specifically, larger eggs provide more nutrients for embryo growth and development which might have a long term effect into the broiler growth cycle. More research is needed to determine the effect of quantitative maternal feed restriction on progeny growth performance.

2.7 Objectives and Hypotheses

The above literature review summarized that feed restriction is a crucial aspect of broiler breeder management; feed restriction controls BW to optimize reproductive performance. However, feed restriction is associated with poor welfare. In addition, broiler breeder BW targets have seen little change since the 1970's, while offspring have been genetically selected for fast growth rates and high yield over a short period of time. Recent evidence suggests reproductive performance of modern breeder birds do not achieve a sufficient BW composition to optimize egg production. Thus, research is needed to evaluate current broiler breeder recommended BW targets and concurrent degrees of feed restriction on reproductive performance and to evaluate hunger through various feeding and feed seeking behaviours. It is of importance to further evaluate offspring growth performance as a result of various degrees of maternal BW and feed restriction levels.

A novel precision feeding (**PF**) system was created to provide small meals to individual birds throughout the day based on live BW. The PF system has been used to implement and test BW trajectories and the response of increased BW on reproductive performance in broiler breeders. However as a new technology, the PF system has challenges specifically associated with the chick training period. During the first 3 wk of life, it is important that chicks learn how to eat from the PF station feeders so that they maintain good health and flock BW uniformity from a young age. An automated marking system (**AMS**) prototype was recently incorporated into a single PF station which identified chicks that have eaten from the station feeder: chicks that ate from the feeder were marked with dye, while those that lacked dye were identified as chicks that needed training to learn how to eat from the feeder. Research is needed to investigate whether the dye markings from the AMS prototype promotes aggression in broiler breeder chicks.

2.7.1 Objectives

The specific objectives of this thesis were as follows:

1) To determine whether dye markings from the AMS prototype promoted aggressive behaviour of precision-fed broiler breeder chicks (Chapter 3).

2) To investigate various degrees of increased BW targets, and by extension relaxed feed restriction, on hunger evaluated through feeding and feed seeking behaviours in female broiler breeders (Chapter 4).

3) To investigate various degrees of increased BW targets, and by extension relaxed feed restriction on egg weight, age at first egg and egg production in broiler breeders (Chapter 4).

4) To evaluate the effect of maternal BW and relaxed maternal feed restriction on broiler offspring BW, feed efficiency and carcass traits (Chapter 5).

5) To evaluate the effect of maternal age and broiler sex on offspring BW, feed efficiency and carcass traits (Chapter 5).

2.7.2 Hypotheses

It was hypothesized that:

1) Dye markings from the AMS would not stimulate aggressive behaviours among broiler breeder chicks because chicks (Chapter 3).

2) Increased BW (lesser degree of feed restriction) would reduce feeding and feed seeking behaviours because birds fed under a lower degree of feed restriction would have access to more feed, which would be evidence of reduced hunger and motivation to eat (Chapter 4).

3) Increased BW (lesser degree of feed restriction) would increase egg weight, delay age at first egg and decrease egg production because the pullets would reach a BW greater than the current recommended BW target at prior to sexual maturity (Chapter 4).

4) Increased maternal BW (lesser degree of maternal feed restriction) would increase offspring BW, breast muscle yield and fatness, and reduce feed efficiency (Chapter 5).

5) Offspring BW, breast muscle, liver, gut weight and fatness would increase, and feed efficiency would decrease as maternal age increased (Chapter 5).

6) Male offspring would have a greater BW and breast muscle yield, reduced fatness and would be more efficient than females (Chapter 5).

2.8 References

Andretta, I., C. Pomar, J. Rivest, J. Pomar, and J. Radünz. 2016. Precision feeding can significantly reduce lysine intake and nitrogen excretion without compromising the performance of growing pigs. Animal. 10:1137–1147.

Angove, J. L., and R. E. A. Forder. 2020. The avian maternal environment: Exploring the physiological mechanisms driving progeny performance. Worlds Poult. Sci. J. 76:100-118.

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2019. The effect of alternative feeding strategies for broiler breeder pullets: 1. Welfare and performance during rearing. Poult. Sci. 98:3377-3390.

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2020. The effect of alternative feeding strategies during rearing on the behaviour of broiler breeder pullets. Appl. Anim. Behav. Sci. https://doi.org/10.1016/j.applanim.2020.104929.

Aviagen, 2018. Ross 708 Parent Stock Handbook. Aviagen, Huntsville, AL.

Aviagen, 2019. Ross 708 Broiler Performance Objectives. Aviagen, Huntsville, AL.

Banhazi, T. M., H. Lehr, J. L. Black, H. Crabtree, P. Schofield, M. Tscharke, and D. Berckmans. 2012. Precision livestock farming: An international review of scientific and commercial aspects. Int. J. Agric. Biol. Eng. 5:1-9.

Basarab, J. A., M. A. Price, J. L. Aalhus, E. K. Okine, W. M. Snelling, and K. L. Lyle. 2003. Residual feed intake and body composition in young growing cattle. Can. J. Anim. Sci. 83:189-204.

Bédécarrats, G. Y. 2015. Control of the reproductive axis: Balancing act between stimulatory and inhibitory inputs. Poult. Sci. 94:810–815.

Bédécarrats, G. Y, M. Baxter, and B. Sparling. 2016. An updated model to describe the neuroendocrine control of reproduction in chickens. Gen. Comp. Endocrinol. 227:58–63.

Bédécarrats, G. Y., H. McFarlane, S. R. Maddineni, and R. Ramachandran. 2009. Gonadotropininhibitory hormone receptor signaling and its impact on reproduction in chickens. Gen. Comp. Endocrinol. 163:7–11.

Bessei, W. 2006. Welfare of broilers: A review. Worlds Poult. Sci. J. 62:455-466.

Borchers, M. R., Y. M. Change, I. C. Tsai, B. A. Wadsworth, and J. M. Bewley. 2016. A validation of technologies monitoring dairy cow feeding, ruminating, and lying behaviors. J. Dairy Sci. 99:7458-7466.

Bowling, M., R. Forder, R. J. Hughes, S. Weaver, and P. I. Hynd. 2018. Effects of restricted feed intake in broiler breeder hens on their stress levels and the growth and immunology of their offspring. Transl. Anim. Sci. 2: 263-271.

Bruggeman, V., O. Onagbesan, E. D'Hondt, N. Buys, M. Safi, D. Vanmontfort, L. Berghman, F. Vandesande, and E. Decuypere. 1999. Effects of timing and duration of feed restriction during rearing on reproductive characteristics in broiler breeder females. Poult. Sci. 78:1424-1434.

Buckley, L. A., V. Sandilands, P. M. Hocking, B. J. Tolkamp, and R. B. D'Eath. 2015. Feed-restricted broiler breeders: State-dependent learning as a novel welfare assessment tool to evaluate their hunger state? Appl. Anim. Behav. Sci. 165:124-132.

Buis, R. B. 2016. Development and application of a precision feeding program using electronic sow feeder and effect on gestation primiparous sow performance. MSc. Thesis. University of Guelph, Ontario, Canada.

Cobb-Vantress. 2016. Cobb Breeder Management Guide. Cobb-Vantress, Siloam Springs, AR.

Cobb-Vantress. 2018. Cobb 500 Broiler Performance and Nutrition Supplement. Cobb-Vantress, Siloam Springs, AR.

Corkery, G., S. Ward, C. Kenny, and P. Hemmingway. 2013. Incorporating smart sensing technologies into the poultry industry. J. Worlds Poult. Res. 3:106-128.

Culbertson M. M., S. E. Speidel, R. K. Peel, R. R. Cockrum, M. G. Thomas, and R. M. Enns. 2015. Optimum measurement period for evaluating feed intake traits in beef cattle. J. Anim. Sci. 93:2482-2487.

Dalton, H. A., B. J. Wood, T. M. Widowski, M. T. Guerin, and S. Torrey. 2018. Comparing the behavioural organization of head pecking, severe feather pecking, and gentle feather pecking in domestic turkeys. Appl. Anim. Behav. Sci. 204:66-71.

David, S. A., M. Mersch, S. Foissac, A. Collin, F. Pitel, and V. Coustham. 2017. Genome-wide epigenetic studies in chicken: A review. Epigenomes. 1:20. doi:10.3390/epigenomes1030020.

D'Eath, R. B., B. J. Tolkamp, I. Kyriazakis, and A. B. Lawrence. 2009. 'Freedom from hunger' and preventing obesity: The animal welfare implications of reducing food quantity or quality. Anim. Behav. 77:275-288.

Decuypere, E., P. M. Hocking, K. Tona, O. Onagbesan, V. Bruggeman, E. K. M. Jones, S. Cassy, N. Rideau, S. Metayer, Y. Jego, J. Putterflam, S. Tesseraud, A. Collin, M. Duclos, J. J. Trevid, and J. Williams. 2006. Broiler breeder paradox: A project report. Worlds Poult. Sci. J. 62:443-453.

de Jong, I. C., H. Enting, S. Van Voorst, E. W. Ruesink, and H. J. Blokhuis. 2005. Do low density diets improve broiler breeder welfare during rearing and laying? Poult. Sci. 84:194-203.

de Jong, I. C., and D. Guémené. 2011. Major issues in broiler breeders. Worlds Poult. Sci. J. 76:73-82.

de Jong, I. C., A. S. van Voorst, and H. J. Blokhuis. 2003. Parameters for qualification of hunger in broiler breeders. Phys. Behav. 78:773-783.

DeVries, T. J., M. A. G. von Keyserlingk, D. M. Weary, and K. A. Beauchemin. 2003. Technical note: validation of a system for monitoring feeding behaviour of dairy cows. J. Dairy Sci. 86:3571-3574.

Dixon, L. M., S. Brocklehurts, V. Sandilands, M. Bateson, B. J. Tolkamp, and R. B. D'Eath. 2014. Measuring motivation for appetite behaviour: Food-restricted broiler breeder chickens cross a water barrier to forage in an area of wood shavings without food. Plos One. 9:1-11. E102322.

Duncan, I. J. H. 1998. Behavior and behavioral needs. Poult. Sci. 77:1766-1772.

Dunn, I. C., and P. J. Sharp. 1990. Photoperiodic requirements for LH release in juvenile broiler and egg-laying strains of domestic chickens fed ad libitum or restricted diets. J. Reprod. Fertil. 90:329-335.

Eastwood, C., M. Trotter, and N. Scott. 2015. Understanding the user: Learning from on-farm application of precision farming technologies in the Australian livestock sector. Aust. J. Multi-disciplinary Eng. 10:41-50.

Ekmay, R. D., C. Salas, J. England, S. Cerrate, and C. N. Coon. 2012. The effects of pullet body weight, dietary nonpyhtate phosphorus intake, and breeder feeding regimen on production performance, chick quality, and bone remodeling in broiler breeders. Poult. Sci. 91:948-964.

Emmans, G. C. 1981. A model of the growth and feed intake of ad libitum fed animals, particularly poultry. Pages 103– 110 in Computers in Animal Production. G. M. Hillyer, C.

T. Whittemore, and R. G. Gunn, ed. Occasional Publication No. 5. British Society of Animal Science (formerly British Society of Animal Production), Penicuik, Midlothian, UK.

Estevez, I., I. L. Andersen, and E. Nævdal. 2007. Group size, density and social dynamics in farm animals. Appl. Anim. Behav. Sci. 103:185-204.

Estevez, I., L. J. Keeling, and R. C. Newberry. 2003. Decreasing aggression with increasing group size in young domestic fowl. Appl. Anim. Behav. Sci. 84:213-218.

Estevez, I., R. C. Newberry, and L. J. Keeling. 2002. Dynamics of aggression in the domestic fowl. Appl. Anim. Behav. Sci. 76:307-325

Fontana, I., E. Tullo, A. Butterworth, and M. Guarino. 2015. An innovative approach to predict the growth in intensive poultry farming. Comput. Electron. Agric. 119:178-183.

Fournel, S., A. N. Rousseau, and B. Laberge. 2017. Rethinking environment control strategy of confined animal housing systems through precision livestock farming. Biosyst. Eng. 155:96-123.

Fraser, D. 2008. Understanding animal welfare: The science and its cultural context. 1 ed. Wiley Blackwell, the United Kingdom.

Frésard, L., M. Morisson, J. M. Brun, A. Collin, B. Pain, F. Minvielle, and F. Pitel. 2013. Epigenetics and phenotypic variability: some interesting insights from birds. Genet. Sel. Evol. 45:16.

Frost, A. R. 2001. An overview of integrated management systems for sustainable livestock production. Integrated management systems for livestock. BSAP Occasional Publication. 28:45-50.

Girard, T. E., M. J. Zuidhof, and C. J. Bench. 2017a. Aggression and social rank fluctuations in precision-fed and skip-a-day broiler breeder pullets. Appl. Anim. Behav. Sci. 187:38-44.

Girard, T. E., M. J. Zuidhof, and C. J. Bench. 2017b. Feeding, foraging, and feather pecking behaviours in precision-fed and skip-a-day-fed broiler breeder pullets. Appl. Anim. Behav. Sci. 188:42-49.

Gompertz, B. 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of Life Contingencies. Trans. R. Philos. Soc. 115:513–585.

Gous, R. M., E. T. Moran Jr., H. R. Stilborn, G. D. Bradford, and G. C. Emmans. 1999. Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. Poult. Sci. 78:812-821.

Groothuis, T. G., W. Muller, and N. von Engelhardt. 2005. Maternal hormones as a tool to adjust offspring phenotype in avian species. Neurosci. Biobehav. Rev. 29:329–352.

Grossman, M., and W. J. Koops. 1988. Multiphasic analysis of growth curves in chickens. Poult. Sci. 67:33-42.

Hadinia, S. H., P. R. O. Carneiro, C. J. Fitzsimmons, G. Y. Bédécarrats, and M. J. Zuidhof. 2020. Post-photostimulation energy intake accelerated pubertal development in broiler breeder pullets. Poult. Sci. 99:2215-2229.

Hadinia, S. H., P. R. O. Carneiro, D. R. Korver and J. M Zuidhof. 2019. Energy partitioning by broiler breeder hens in conventional daily-restricted feeding and precision feeding systems. Poult. Sci. 98:6721-6732.

Hayward, L. S., D. G. Satterlee, and J. C. Wingfield. 2005. Japanese quail selected for high plasma corticosterone response deposit high levels of corticosterone in their eggs. Physiol. Biochem. Zool. 78:1026-1031.

Hocking, P. M. 1993. Roles of body weight and feed intake in ovarian follicular dynamics in broiler breeders at the onset of lay and after a forced molt. Poult. Sci. 83:2044-2050.

Hocking, P. M. 2004. Roles of body weight and feed intake in ovarian follicular dynamics in broiler breeders at the onset of lay and after a forced molt. Poult. Sci. 82:2044-2050.

Hocking, P. M., R. Bernard, and G. W. Robertson. 2002a. Effects of low dietary protein and different allocations of food during rearing and restricted feeding after peak rate of lay on egg production, fertility and hatchability in female broiler breeders. Br. Poult. Sci. 43:94-103.

Hocking, P.M., and S. R. I. Duff. 1989. Musculo-skeletal lesions in adult male broiler breeder fowls and, their relationships with body weight and fertility at 60 weeks of age. Br. Poult. Sci. 30: 777-784.

Hocking, P. M., A. B. Gilbert, M. Walker, and D. Waddington. 1987. Ovarian follicular structure of white leghorns fed ad libitum and dwarf and normal broiler breeders ad libitum or restricted until point of lay. Br. Poult. Sci. 28:493-506.

Hocking, P.M., M. H. Maxwell, G. W. Robertson, and M. A. Mitchell. 2001. Welfare assessment of modified rearing programmes for broiler breeders. Br. Poult. Sci. 42:424-432.

Hocking, P. M., M. H. Maxwell, G. W. Robertson, and M. A. Mitchell. 2002b. Welfare assessment of broiler breeders that are food restricted after peak rate of lay. Br. Poult. Sci. 43:5–15.

Hocking, P.M., V. Zaczek, E. K. M. Jones, and M. G. McLeod. 2004. Different concentrations and sources of dietary fibre may improve the welfare of female broiler breeders. Br. Poult. Sci. 45: 9-19.

Hornick, J. L., C. Van Eanaeme, O. Gerard, I. Dufrasne, and L. Istasse. 2000. Mechanisms of reduced and compensatory growth. Domest. Anim. Endocrinol.19:121-132.

Hu, Y., Y. Ni, and L. Ren. 2008. Leptin is involved in the effects of cysteamine on egg laying of hens, characteristics of eggs, and posthatch growth of broiler offspring. Poult. Sci. 87:1810-1817.

Humphreys, K. D. 2020. Implications of altering maternal feed availability and feeding system on offspring performance. MSc. Thesis. University of Alberta, Edmonton, Alberta, Canada.

Hutchison, T. W. S., and C. Riddell. 1990. A study of hepatic lesion in broiler chickens at processing plants in Saskatchewan. Can. Vet. J. 31:20–25.

Iqbal, J., S. H. Khan, N. Mukhtar, T. Ahmed, and R. A. Pasha. 2016. Effects of egg size (weight) and age on hatching performance and chick quality of broiler breeder. J. Appl. Anim. Res. 44:54-64.

John, A. J., C. E. F. Clark, M. J. Freeman, and K. L. Kerrisk. 2016. Review: Milking robot utilization, a successful precision livestock farming evolution. Anim. 10:1484-1492.

Katanbaf, M. N., E. A. Dunnington, and P. B. Siegel. 1989. Restricted feeding in early and late-feathering chickens. Poult. Sci. 68:352-358.

Kwakkel, R P., B. J. Ducro, and W. J. Koops, 1993. Multiphasic analysis of growth of the body and its chemical components in White Leghorn pullets. Poult. Sci. 72:1421-1432.

Kwakkel, R. P., J. A. W. van Esch, B. J. Durco, and W. J. Koops. 1995. Onset of lay related to multiphasic growth and body composition in white leghorn pullets provided ad libitum and restricted diets. Poult. Sci. 74:821-832.

Lees, J. J., C. Lindholm, P. Batakis, M. Busscher, and J. Altimiras. 2017. The physiological and neuroendocrine correlates of hunger in the Red Junglefowl (Gallus gallus). Scientific reports. 7:17984. doi:10.1038/s41598-017-17922-w.

Leeson, S. 2007. Metabolic challenges: Past, present, and future. J. Appl. Poult. Res. 16:121-125.

Leeson, S., and T. Walsh. 2004. Feather in commercial poultry. 2. Factors influencing feather growth and feather loss. Worlds Poult. Sci. J. 60:52-63.

Lesuisse, J., C. Li, S. Schallier, J. Leblois, N. Everaert, and J. Buyse. 2017. Feeding broiler breeders reduced balanced protein diet during the rearing and laying period impairs reproductive performance but enhances broiler offspring performance. Poult. Sci. 96:3949-3959.

Lewis, P. D. 2006. A review of lighting for broiler breeders. Br. Poult. Sci. 47:393-404.

Lourens, A., R. Molenaar, H. van den Brand, M. J. W. Heetkamp, R. Meijerhof, and B. Kemp. 2006. Effect of egg size on heat production and the transition of energy from egg to hatchling. Poult. Sci. 85:770-776.

McDaniel, G. R. 1983. Factors affecting broiler breeder performance. 5. Effects of preproduction feeding regimens on reproductive performance. Poult. Sci. 62:1949-1953.

McDaniel, G. R., J. Brake, and M. K. Eckman. 1981. Factors affecting broiler breeder performance. 4. The relationship of some reproductive traits. Poult. Sci. 60:1792-1797.

Mellor, E., B. Brilot, and S. Collins. 2018. Abnormal repetitive behaviours in captive birds: A tinbergian review. Appl. Anim. Behav. Sci. 198:109-120.

Melnychuk, V. L., J. D. Kirby, Y. K. Kirby, D. A. Emmerson, and N. B. Anthony. 2004. Effect of strain, feed allocation program, and age at photostimulation on reproductive development and carcass characteristics of broiler breeder hens. Poult. Sci. 83:1861-1867.

Mench, J. A. 1988. The development of aggressive behavior in male broiler chicks: A comparison with laying-type males and the effects of feed restriction. Appl. Anim. Behav. Sci. 21:233-242.

Mench, J. A. 2002. Broiler breeders: feed restriction and welfare. Worlds Poult. Sci. J. 58:23-29.

Merlet, F., J. Puterflam, J. M. Faure, P. M. Hocking, M. S. Magnusson, and M. Picard. 2005. Detection and comparison of time patterns of behaviours of two broiler breeder genotypes fed ad libitum and two levels of feed restriction. Appl. Anim. Behav. Sci. 94:255–271.

Mohiti-Asli, M., M. Shivazad, M. Zaghari, M. Rezaian, S. Aminzadeh, and G. G. Mateos. 2012. Effects of feeding regimen, fiber inclusion, and crude protein content of the diet on performance and egg quality and hatchability of eggs of broiler breeder hens. Poult. Sci. 91:3097–3106.

Moran, E. T. Jr. 2007. Nutrition of the developing embryo and hatchling. Symposia: managing the embryo for performance. Poult. Sci. 86:1043-1049.

Morrissey, K. L. H., T. Widowski, S. Leeson, V. Sandilands, A. Arnone, and S. Torrey. 2014. The effect of dietary alterations during rearing on growth, productivity, and behaviour in broiler breeder females. Poult. Sci. 93:285–295.

Mortensen, A. K., P. Lisouski, and P. Ahrendt. 2016. Weight prediction of broiler chickens using 3D computer vision. Comp. Elect. Agric. 123:319-326.

Mottram, T. 2016. Animal board invited review: precision livestock farming for dairy cows with a focus on oestrus detection. Anim. 10:1575-1584.

Nicol, C. J., M. Bestman, A. M. Gilani, E. N. de Haas, I. C. de Jong, S. Lambton, J. P. Wagenaar, C. A. Weeks, and T. B. Rodenburg. 2013. The prevention and control of feather pecking: Application to commercial systems. Worlds Poult. Sci. J. 69:775-788.

Pishnamazi, A., R. A. Renema, M. J. Zuidhof, and F. Robinson. 2014. Effect of age at photostimulation on sexual maturation in broiler breeder pullets. Poult. Sci. 93:1274-1281.

Pomar, C., J. Pomar, F. Dubeau, E. Joannopoulos, and J. P. Dussault. 2014. The impact of daily multiphase feeding on animal performance, body composition, nitrogen and phosphorus excretions, and feed costs in growing-finishing pigs. Anim. 8:704–713.

Pomar, C., and A. Remus. 2019. Precision pig feeding: A breakthrough toward sustainability. Anim. Front. 9:52-59.

Rao, K., J. Xie, X. Yang, L. Chen, R. Grossmann, and R. Zhao. 2009. Maternal low-protein diet programs offspring growth in association with alterations in yolk-sac membrane, hypothalamus and muscle of developing Langshan chicken. Br. J. Nutr. 102:848-857.

Renema, R. A., and F. E. Robinson. 2004. Defining normal: Comparison of feed restriction and full feeding of female broiler breeders. Worlds Poult. Sci. J. 60:508-522.

Renema, R. A., F. E. Robinson, P. R. Goerzen, and M. J. Zuidhof. 2001. Effects of altering growth curve and age at photostimulation in female broiler breeders. 2. Egg production parameters. Can. J. Anim. Sci. 81:477–486.

Renema, R. A., F. E. Robinson, J. A. Proudman, M. Newcombe, and R. I. McKay. 1999. Effects of body weight and feed allocation during sexual maturation in broiler breeder hens. 2. Ovarian morphology and plasma hormone profiles. Poult. Sci. 78:629–639.

Renema, R. A., M. E. Rustad, and F. E. Robinson. 2007. Implications of changes to commercial broiler and broiler breeder body weight targets over the past 30 years. Worlds Poult. Sci. J. 63:457-472.

Richards, M. P., and M. Proszkowiec-Weglarz. 2007. Mechanisms regulating feed intake, energy expenditure, and body weight in poultry. Poult. Sci. 86:1478–1490.

Richards, M. P., R. W. Rosebrough, C. N. Coon, and J. P. McMurtry. 2010. Feed intake regulation for the female broiler breeder: In theory and in practice. J. Appl. Poult. Res. 19:182-193.

Riedstra, B., and T. G. G. Groothuis. 2002. Early feather pecking as a form of social exploration: The effect of group stability on feather pecking and tonic immobility in domestic chicks. Appl. Anim. Behav. Sci. 77:127-138.

Robinson, F. E., N. A. Robinson, and T. A. Scott, 1991. Reproductive performance, growth rate and body composition of full-fed versus feed-restricted broiler breeder hens. Can J. Anim. Sci. 71:549–556.

Rosales, A. G. 1994. Managing stress in broiler breeders: A review. J. Appl. Poult. Res. 3:199-207.

Saccone, V., and P. L. Puri. 2010. Epigenetic regulation of skeletal myogenesis. Organogenesis. 6:48–53.

Sandilands, V., B. J. Tolkamp, and I. Kyriazakis. 2005. Behaviour of food restricted broilers during rearing and lay—effects of an alternative feeding method. Physio. Behav. 85:115–123.

Sandilands, V., B. J. Tolkamp, C. J. Savory, and I. Kyriazakis. 2006. Behavior and welfare of broiler breeders fed qualitatively restricted diets during rearing: are there viable alternatives to quantitative restriction? Appl. Anim. Behav. Sci. 96: 53-67.

Savory, C. J. 1995. Feather pecking and cannibalism. Worlds Poul. Sci. J. 51:215-219.

Savory, C. J., P.M. Hocking, J. S. Mann, and M. H. Maxwell. 1996. Is broiler breeder welfare improved by using qualitative rather than quantitative food restriction to limit growth rate? Anim. Welf. 5:105-127.

Savory, C. J., and K. Maros. 1993. Influence of degree of food restriction, age and time of day on behaviour of broiler breeder chickens. Behav. Processes. 29:179-190.

Savory, C. J., K. Maros, and S. M. Rutter. 1993. Assessment of hunger in growing broiler breeders in relation to a commercial restricted feeding programme. Anim. Welf. 2:131-152.

Scholtz, M. M., J. P. van Zyl, and A. Theunissen. 2014. The effect of epigenetic changes on animal production. Appl. Anim. Husb. Rural Dev. 7:7-10.

Shariatmadari, F. 2012. Plans of feeding broiler chickens. Worlds Poult. Sci. J. 68:21-30.

Shao, W., R. Wawakami, R. Yoshihashi, S. You, H. Kawase, and T. Naemura. 2020. Cattle detection and counting in UAV images based on convolutional neural networks. Int. J. Remote Sens. 41:31-52.

Shea, M. M., J. A. Mench., and O. P. Thomas. 1990. The effect of dietary tryptophan on aggressive behavior in developing and mature broiler breeder males. Poult. Sci. 69:1664-1669.

Shi, L., Y. Sun, H. Xu, Y. Liu, Y. Li, Z. Huang, A. Ni, C. Chen, D. Li, P. Wang, J. Fan, H. Ma, and J. Chen. 2020. Effect of age at photostimulation on sexual maturation and egg-laying performance of layer breeders. Poult. Sci. 99:812-819.

Sun, J., and C. N. Coon. 2005. The effects of body weight, dietary fat, and feed withdrawal rate on the performance of broiler breeders. J. Appl. Poult. Res. 14:728-739.

Tallentire, C. W., I. Leinonen, and I. Kyriazakis. 2016. Breeding for efficiency in the broiler chicken: A review. Agron. Sustain. Dev. 36:66.

Tolkamp, B. J., and R. B. D'Eath. 2016. Hunger associated with restricted feeding systems. Pages 11-27 in Nutrition and the Welfare of Farm Animals. Phillips, C. J. C., ed. Springer, Switzerland.

Tompić, T., J. Dobša, S. Legen, N. Tompić, and H.Medić. 2011. Modeling the growth pattern of in-season and off-season Ross 308 broiler breeder flocks. Poult. Sci. 90:2879-2887.

Tona, K., O. Onagbesan, B. De Ketelaere, E. Decuypere, and V. Bruggeman. 2004. Effects of age of broiler breeders and egg storage on egg quality, hatchability, chick quality, chick weight, and chick posthatch growth to forty-two days. J. Appl. Poult. Res. 13:10-18.

Uni, Z., L. Yadgary, and R. Yair. 2012. Nutritional limitations during poultry embryonic development. J. Appl. Poult. Res. 21:175-184.

van der Klein, S. A. S., G. Y. Bédécarrats, F. E. Robinson, and M. J. Zuidhof. 2018a. Early photostimulation at the recommended body weight reduced broiler breeder performance. Poult. Sci. 97:3736-3745.

van der Klein, S. A. S., G. Y. Bédécarrats, and M. J. Zuidhof. 2018b. The effect of rearing photoperiod on broiler breeder reproductive performance depended on body weight. Poult. Sci. 97:3286-3294.

van der Klein, S. A. S., M. J. Zuidhof, and G. Y. Bédécarrats. 2020. Diurnal and seasonal dynamic affecting egg production in meat chickens: A review of mechanisms associated with reproductive dysregulation. Anim. Reprod. Sci. 213:106257.

van der Waaij, E. H., van den Brand, J. A. M. van Arendonk, and B. Kemp. 2011. Effect of match or mismatch of maternal-offspring nutritional environment on the development of offspring in broiler chickens. Animal. 5:741-748.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, H. van den Brand, and W. H. Hendriks. 2015. Effects of growth patterns and dietary protein levels during rearing of broiler breeders on fertility, hatchability, embryonic mortality, and offspring performance. Poult. Sci. 94:681-691.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, and W. H. Hendriks. 2013. Effects of growth patterns and dietary crude protein levels during rearing on body composition and performance in broiler breeder females during the rearing and laying period. Poult. Sci. 92:2091-2100.

van Hierden, Y. M., S. M. Korte, E. W. Ruesink, C. G. van Reenen, B. Engel, J. M. Koolhaas, and H. J. Blokhuis. 2002. The development of feather pecking behaviour and targeting of pecking in chicks from a high and low feather pecking line of laying hens. Appl. Anim. Behav. Sci. 77:183-196.

van Middelkoop, J. H. 1978. Types of eggs produces in white plymouth rock hens. Worlds Poult. Sci. J. 34:69–80.

Vranken, E., and D. Berckmans. 2017. Precision livestock farming for pigs. Anim. Frontiers. 7:32-37.

Wathes, C. M., H. H. Kristensen, J. M Aerta, and D. Berckmans. 2008. Is precision livestock feeding an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? Comput. Electron. Agric. 64:2-10.

Wang, Z, J. D. Nkrumah, C. Li, J. A. Basarab, L. A. Goonewardene, E. K. Okine, D. H. Crews Jr., and S. S. Moore. 2006. Test duration for growth, feed intake, and feed efficiency in beef cattle using the GrowSafe System. J. Anim. Sci. 84:2289-2298.

Wang, Z., and M. J. Zuidhof. 2004. Estimation of growth parameters using a nonlinear mixed Gompertz model. Poult. Sci. 83:847-852.

Welberg, L. A. M., and J. R. Seckl. 2001. Prenatal stress, glucocorticoids and the programming of the brain. J. Neuroendocrinol. 13:113-128.

Werkheiser, I. 2018. Precision livestock farming and farmers' duties to livestock. J. Agric. Environ. Ethics. 31:181-195.

Wilson, H. R. 1991. Interrelationship of egg size, chick size, posthatching growth and hatchability. Worlds Poult. Sci. J. 47:5-20.

Wilson, H. R. 1997. Effects of maternal nutrition on hatchability. Poult. Sci. 76:134-143.

Wilson, C. M., and F. M. McNabb. 1997. Maternal thyroid hormones in Japanese quail eggs and their influence on embryonic development. Gen. Comp. Endocrinol. 107:153-165.

Yu, M. W., F. E. Robinson, R. G. Charles, and R. Weingardt. 1992. Effect of feeding allowance during rearing and breeding on female broiler breeders. 2. Ovarian morphology and production. Poult. Sci. 71:1750-1761.

Zajonc, R. B., W. R. Wilson, and D. W. Rajecki. 1975. Affiliation and social discrimination produced by brief exposure in day-old domestic chicks. Anim. Behav. 23:131-138.

Zubair, A. K., and S. Leeson. 1996. Compensatory growth in the broiler chicken: a review. Worlds Poult. Sci. J. 52:189-201.

Zuidhof, M. J. 2018. Lifetime productivity of conventionally and precision-fed broiler breeders. Poult. Sci. 97:3921-3937.

Zuidhof, M. J. 2020. Multiphasic poultry growth models: Method and application. Poult. Sci. doi https://doi.org/10.1016/j.psj.2020.08.049.

Zuidhof, M. J., M. V. Fedorak, C. C. Kirchen, E. H. M. Lou, C. A. Ouellette, and I. I. Wenger. 2019. System and method for feeding animals. PrecisionZX, Inc., assignee. US Pat. No. 10,506,793.

Zuidhof, M. J., M. V. Fedorak, C. A. Ouellette, and I. I. Wenger. 2017. Precision feeding: innovative management of broiler breeder feed intake and flock uniformity. Poult. Sci. 96:2254-2263.

Zuidhof, M. J., D. E. Holm, R. A. Renema, M. A. Jalal, and F. E. Robinson. 2015. Effects of broiler breeder management on pullet body weight and carcass uniformity. Poult. Sci. 94:1389-1397.

Zuidhof, M. J., B. L. Schneider, V. L. Carney, D. R. Korver, and F. E. Robinson. 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. Poult. Sci. 93:2970-2982.

3.0 Chapter 3: Effect of an Automated Marking System in Precision-fed Broiler Breeder Chicks on Aggressive Behaviour

3.1 Summary

Precision feeding (**PF**) technology has been developed to feed individual broiler breeders based on real time body weight (**BW**). Precision fed broiler breeder chicks undergo training up to 21 d of age to learn how to eat from the PF stations. Training is crucial to achieve high flock uniformity and successful growth from a young age. An automated marking system (**AMS**) prototype has been integrated into a PF station to identify chicks that require training from those that have successfully learned to eat from the stations: chicks marked with dye have successfully visited and eaten from the feeder, while chicks with no or little dye are late adopters that require training. Before implementing the AMS prototype on a larger scale, it was necessary to determine if dye markings from the AMS prototype promoted aggressive behaviors among chicks. In the current study the dye markings promoted aggressive pecks at 26 d of age, however this is beyond the time the AMS prototype is required as an identification method in a PF system.

Key words: precision livestock feeding, artificial marking, aggression, feed restriction

3.2 Description of Problem

The primary focus in broiler breeder management is to optimize reproductive performance which is achieved by controlling body weight (**BW**). Broiler breeder females are rigorously feed restricted during the rearing period to control BW and body composition leading up to sexual maturity. While beneficial to manage flock BW, quantitative feed restriction creates welfare challenges such as chronic hunger, stress, frustration and boredom (Tolkamp and D'Eath, 2016; Mench, 2002). However, feed restriction is crucial to manage feed intake to prevent over eating and obesity, and potential lameness and death (Mench, 2002). Without controlling BW during rearing, female broiler breeders may be above the recommended BW. In turn, females with a higher BW reach sexual maturity earlier than females with a lower BW (Renema et al., 2001; Hocking, 2004). In North America, skip-a-day feeding is the common method that restricts feed intake by providing birds with a meal every second day. The European Union allows skip-a-day feeding programs as long as broiler breeders are provided with a sufficient amount of feed to meet their physiological requirements (Council Directive, 1998). However, specific physiological requirements are not well defined. Some European countries, such as countries in the UK, do not allow skip-a-day feeding as broiler breeders cannot go without feed for more than 24 h (The Welfare of Farmed Animals (England) Regulations, 2007; The Welfare of Farmed Animals (Wales) Regulations, 2007; The Welfare of Farmed Animals (Scotland) Regulations, 2010; The Welfare of Farmed Animals Regulations (North Ireland), 2012).

Recommendations for commercial broiler breeder flock BW targets have remained relatively constant over the past 50 years (Renema et al., 2007). Due to increasing consumer demand for chicken meat the poultry industry has placed greater focus on optimizing broiler growth potential and efficiency (USDA, Economic Research Service, 2020). As a result broiler growth rates have increased by 400% and feed efficiency has increased by 50% over the past 50 years (Zuidhof et al., 2014). In turn there is an increasing gap between broiler breeder and broiler BW targets (Renema et al., 2007). Recent literature has reported broiler breeder hens reared 22% above the recommended BW targets using precision-feeding technology increased egg production by 39% during the laying period (van der Klein et al., 2018a). This suggests using precise feeding technology to increase broiler breeder BW targets does not negatively affect reproductive success.

An automated precision feeding (**PF**) system has been developed with the goal of providing the right amount of feed to individual broiler breeders at the right time (Zuidhof et al., 2019). The PF system is unique as it strictly manages BW on an individual bird basis and provides birds an opportunity to access small meals throughout a 24 h period. Thus, birds have access to feed during light and dark periods. After voluntarily entering the system, each bird is recognized and weighed. A decision regarding the bird's BW is then made: if the bird's live BW is lower than its target BW, which is programmed within the PF system software, it is allowed access to a meal. The feeding system has increased flock uniformity by achieving a coefficient of variation in BW of less than 2% (Zuidhof et al., 2017; van der Klein et al., 2018b) and increased feed efficiency by 4.6% in comparison to a conventional feeding method in a controlled research setting (Zuidhof, 2018).

Precision-fed chicks undergo training up to 21 d of age to learn how to eat from the system. The goal during the training period is to teach chicks to locate and eat from the feeder within the PF stations (Zuidhof, 2018). It is crucial to identify chicks that have not learned how to eat from within the PF station during the training period to provide the chicks with a good start contributing to growth and reproductive success later on in life, and to maintain uniform flock BW from a young age.

The PF system prototypes relied on radio frequency identification (**RFID**) transponders to identify and monitor individual bird success. However, the RFID transponders would be costly to implement in a large commercial flock. As a result, an automated marking system (**AMS**) prototype was developed and incorporated into the PF system to mark chicks with dye as they eat from the system feeder. In such a system, chicks with little or no dye marking could be identified as chicks that learned how to eat from the PF system at a slow rate compared to other chicks, and therefore require training.

Previous studies have reported that birds artificially marked with dye received high rates of aggressive pecks and encounters from pen mates, clearly indicating a welfare issue (Estevez et al., 2003; Dennis et al., 2008). The effect of dye markings on aggression in chicks is not currently known. To be implemented on a larger research or commercial farm scale, the AMS must be tested to ensure that the dye markings do not provoke aggressive behavior among the chicks during the training period. Therefore, the objective of the current study was to determine if the dye marking from the AMS influenced aggressive behavior of precision-fed chicks during the training period. Our null hypothesis was that the dye marking would not stimulate aggressive behavior; there would be no difference in aggressive behavior between chicks with dye markings from those that lacked dye markings.

3.3 Materials and Methods

3.3.1 Experimental Design

The animal protocol for the study was approved by the University of Alberta Animal Care and Use Committee for Livestock and followed principles established by the Canadian Council on Animal Care Guidelines and Policies (CCAC, 2009). The pilot study was conducted using a PF system (Xanantec Technologies, Inc., Edmonton, AB, Canada) with 3 treatments: 1) control (**CON**) treatment in which no dye solution was applied (n = 2 pens of 26 and 27 birds), 2) manual marking (**MM**) treatment in which a dye solution was manually applied (n = 2 pens of 26 and 27 birds), and 3) automatic marking (**AM**) in which the birds were marked with a dye solution from the AMS prototype (n = 1 pen of 52 birds). Pen was the experimental unit and behavior observations were replicated twice each day. Pen (n = 2) and behavior observations over time served as replication for the CON and MM treatments. The AM pen could not be replicated because only 1 AMS prototype was available for use. Thus, the only possible replication for the AM treatment was through repeated behavior observations over time. Upon delivery from the hatchery, all chicks were randomly assigned to a treatment and pen. Each pen contained 1 PF station and a bell drinker with 8 nipples for ad libitum access to water.

3.3.2 Animal Stocks and Management

The experiment was conducted over 26 d using 158 mixed-sex Ross 708 broiler breeders (n = 126 pullets; n = 32 cockerels; Aviagen Inc., Huntsville, AL). Chicks were reared in 3 environmental chambers that were divided in half, creating 2 pens in each chamber (n = 6). The chambers measured 3.9 m wide x 4.4 m long. In 2 of the chambers, one pen housed CON chicks while the other housed MM chicks. The third chamber contained a single pen of the AM group. Chicks were randomly assigned to pens according to treatment with a male: female ratio of 1:4. Chicks were fed a standard commercial broiler breeder starter crumble (2,762 kcal AME, 21.1% CP, and 0.993% Ca; HiPro Feeds, Sherwood Park, AB, Canada). The environmental chambers were programmed to provide a 24L:0D photoschedule at 100 lx from 0 to 3 d, then reduced to an 8L:16D photoschedule at 15 lx from 4 to 26 d. On d 0 the temperature was set at 34.5°C and decreased by 0.5°C daily until 23.5°C at d 22. For identification, all birds were given a unique neck tag on d 0 (Ketchum Manufacturing Inc., Brockville, ON, Canada), and were wing banded with a RFID tag on their right wing on d 7 (23 mm glass transponders, 481-1109-2-ND, RI-TRP-RR3P-30, 134.2KHZ; Texas Instruments, Dallas, TX).

3.3.3 Precision Feeding System

Each PF station consisted of 2 motorized entry doors, a sorting and feeding stage, and feeder (Figure 3.1). The chicks had 24 h access to the station, with green LED lighting illuminating the station when the chamber lights were off. The stations contained an RFID reader and body weight scale to identify and compare each chick's BW in real-time to its programmed target BW. Chicks were given access to 70 g of feed within the feeder within a 60 s feeding bout.

3.3.4 Chick Training

The goal throughout the training period (0 to 14 d of age) was to introduce chicks to the PF station and to have them learn to eat individually from it. To accomplish this, the PF software had 4 programmed training modes: training, movement training, transition, and individual feeding mode (Table 3.1). Each mode progressively introduced station movements and sounds, and acclimatized chicks to individual feeding. Training mode (d 0 to 6) was programmed such that all entry doors were continuously open for multiple chick access to feed. In movement training mode (d 7 to 10), entry doors were programmed to close and ejector panels gently removed chicks from the station every 5 min. Transition mode (d 11 to 13) alternated between movement training and individual feeding modes which allowed both group and individual eating in 15 min bouts. Individual feeding mode commenced by d 14 and was programmed for individual bird entry to the station and access to the feeder. In addition to feed availability from the station feeder, supplemental feed was provided throughout the station and was gradually removed over the first 7 d to encourage chicks to travel independently into the station to reach the feeder. Supplemental feed was placed on a paper plate at the base of the ramp (d 0 to 2), on the ramp (d 0 to 6), and on paper plates located on the feeding and sorting stage platforms (d 0 to 7). Supplemental feed was completely removed by d 8.

Training was provided from d 0 to 22 to chicks (n = 157) that required assistance learning how to eat from the PF stations. From d 0 to 11 chicks were trained if their BW gain was less than 5 g, average daily feed intake (**ADFI**) was less than 2 g, or had less than 3 station visits over the past 24 h. From d 0 to 6, training involved placing chicks directly onto supplemental feed sources in the sorting and feeding stage. From d 7 to 11, chicks were placed directly at the feeder to eat because supplemental feed was no longer present in the stations. From d 12 to 22 chicks (n = 28) were introduced to a remedial training pen with 1 PF station if their ADFI was less than 2 g or had less than 3 station visits over 2 or more consecutive days. In the remedial training pen, each chick was trained by being placed at the bottom of the ramp and was required to walk through the station to reach the feeder. Chicks were gently guided through each stage and to the feeder by training personnel if they were hesitant or did not travel through the station on their own. The number of chicks in the remedial training pen varied each d (Table 3.2). Chicks were returned to their original pen if their ADFI was greater than 2 g and had more than 2 station visits over 24 h. By d 23 all chicks were successfully trained and returned to their original pens.

3.3.5 Automated Marking System Prototype

A Chemyx Syringe Pump (Fusion 100; Chemyx Inc., Stafford, TX) was incorporated into 1 PF station. The syringe pump had two 60 mL syringes that would release one drop (approximately 0.03 mL) of a dye solution from a fixed position above the feeder onto chicks eating from the feeder. The syringe pump was programmed to release a single drop once a 0.5 g difference was measured at the feeder, and no more than once per 45 s to prevent overly intense marking. The dye solution consisted of a 1:8 dilution of a Sprayolo Long-Lasting Livestock Marker Spray stock solution to water (Sprayolo, MAE Inc., Royal, IA). Green dye was used from d 0 to 10 during training and movement training modes. Blue dye was used from d 11 to 26 during transition and individual feeding modes because it appeared darker on top of the green dye to distinguish which chicks were successfully eating during individual feeding mode. Each chick in the MM treatment was marked manually once per week over the course of the experiment, at least 48 h prior to behaviour observations. The MM chicks were randomly assigned to 1 of 5 marking intensities that reflected the range of intensity seen from the AMS dye markings (Figure 3.2), and were marked with a specific volume of dye solution (Table 3.3). Marking intensity was scored and recorded on an individual chick basis throughout the experiment.

3.3.6 Data Collection

3.3.6.1 BW Gain, ADFI and Station Visits

BW gain, ADFI and station visit frequency were recorded to make decisions during chick training. BW was measured and average daily gain was calculated for each bird from d 0 to 10 (Sartorius Digital Lab Scale, BP4100). Starting on d 11 through d 26 BW and station visit frequency were recorded upon every entry to the PF station. Feed intake was recorded during every meal.

3.3.6.2 Behaviour Data

Six aggressive behaviours were evaluated based on an ethogram described in Table 3.4. Observers were trained prior to the beginning of the experiment to ensure they were able to consistently differentiate the behaviours. Observers were evaluated weekly before each observation session to ensure an inter-observer reliability of at least 90% throughout the experiment. Behaviour observations took place on 7, 9, 14, 16, 19, 21, 23 and 26 d of age. All observation sessions began between 14:00 and 14:30. Each observation session consisted of two 20-minute observation periods. Behaviours were recorded on an individual bird basis, then converted to the frequency of behaviour performed per bird per h. A total of 10 observers took part in behaviour observations each day, with 2 observers being randomly assigned to each pen per period. The order in which pens were observed for each observer was randomized. Observers were positioned on stools (Marius model; IKEA Canada, Burlington, ON) at the back and front of each pen to ensure every part of the pen could be seen. For each period, once observers entered the pen, a 5-minute period was allocated for chick acclimatization to observer presence before behaviour recording began. The total number of aggressive behaviours was calculated from the sum of aggressive pecks, fights, gentle feather pecks, pecks at ID, severe feather pecks and threats.

3.3.6.3 Marking Intensity Score

Each chick's dye marking was compared to a standard range of marking intensities (Figure 3.2) that was used as a guide to score the dye markings on a scale from 0 to 8. The intensity was scored by a single person for consistency. Marking intensity was scored and recorded for chicks (n = 158) on d 3, 4, 5, 7, 8, 9, 12, 13 and 14. CON treatment chicks were given a score of 0 (no dye). Marking intensity was further scored and recorded for AM chicks throughout individual feeding mode from d 15 to 26.

3.3.7 Statistical Analysis

A two-way analysis of variance was performed using the MIXED procedure in SAS (Version 9.4. SAS Institute Inc., Cary, NC, 2016) to determine the effect of treatment and age on marking intensity on d 3, 4, 5, 7, 8, 9, 12, 13 and 14. Age was considered the random effect with individual birds as subjects. To determine the effect of treatment and age on the frequency of aggressive behaviours, a two-way analysis of variance was conducted using the MIXED procedure of SAS (Version 9.4. SAS Institute Inc., Cary, NC, 2016). Pen was the experimental unit (n = 5) and behaviour observations were replicated twice each day. Pen was included in the model as a random effect. Pairwise differences between means were determined with the PDIFF option of the LSMEANS statement, and were reported as different where $P \leq 0.05$. Trends were reported where $0.05 < P \leq 0.10$.

3.4 Results and Discussion

3.4.1 Marking Intensity

Marking intensity depended on treatment and age (Figure 3.3). Marking intensity in the MM treatment was higher on d 3, 4, 5, 7, 8 and 9 compared to the AM treatment (Figure 3.3). Marking intensity did not differ between MM (3.32) and AM (2.80) treatments on d 12. Dye markings in the AM treatment had a higher intensity on d 13 (4.22) and d 14 (3.25) than the MM treatment (2.85 and 1.98, respectively). During individual feeding mode, the AM treatment had the highest average marking intensity on d 26 (6.00), while the lowest marking intensity was on d 19 and 25 (2.92). Chicks in the MM treatment were marked with dye once a week beginning on d 3 according to a randomly assigned marking intensity. Thus each MM chick had dye markings and the treatment as a whole reflected the range of marking intensity scores on days that they were manually marked. Additionally, the dye remained on chicks in the MM treatment over the week until they were manually marked again. In contrast, chicks in the AM treatment were marked with dye when they ate from the station feeder. The AM treatment chicks began to eat from the feeder during transition mode (d 11 to 13) and into individual feeding mode (d 14 to 26). The dye markings became more intense in the AM treatment because the chicks adapted to eating solely from the station feeder on d 13 and 14, and were consequently marked with dye more frequently than the MM treatment chicks.

3.4.2 Aggressive Pecks

The effect of treatment on aggressive pecks depended on the age of the chicks (Table 3.5). On d 26 the AM treatment performed more aggressive pecks (12.9) than the MM (3.12) and CON (0.91) treatments (Figure 3.4). During individual feeding mode, the AM treatment was given the highest marking intensity score on d 26 (Figure 3.3). By d 26 chicks had begun to develop their chick plumage (Leeson and Walsh, 2004). The matured feathers absorbed the dye more than the immature chick plumage. Consequently, mark intensity was greater on the white feathers which, as a novel item, may have promoted pecking (Figure 3.5). Dennis et al. (2008) similarly gave birds a black artificial mark. It was reported that the increased rate of aggressive pecks directed at the marked birds was promoted by the novelty of the mark. Additionally, by d 26 all AM chicks were eating individually from the PF station meaning the AMS precisely dropped dye on the neck and head while chicks were eating from the feeder, which may have led to pecking directed at those specific areas. Thus, the AMS should not be used as an identification method beyond the age at which chicks begin to develop their white chick plumage.

Aggression is reported to increase with stocking density in poultry species (Estevez et al., 2007). In the current study, the frequency of aggressive pecks performed by the AM treatment many have been influenced by a greater stocking density (6.25 chicks per m^2) compared to the CON and MM treatments (approximately 3.23 chicks per m^2). However, it is unknown if stocking density effects aggression among broiler breeder chicks.

3.4.3 Feather Pecks

Overall, the MM and CON treatments performed 6.3 and 5.3 times more gentle feather pecks than AM chicks, respectively (Table 3.5). Gentle feather pecks tended to increase from d 7 to 19 (Table 3.5). There was no effect of age or treatment on the frequency of severe feather pecks (Table 3.5). On d 23 there was a noticeable increase of gentle feather pecks in the MM and CON treatment groups. Anecdotally, birds in the AM treatment performed more gentle feather pecks after the experiment ended. The lower frequency of gentle feather pecks performed by the AM treatment may have been due to the larger group size (n = 52) in comparison to the other pens holding the MM and CON treatments (n = 26 or 27 chicks per pen). Campderrich et al.

(2017) reported at a fixed stocking density of 8 birds per m^2, pullets in a small group size (n =10) performed a higher frequency of exploratory pecks in comparison to pullets in a large group size (n = 40). Estevez et al. (2007) suggested that a large group size may limit bird movements to specific areas within a given space. In turn, those birds would develop a stable hierarchy resulting in less aggressive pecking and more exploratory pecking. Stocking densities greater than 12 birds per m^2 are associated with a higher incidence of gentle feather pecking (Zimmerman et al., 2006; Nicol et al., 2013), however these results were reported beyond 21 d of age. The current study followed recommended stocking densities according to Aviagen (2016), however the AM treatment housed at a stocking density of 6.25 chicks per m^2 performed fewer gentle feather pecks than the MM and CON treatments housed at a lower stocking density (approximately 3.23 chicks per m^2).

Gentle feather pecks are commonly defined as an exploratory behaviour performed as early as right after hatch and throughout the rearing phase, while severe feather pecking resulting in feather loss and injuries often occurs once hens come into lay and their adult plumage is fully developed (Riedstra and Groothuis, 2002; Nicol et al., 2013). In the current study, a behaviour diagnosed as feather licking directed at the wings and tail was observed among all treatment groups after the current study period. Feather licking is defined as oral repetitive preening, and in addition to feather pecking has been reported to develop into stereotypic preening unto oneself or directed at others (Arrazola et al., in press). Feather licking and feather pecking are common in broiler breeder flocks, and may be influenced by genetics, age, a lack of protein, salt and sulphur amino acids as a result of feed restriction, or from a change in the environment such as temperature, high light intensity, low humidity (Leeson and Walsh, 2004; Nicol et al., 2013). In the current study these aspects of the environment were controlled among the 3 chambers and are therefore unlikely to have caused differences in feather pecking and feather licking rates.

3.4.4 Total Aggressive Behaviours

The frequency of total aggressive behaviours was greater on d 26 compared to d 7 and 9 (Table 3.5). This was due to the large contribution of aggressive pecks performed by the AM treatment on d 26 that may have been influenced by the high intensity of dye markings at that time (Figure 3.3). Gentle feather pecking tended to increase with age which may have also contributed to the higher frequency of total aggressive behaviours on d 26 (Table 3.5). The overall frequency of total aggressive behaviours in the MM treatment was 3.5 times greater than in the AM treatment, which did not differ from the CON treatment (Table 3.5). This difference was due to the high frequency of gentle feather pecks observed in the MM and CON treatments compared to the AM treatment. To prevent intense dye markings that could contribute toward the frequency of total aggressive behaviours, the AMS should not be used as an identification method in a PF system beyond 21 d of age.

3.4.5 Fights, Pecks at ID and Threats

There were no age or treatment effects on frequencies of fights, pecks at ID and threat behaviours (Table 3.5). In poultry species, the purpose of aggressive encounters such as fights and threats is to establish a dominance hierarchy (Estevez et al., 2002). However this hierarchy is typically not formed until 6 to 12 wk of age in domestic fowl, or until 7 wk of age in male broiler breeder flocks (Mench, 1988; Shea et al., 1990). Feed restriction, feeding motivation and mating are additional factors that stimulate fights and threats within broiler breeder flocks, but occur beyond the first 21 d of life (Mench, 1988; Girard et al., 2017; de Jong and Guémené, 2011). The current study suggests fights and threats are less common among broiler breeder chicks, but rather observed at an older age beyond the time that the AMS would be used as an identification method in a PF system.

3.5 Conclusions and Applications

1. Dye markings from the AMS did not increase frequencies of aggressive behaviours from 0 to 21 d of age.
2. The frequency of aggressive pecks in the AM treatment increased on d 26, which may have been due to development of white chick plumage and the intense appearance of dye markings on the chicks' head and neck.
3. The AMS should not be used in PF stations beyond the first 21 d of the training period to avoid stimulating aggressive behaviours.

3.6 Acknowledgements

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3.7 References

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2020. The effect of alternative feeding strategies during rearing on the behaviour of broiler breeder pullets. Appl. Anim. Behav. Sci. 224:104929.

Aviagen, 2016. Parent Stock Performance Objectives. Aviagen, Huntsville, AL.

Campderrich, I., G. Liste, and I. Estevez. 2017. Group size and phenotypic appearance: Their role on the social dynamics in pullets. Appl. Anim. Behav. Sci. 189:41–48.

Canadian Council on Animal Care. 2009. CCAC guidelines on: The care and use of farm animals in research, teaching, and testing. Canadian Council on Animal Care, Ottawa, ON.

Council Directive. 1998. No. 98/58/EC. Concerning the protection of animals kept for farming purposes. Official journal L221, p. 23. Amended as council regulation (EC) No. 806/2003 Apr. 14, 2003. Official journal L122, p. 1.

Dalton, H. A., B. J. Wood, T. M. Widowski, M. T. Guerin, and S. Torrey. 2018. Comparing the behavioural organization of head pecking, severe feather pecking, and gentle feather pecking in domestic turkeys. Appl. Anim. Behav. Sci. 204:66–71.

de Jong, I. C., and D. Guémené. 2011. Major issues in broiler breeders. Worlds Poult. Sci. J. 76:73–82.

Dennis, R. L., R. C. Newberry, H. W. Cheng, and I. Estevez. 2008. Appearance matters: Artificial marking alters aggression and stress. Poult. Sci. 87:1939–1946.

Estevez, I., I. L. Andersen, and E. Nævdal. 2007. Group size, density and social dynamics in farm animals. Appl. Anim. Behav. Sci. 103:185–204.

Estevez, I., L. J. Keeling, and R. C. Newberry. 2003. Decreasing aggression with increasing group size in young domestic fowl. Appl. Anim. Behav. Sci. 84:213–218.

Estevez, I., R. C. Newberry, and L. J. Keeling. 2002. Dynamics of aggression in the domestic fowl. Appl. Anim. Behav. Sci. 76:307–325.

Girard, T. E., M. J. Zuidhof, and C. J. Bench. 2017. Aggression and social rank fluctuations in precision-fed and skip-a-day broiler breeder pullets. Appl. Anim. Behav. Sci. 187:38–44.

Hocking, P. M. 2004. Roles of body weight and feed intake in ovarian follicular dynamics in broiler breeders at the onset of lay and after a forced molt. Poult. Sci. 83:2044–2050.

Leeson, S., and T. Walsh. 2004. Feather in commercial poultry. 2. Factors influencing feather growth and feather loss. Worlds Poult. Sci. J. 60:52–63.

Mench, J. A. 1988. The development of aggressive behavior in male broiler chicks: A comparison with laying-type males and the effects of feed restriction. Appl. Anim. Behav. Sci. 21:233–242.

Mench, J. A. 2002. Broiler breeders: Feed restriction and welfare. Worlds Poult. Sci. J. 58:23–29.

Nicol, C. J., M. Bestman, A. M. Gilani, E. N. de Haas, I. C. de Jong, S. Lambton, J. P. Wagenaar, C. A. Weeks, and T. B. Rodenburg. 2013. The prevention and control of feather pecking: Application to commercial systems. Worlds Poult. Sci. J. 69:775–788.

Nicol, C. J., N. G. Gregory, T. G. Knowles, I. D. Parkman, and L. J. Wilkins. 1999. Differential effects of increased stocking density, mediated by increased flock size, on feather pecking and aggression in laying hens. Appl. Anim. Behav. Sci. 65:137–152.

Renema, R. A., F. E. Robinson, P. R. Goerzen, and M. J. Zuidhof. 2001. Effects of altering growth curve and age at photostimulation in female broiler breeders. 2. Egg production parameters. Can. J. Anim. Sci. 81:477–486.

Renema, R. A., M. E. Rustad, and F. E. Robinson. 2007. Implications of changes to commercial broiler and broiler breeder body weight targets over the past 30 years. Worlds Poult. Sci. J. 63:457–472.

Riedstra, B., and T. G. G. Groothuis. 2002. Early feather pecking as a form of social exploration: The effect of group stability on feather pecking and tonic immobility in domestic chicks. Appl. Anim. Behav. Sci. 77:127–138.

Shea, M. M., J. A. Mench., and O. P. Thomas. 1990. The effect of dietary tryptophan on aggressive behavior in developing and mature broiler breeder males. Poult. Sci. 69:1664–

1669.

The Welfare of Farmed Animals (England) Regulations. 2007. No. 2078 in general conditions under which farmed animals must be kept in feed, water and other substances. Accessed on Mar. 20, 2020. http://www.legislation.gov.uk/uksi/2007/2078/schedule/1/made.

The Welfare of Farmed Animals (Wales) Regulations. 2007. No. 3070 in general conditions under which farmed animals must be bred or kept in feed, water and other substances. Accessed on Mar. 20, 2020. http://www.legislation.gov.uk/wsi/2007/3070/made.

The Welfare of Farmed Animals (Scotland) Regulations. 2010. No. 388 in general conditions under which farmed animals must be bred kept. Accessed on Mar. 20, 2020. http://www.legislation.gov.uk/ssi/2010/388/schedule/1/made.

The Welfare of Farmed Animals Regulations (North Ireland). 2012. No. 156 in general conditions under which farmed animals must be kept. Accessed on Mar. 20, 2020. https://www.legislation.gov.uk/nidsr/2012/9780337986475/schedule/1.

Tolkamp, B. J., and R. B. D'Eath. 2016. Hunger associated with restricted feeding systems. Pages 11–27 in Nutrition and the Welfare of Farm Animals. Phillips, C. J. C., ed. Springer, Switzerland.

USDA, 2020. USDA, Economic Research Service. Food availability (per capita) data system: Poultry (chicken and turkey). Accessed Jan. 23, 2020. https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/.

van der Klein, S. A. S., G. Y. Bédécarrats, F. E. Robinson, and M. J. Zuidhof. 2018a. Early photostimulation at the recommended body weight reduced broiler breeder performance. Poult. Sci. 97:3736–3745.

van der Klein, S. A. S., G. Y. Bédécarrats, and M. J. Zuidhof. 2018b. The effect of rearing photoperiod on broiler breeder reproductive performance depended on body weight. Poult. Sci. 97:3286–3294.

Zimmerman, P. H., A. C. Lindberg, S. J. Pope, E. Glen, J. E. Bolhuis, and C. J. Nicol. 2006. The effect of stocking density, flock size and modified management on laying hen behaviour and welfare in a non-cage system. Appl. Anim. Behav. Sci. 101:111–124.

Zuidhof, M. J. 2018. Lifetime productivity of conventionally and precision-fed broiler breeders. Poult. Sci. 97:3921–3937.

Zuidhof, M. J., M. V. Fedorak, C. C. Kirchen, E. H. M. Lou, C. A. Ouellette, and I. I. Wenger. 2019. System and method for feeding animals. PrecisionZX, Inc., assignee. US Pat. No. 10,506,793.

Zuidhof, M. J., M. V. Fedorak, C. A. Ouellette, and I. I. Wenger. 2017. Precision feeding: Innovative management of broiler breeder feed intake and flock uniformity. Poult. Sci. 96:2254–2263.

Zuidhof, M. J., B. L. Schneider, V. L. Carney, D. R. Korver, and F. E. Robinson. 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. Poult. Sci. 93:2970–2982.

3.8 Tables

Table 3.1 Precision feeding station activity during the 4 software modes implemented during the training period.[1]

	Training mode	Movement training mode	Transition mode	Individual feeding mode
Duration (age)	0 to 6 d	7 to 10 d	11 to 13 d	14 to 26 d
Supplemental feed	Yes	Yes	No	No
Group access to feed	Yes	Yes	Yes	No
Individual access to feeder	No	No	Yes	Yes
Entry door movement	No	Yes	Yes	Yes
Ejection door movement	No	Yes	Yes	Yes
RFID reader activated	No	No	Yes	Yes
Individual BW recorded	No	No	Yes	Yes

[1] Adapted from Zuidhof (2018).

Table 3.2 Number of chicks in the remedial training pen from d 12 to 22.

Age (d)	Number of chicks
12	11
13	11
14	7
15	9
16	4
17	5
18	4
19	5
20	3
21	4
22	2

Table 3.3 Five marking intensities and respective volume of dye solution manually applied on each chick in the MM treatment group. The dye solution was applied to the back of the head and neck area with a syringe.

Marking intensity	Volume (mL)
0	0.0
2	0.4
4	0.8
6	1.2
8	1.6

Table 3.4 Ethogram of the 6 aggressive behaviours evaluated during behaviour observations.

Behaviour	Definition[1]
Aggressive peck	A rapid and forceful thrusting motion in which the beak of one bird makes contact with the head or neck of another bird.
Gentle feather peck	The beak of one bird makes contact with the feathers or skin on the back, wings, tail, or other region of another bird in an exploratory manner, without causing the recipient bird to move away.
Severe feather peck	A thrusting motion of the beak of one bird that makes contact with the plumage of another bird, causing the recipient to move away, and/or resulting in vigorous pulling or removal of feathers or skin.
Peck at ID	A thrusting motion of the beak of one bird that makes contact with the identification tag of another bird.
Fight	Face-to-face encounter in which both birds attempt to or successfully peck at the head or neck of the other bird.
Threat	A bird faces another bird in an elevated position, looking downwards onto another bird while remaining still.

[1] Adapted from Nicol et al., 1999; Girard et al., 2017; Dalton et al., 2018.

Table 3.5 Mean frequencies of the aggressive behaviours according to age, treatment[1] and age by treatment effects.

Effect	Age (d)	Treatment	Aggressive pecks	Fights	Gentle feather pecks	Pecks at ID	Severe feather pecks	Threats	Total aggressive behaviors[2]
			/bird·h						
Age (A)	7		1.06^{b}	-	1.36	0.55	0.26	0.05	3.28^{b}
	9		1.32^{b}	0.02	0.99	0.14	-	0.05	2.51^{b}
	14		0.66^{b}	0.01	7.05	0.22	0.44	0.02	8.40^{ab}
	16		1.32^{b}	0.02	7.76	0.02	1.06	0.03	10.20^{ab}
	19		1.67^{b}	0.01	19.90	0.37	6.17	0.04	28.10^{ab}
	21		3.19^{ab}	-	18.80	0.48	3.83	0.02	26.30^{ab}
	23		1.31^{b}	-	19.40	0.60	5.11	0.05	26.50^{ab}
	26		5.64^{a}	0.01	19.70	0.48	10.80	0.04	36.70^{a}
SEM			0.71	0.01	4.70	0.32	2.90	0.03	6.40
Treatment (T)		CON	1.01^{b}	0.01	14.90^{a}	0.42	3.89	0.04	20.30^{ab}
		MM	2.01^{ab}	0.01	17.80^{a}	0.40	5.36	0.04	25.70^{a}
		AM	3.04^{a}	0.01	2.82^{b}	0.26	1.15	0.03	7.32^{b}
SEM			0.46	0.01	2.91	0.20	1.76	0.02	4.00
Source of variation			Probability						
A			0.024	0.76	0.072*	0.90	0.26	0.98	0.026
T			0.034	0.90	0.006	0.84	0.24	0.97	0.020
A x T			0.031	0.83	0.93	0.90	0.79	0.85	0.92

[a, b] Means within columns with no common superscript differ significantly ($P < 0.05$).
Asterisk indicates a trend within column and row ($0.05 < P \leq 0.10$).
[1] The treatments: control (CON), manual marking (MM) and automatic marking (AM).
[2] The sum of aggressive pecks, fights, gentle feather pecks, pecks at ID, severe feather pecks and threats.

3.9 Figures

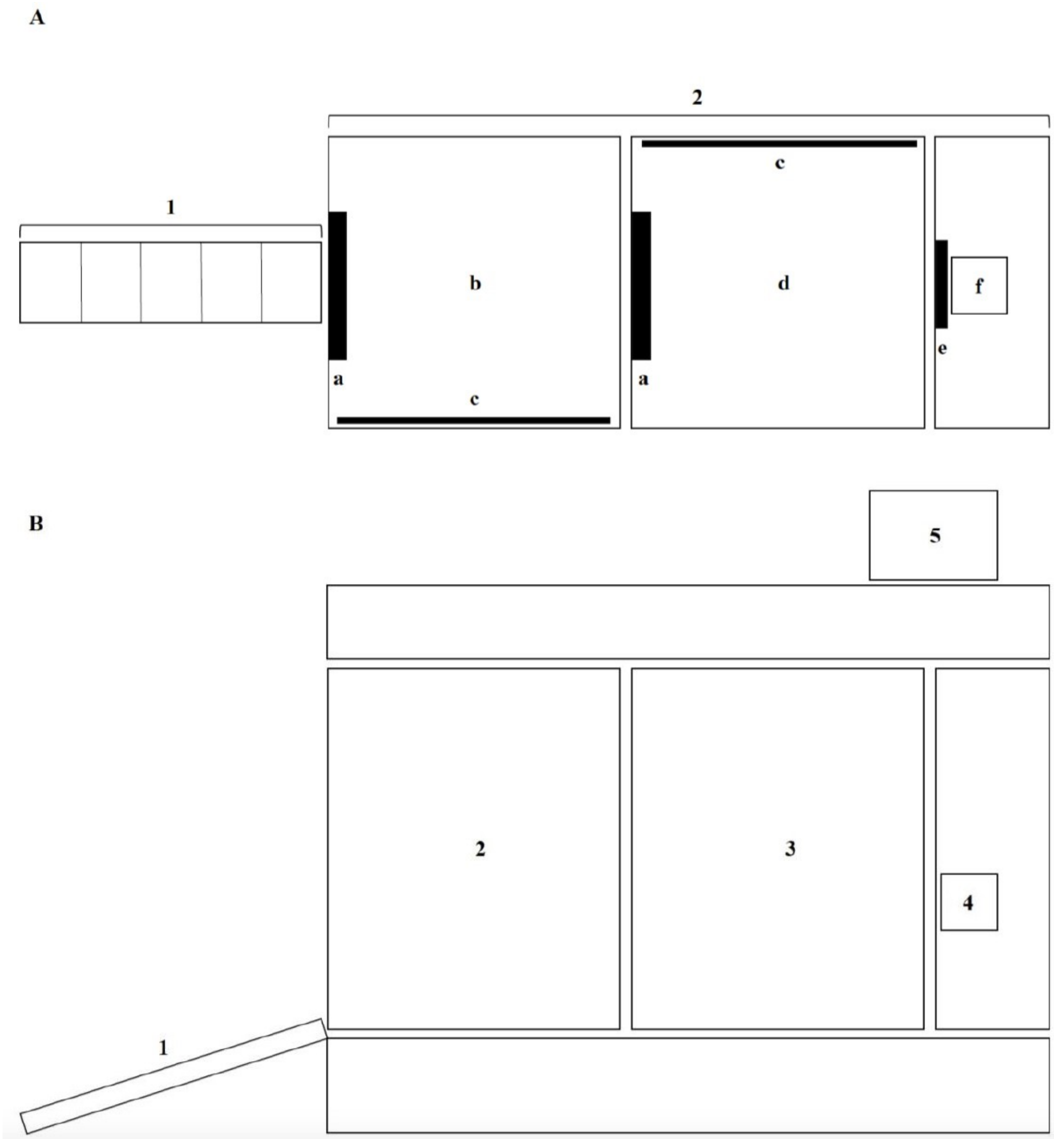

Figure 3.1 Top view (A) of a precision feeding station. After entering the station on the ramp (1) through the entry door (2a), each chick was weighed and identified in the sorting stage (2b). If the chick's live BW was greater than the target BW, it was ejected from the sorting stage by an ejector panel (2c). If the chick's BW was below the target BW, the second entry door opened giving access to the feeding stage (2d). The feed cover (2e) opened once a chick entered the feeding stage, which gave access to the feeder (f). Chicks are ejected from the feeding stage once the 60 s feeding bout is complete. Side view (B) of a precision feeding station. A bird walks up the ramp (1) through the sorting stage (2) and feeding stage (3) to reach the feeder (4). A hopper (5) is located on top of the station. An auger turns pushing the feed down a long tube located directly above the feeder.

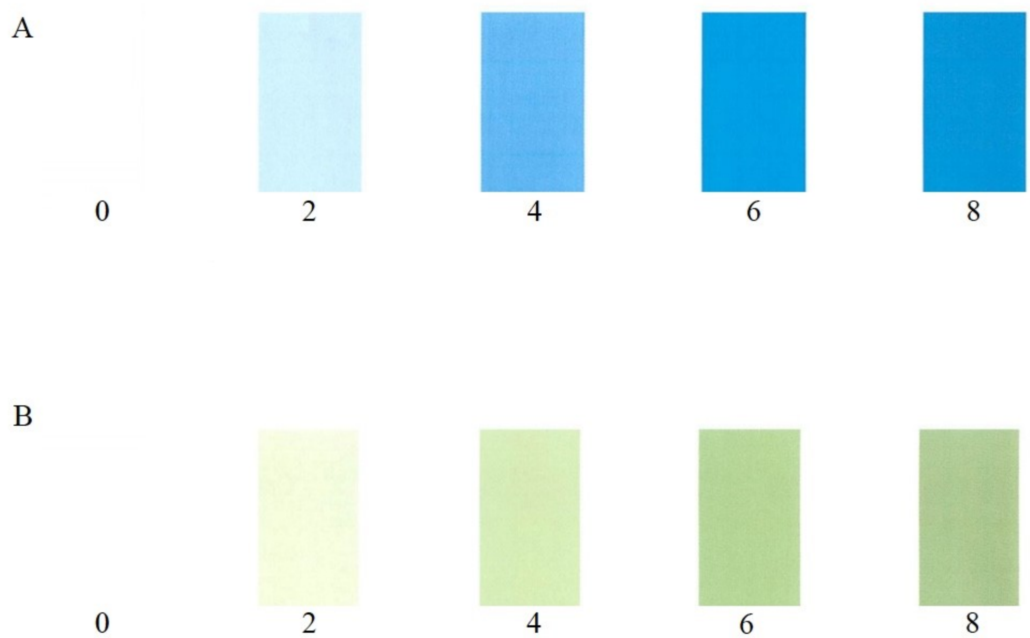

Figure 3.2 Range of marking intensity for blue (A) and green (B) dye. The intensity ranged from 0 being a lack of intensity from no dye to 8 being the most intense. An intensity of 0, 2, 4, 6 or 8 was randomly assigned to the manual marking (MM) chicks. Dye markings of each chick were given an intensity score based on a scale from 0 to 8.

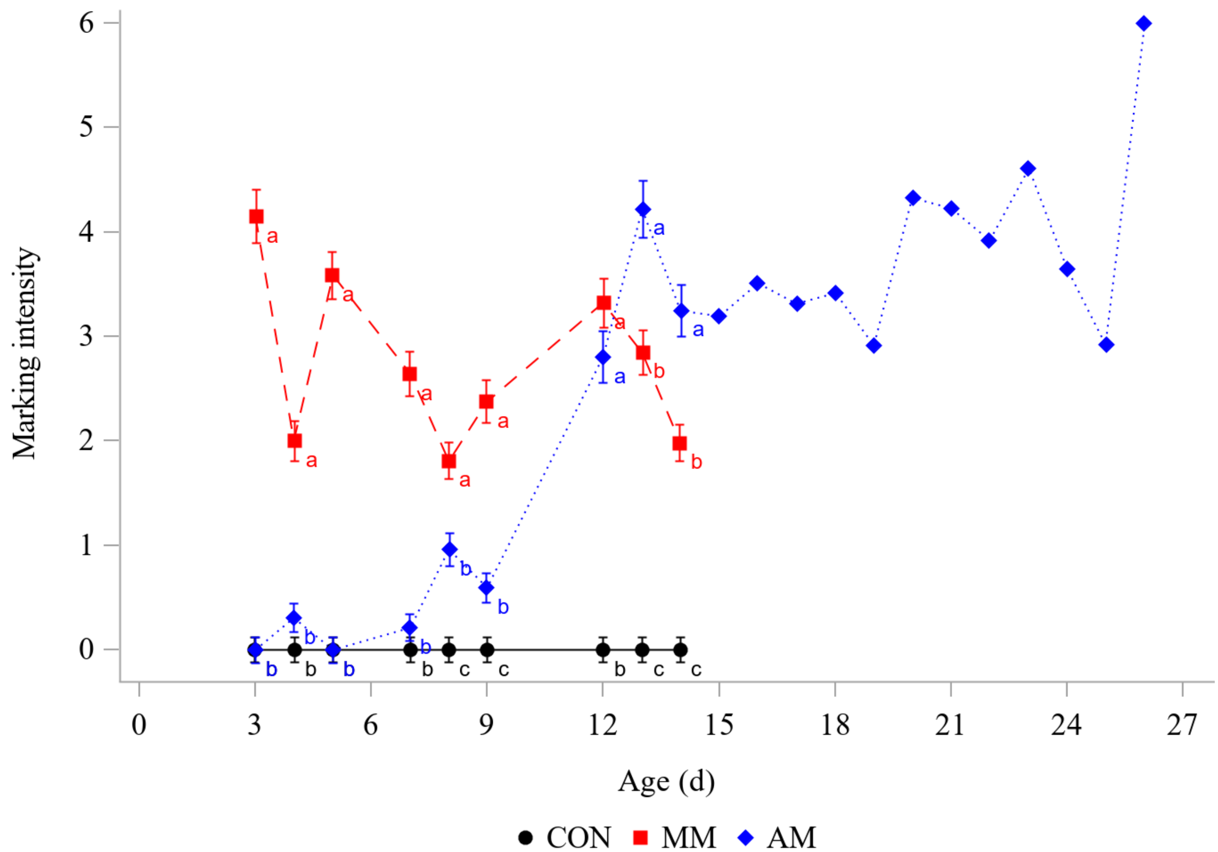

Figure 3.3 Average marking intensity for control (CON), manual marking (MM) and automatic marking (AM) treatments. Chicks in all treatments were scored on d 3, 4, 5, 7, 8, 9, 12, 13 and 14 ($P < 0.001$). Marking intensity was scored during individual feeding mode from d 15 to 26 for the AM treatment. [a, b, c] Means within age with no common superscript differ significantly ($P < 0.05$).

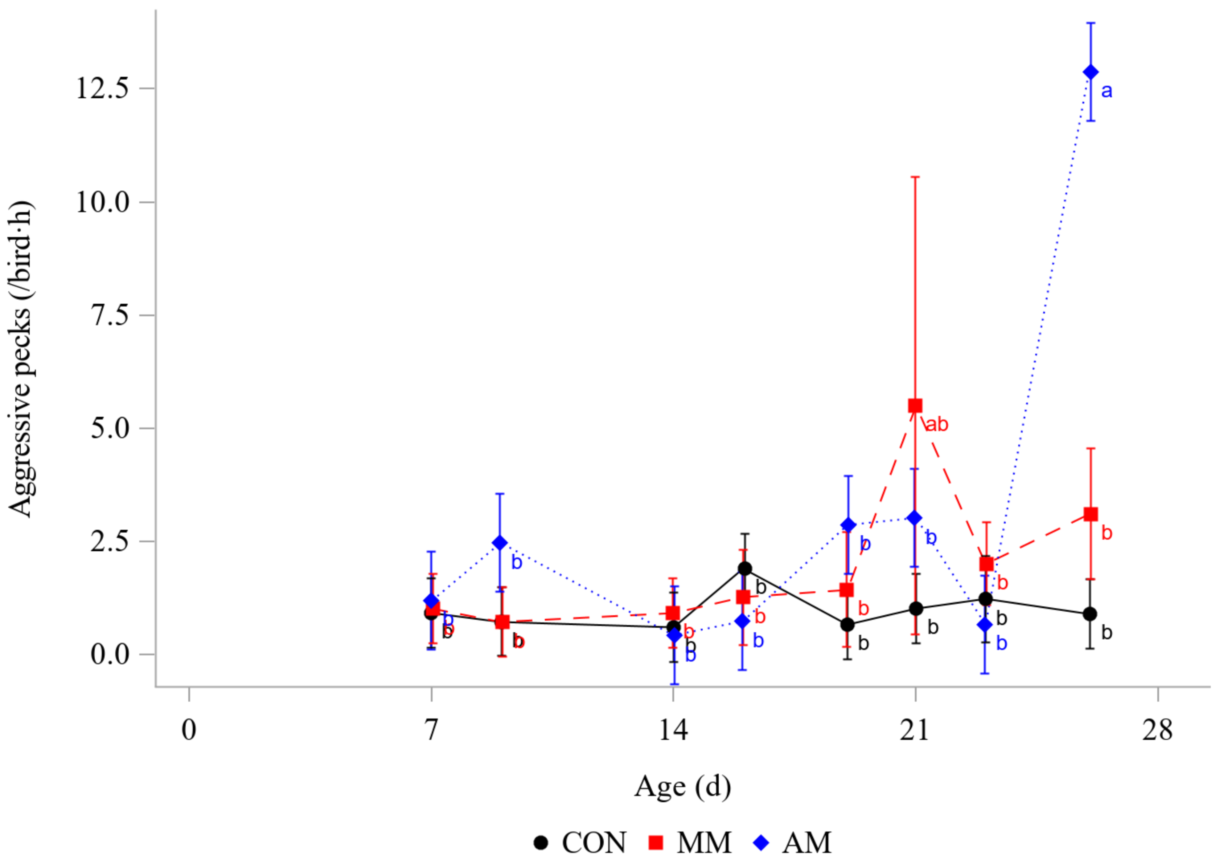

Figure 3.4 Mean frequencies of aggressive pecks by age for control (CON), manual marking (MM) and automatic marking (AM) treatments groups (P = 0.031, SEM = 1.12). [a, b] means within age and treatment with no common superscript differ significantly (P < 0.05).

Figure 3.5 Example of dye markings on a chick that has maturing white chick plumage (left) and a chick that has immature yellow chick plumage (right) at 26 d of age.

4.0 Chapter 4: Feeding, Feed Seeking Behaviour and Reproductive Performance of Broiler Breeders under Conditions of Relaxed Feed Restriction

4.1 Abstract

Broiler breeders are feed restricted to optimize reproductive performance. A randomized controlled study was conducted to investigate the effect of increasing female broiler breeder body weight (**BW**) on feeding, feed seeking behaviour and reproductive performance. It was hypothesized that a greater BW would decrease feeding and feed seeking behaviour, and reduce reproductive performance. Ross 708 female broiler breeders (n = 36) were fed using a precision feeding (**PF**) system from 2 to 42 wk of age. Ten BW trajectories were created from a multiphasic Gompertz growth model that increased growth from 0 to 22.5% in the pre-pubertal and pubertal phases of growth, in 2.5% increments. Six unrestricted birds were not limited to a maximum BW. Body weight was evaluated as a 2-way ANOVA. Two linear regression analyses were conducted, one which included all birds, and one which excluded the unrestricted birds. For the regression analyses, BW at photostimulation (22 wk of age) was used as the continuous independent variable to represent the degree of variation between trajectories. Differences were reported at $P \leq 0.05$. Body weight increased as trajectory-specific BW targets increased from 6 to 28 wk of age. Differences of BW between BW trajectories decreased during the laying period, which was a result of individual bird variation within BW trajectories. Station visit frequency decreased per kilogram increase in BW for all birds during rearing and lay, and within feed restricted birds during lay only. The number of meals and average daily feed intake (**ADFI**) increased with age, which reflected nutrient intake to support maintenance, growth and reproductive requirements. Mean egg weight (**EW**) of all birds increased by 0.72 g per kilogram increase in BW from 22 to 41 wk of age. From 22 to 29 wk of age, mean EW of feed restricted

birds increased by 2.78 g per kilogram increased in BW. For every kilogram increase in BW, age at first egg comparing all birds decreased by 10.83 d. Two unrestricted birds came into lay prior to photostimulation. In contrast with the hypotheses, BW increased up to 22.5% above the recommended target did not reduce feeding and feed seeking behaviour, or negatively impact reproductive performance.

Key words: precision livestock feeding, body weight, hunger, unrestricted feed intake, sexual maturity

4.2 Introduction

Broiler breeders are feed restricted to control body weight (**BW**) throughout their life cycle. In particular, broiler breeders have been restricted 25 to 50% less feed than what unrestricted birds would consume on a daily basis (Rosales, 1994; Renema et al., 2007). As a result, broiler breeders experience chronic hunger and concomitant feeding frustration that have been identified through behavioural assessments (Savory and Maros, 1993; Hocking et al., 2002; Merlet et al., 2005) and physiological parameters (Hocking et al., 1996; de Jong et al., 2002). As such, feed restriction clearly leads to poor welfare. However, unrestricted feed intake can lead to health issues related to rapid growth and obesity, which is also considered to be a welfare issue. This reiterates the paradox described by Decuypere et al. (2010) that feed restriction is required as part of broiler breeder management to optimize reproduction, but to also avoid metabolic disorders and mortality.

In the past, feed restriction has been considered crucial during rearing to optimize reproductive performance and reduce health problems (reviewed by de Jong and Guémené, 2011 and D'Eath et al., 2009). Specifically, unrestricted feed intake has advanced sexual maturity and reduced egg production (Robinson et al., 1991; Bruggeman et al., 1999; Heck et al., 2004), and obesity-related lameness and death. Recent literature reported that broiler breeders reared to be 9.1% above the recommended BW target had similar egg production compared to restricted broiler breeders (van Emous et al., 2013). Moreover, cumulative egg production was 39% greater for precision-fed broiler breeders reared 22% above the recommended BW target than broiler breeders reared on a standard BW curve (van der Klein et al., 2018a). This suggests there is potential to increase broiler breeder BW targets without negatively affecting reproductive performance. In turn, the degree of feed restriction may be able to be relaxed to address chronic hunger and improve bird welfare.

A sequential precision feeding (**PF**) system has been created to control individual bird feed intake based on live BW (Zuidhof et al., 2019). This PF system provides birds with multiple meals of short duration throughout the day to achieve predetermined BW targets. To date, the PF system has been used to investigate feeding and feed seeking behaviours (Girard et al., 2017; Zuidhof et al. 2017), and to precisely implement BW curves to explore the effect of various degrees of relaxed feed restriction on broiler breeder growth and reproductive performance (van der Klein et al., 2018a, 2018b; Hadinia et al., 2019; Zuidhof, 2018). Girard et al. (2017) assessed hunger through feeding and feed seeking behaviours of conventionally skip-a-day and PF fed broiler breeder pullets. The authors reported that precision-fed broiler breeders demonstrated less feather pecking but more object pecking than did skip-a-day-fed birds. Thus, multiple meals throughout the day did not eliminate hunger. Recent studies have demonstrated precision-fed hens reared according to recommended BW trajectories produced 27 and 10.3% less eggs than daily-fed pullets (Zuidhof, 2018; Hadinia et al., 2019). Zuidhof et al. (2018) hypothesized that increased meal frequency of PF pullets might not provide a sufficient amount of nutrients for carcass fat deposition to support egg production. It was suggested that broiler breeder feed restriction could be relaxed during rearing, particularly when using a PF system, to increase nutrient intake prior to sexual maturity and increase egg production.

The objective of the current study was to implement a variety of BW trajectories using a PF system to evaluate the effect of varying degrees of relaxed feed restriction on feeding, feed seeking behaviour and reproductive performance of broiler breeders. It was hypothesized that increased BW (lesser degree of feed restriction) would decrease station visit frequency and meal size due to reduced hunger, while average daily feed intake (**ADFI**) and meal frequency would increase because birds would be fed more to achieve greater BW targets. It was also hypothesized that egg weight (**EW**) would increase, age at first egg (**AFE**) would advance, and egg production would decrease with increased BW.

4.3 Materials and Methods

The animal protocol for the study was approved by the University of Alberta Animal Care and Use Committee for Livestock and followed principles established by the Canadian Council on Animal Care Guidelines and Policies (CCAC, 2009).

4.3.1 Experimental Design

The study was a completely randomized controlled study with 10 unique BW trajectories that were applied from 2 to 42 wk of age using a PF system. The trajectories were created from a 3-phase Gompertz growth model that manipulated the first 2 phases (pre-pubertal and pubertal) of growth. In the current study, the recommended Ross 708 BW curve (Aviagen, 2016a) was fit to the model to estimate pre-pubertal and pubertal growth. Trajectories differed in 2.5% increment increases of target BW gain during both the pre-pubertal and pubertal growth phases, which started from the Ross 708 recommended BW trajectory (CON) up to 22.5% above the recommended BW trajectory (CON+2.5%, CON+5%, CON+7.5%, CON+10%, CON+12.5%, CON+15%, CON+17.5%, CON+20% and CON+22.5%). The degree of feed restriction was relaxed to allow birds to reach increased BW targets. Three female broiler breeders were randomly assigned to each BW trajectory and 6 additional females were assigned to an unrestricted group, meaning they were fed ad libitum (not limited to a maximum BW and were given access to a meal upon every PF station visit). Each bird was considered to be an experimental unit.

4.3.2 Stocks and Management

Ross 708 broiler breeder pullets (n = 36) were reared in a single chamber with Ross Yield Plus males (n = 8) with a stocking rate of 3.16 birds per m^2. Males followed the Ross Yield Plus BW target (Aviagen, 2016b). All birds had access to 2 PF stations 24 h per day and ad libitum access to water throughout the experiment. On d 7, a wing tag with a radio frequency identification (**RFID**) transponder was applied to the right wing web for individual identification in the PF stations. Birds were fed commercial diets as follows: a poultry starter crumble from wk 0 to 5 (2,762 kcal ME, 21% CP, and 0.99% Ca), a broiler breeder grower mash from wk 6 to 26 (2,799 kcal ME, 15% CP, and 0.79% Ca), and a broiler breeder layer diet from wk 26 to 46 (2,798 kcal ME, 15% CP, and 3.40% Ca). The photoschedule was 24L:0D (100 lx) from d 0 to 3 then reduced to 8L:16D (15 lx) on d 4. Light intensity was reduced to 5 lx on d 26 until wk 21 in attempt to reduce feather pecking. Hens were photostimulated at wk 22 as the photoperiod was increased to 11L:13D (20 lx). The photoperiod increased to 12L:12D (25 lx) on wk 23, then again at wk 24 to 13L:11D (50 lx) for the remainder of the experiment. Each PF station had 5 green LED lights (2 lx) that illuminated the station so that birds could see their way through the station during hours of darkness, without causing photorefractoriness (Rodriguez, 2017). Temperature was set at 34.5°C on d 0 and decreased 0.5°C/d until d 22, after which it remained constant at 23.5°C. A single RFID-equipped nest box (8 nesting sites) and trap nest box (10 nesting sites) were introduced to the chamber at 14 wk of age so that pullets could familiarize themselves with the nests prior to the onset of lay. Each RFID nesting site was equipped with an RFID reader which identified a hen with each egg that was laid.

4.3.3 Precision Feeding System

The design and operation details of the PF system and individual stations have been more fully described elsewhere (Zuidhof et al., 2019). Briefly, the PF system fed birds individually based on live BW measurements compared to a target BW within the system software. Individual birds were recognized in the system through a unique RFID transponder. Each PF station consisted of a sorting and feeding stage. The sorting stage isolated each bird and recorded its live BW upon entry when a decision was made: if the bird's live BW was greater than its programmed target BW, the bird was gently ejected from the station without access to a meal. If the bird's live BW was less than its programmed target BW, it was given access to feed in the feeding stage for 60 s. The BW trajectories of feed restricted birds were automatically updated within the system software hourly.

4.3.4 Data Collection

Collection and recording of BW, station visit frequency, feed intake, number of meals and meal size data has been fully described by Zuidhof et al. (2017). Briefly, BW was recorded within the PF system software upon entry into the station. Station visit frequency, ADFI, the number of meals and meal size were derived from records in the PF system database. Data collection began on wk 2 to align with the time that individual feeding from the PF stations was fully implemented. Body weight was evaluated in 2 wk periods from 2 to 42 wk of age. Feeding and feed seeking behaviours and EW were evaluated in ten 4-wk periods: 2 to 5, 6 to 9, 10 to 13, 14 to 17, 18 to 21, 22 to 25, 26 to 29, 30 to 33, 34 to 37, and 38 to 41 wk of age. Floor eggs were found beginning at 20 wk of age, and were assumed to be produced by unrestricted hens due to their high BW which could have advanced sexual maturation (Heck et al., 2004; Renema and Robinson, 2004). To ensure a precise estimate of AFE, the cloaca of each unrestricted hen was palpated daily to detect the presence or absence of a hard-shell egg in the shell gland from wk 20 to 22. Thus, all floor eggs were appropriately identified to individual unrestricted hens. The cloaca of all hens were palpated daily from wk 22 to 35. Eggs were collected, weighed and assigned to individual hens daily.

4.3.5 Statistical Analysis

Body weight was evaluated as a 2-way ANOVA using the MIXED procedure in SAS (Version 9.4. SAS Institute Inc., Cary, NC, 2016) with BW trajectory and time period as the fixed effects. Because of model convergence issues, the rearing and laying phases were analyzed independently. Age was included in the model as a random effect with individual bird as the subject to account for within-bird variation. Two linear regression analyses were conducted using the REG procedure of SAS (Version 9.4. SAS Institute Inc., Cary, NC, 2016) to determine the relationship of BW at photostimulation with feeding and feed seeking behaviours, EW, AFE and cumulative egg production. Body weight at photostimulation was used as a continuous independent variable that served as a proxy for the various degrees of separation of BW trajectories throughout rearing. The first regression analysis included all birds (feed restricted and unrestricted birds), while the second analysis included feed restricted birds (excluded unrestricted birds) to determine the effects of BW at photostimulation within feed restricted birds only. Feeding and feed seeking behaviours and EW were evaluated independently for each period from 2 to 42 wk of age. All means were adjusted using Tukey's pairwise comparisons to estimate significance of difference between least squares means. Differences were reported where $P \leq 0.05$. Trends were reported where $0.05 < P \leq 0.10$.

4.4 Results and Discussion

A total of 5 birds were culled during the study: a bird from each of the CON+10%, CON+17.5%, and unrestricted groups at 35, 14, 24 wk of age, respectively, and 2 birds from the CON+22.5% group at 35 and 36 wk of age.

4.4.1 Body Weight

Body weight was similar across BW trajectories at 2 and 4 wk of age (Table 4.1). Precision-fed chicks underwent training during the first 2 to 3 wk of life as they learn how to move through and eat from the PF stations. The majority of chicks were eating individually from the station feeder by 2 wk of age, however, some chicks required additional training to learn how to successfully eat from the feeder. Thus, BW was similar across BW trajectories because not all birds reached their trajectory-specific BW during the training period.

As designed, BW increased from 6 to 20 wk of age as trajectory-specific BW targets increased ($P < 0.001$, Table 4.1). Similarly at photostimulation (22 wk of age), there was a clear effect of BW trajectory on BW ($P < 0.001$, Table 4.1), and differences in BW between BW trajectories increased concomitantly with BW targets (Figure 4.1). In particular, the unrestricted birds weighed 2,007 ± 59.1 g more than the CON birds at photostimulation. During the onset of lay, BW of the unrestricted birds remained greater than the feed restricted birds (Table 4.1). However, beginning at 26 wk of age, differences of BW across feed restricted birds began to decrease due to higher variation (Figure 4.2). At peak lay (approximately 30 wk of age), BW variation further decreased across BW trajectories (Figure 4.2). Specifically at wk 30, BW of the unrestricted birds (4,591, ± 160.0 g) was similar to the CON+22.5% birds (4,766, ± 154.3 g), which did not differ from the BW of the remaining feed restricted birds (Table 4.1; Figure 4.1). Body weight continued to increase with age as trajectory-specific BW targets increased post-peak production, however, differences in BW across all birds decreased (Table 4.1; Figure 4.1): by 40 wk of age, the unrestricted birds weighed 4,780 g (± 146.9), which did not differ from the CON+22.5% (4,298) and CON+20% birds (4,069 ± 90.9 g). Lack of significant differences in BW during the laying period was largely due to the small sample size per BW trajectory among the feed restricted hens (n = 3), which is why the current study focused on regression analyses rather than ANOVA.

In the current study, differences in BW among birds reflected trajectory-specific BW targets throughout the rearing period and at the time of photostimulation; feed intake increased (the degree of feed restriction decreased) as BW targets increased. This was expected, as feed restriction is reportedly most severe from 8 to 16 wk of age when broiler breeders are restricted 25 to 30 % of the intake of unrestricted birds (de Jong and Jones, 2006). There was large variation in individual bird BW within each BW trajectory from 26 to 40 wk of age. This means that not all birds within their respective BW trajectory groups reached the same BW. The individual bird variation might have been due to a combination of using the PF system and genetic differences in mature BW. In a recent PF study, Zuidhof (2018) hypothesized that each individual bird might have a unique optimal BW upon sexual maturity, and the current recommended BW targets and concurrent growth trajectories do not sufficiently meet the optimal BW threshold of all individual birds. These differences in individual BW are detectable when using PF system due to precise feeding and BW management according to a pre-assigned BW trajectory, which was demonstrated in the current study as there was large variation of BW among individual birds during lay within various BW trajectories (Figure 4.2).

4.4.2 Daily Station Visits

4.4.2.1 All Birds (feed restricted and unrestricted)

As BW increased among all birds, motivation to seek for feed decreased during the rearing period and toward the end of lay. The number of daily station visits decreased significantly from 2 to 29 wk of age over a range of 8.6 to 27.9 visits per kilogram increase in BW, and from 38 to 42 wk of age by 8.1 visits per kilogram increase in BW (Table 4.2). There was no effect of BW on the number of daily station visits from 30 to 37 wk of age (Table 4.2).

4.4.2.2 Feed Restricted Birds (excluding unrestricted)

In contrast, motivation to search for feed decreased as BW increased among feed restricted birds during the laying period. The number of daily station visits significantly decreased by 41.8, 45.3 and 41.6 visits per kilogram increase in BW from wk 22 to 25, 30 to 33 and 38 to 41, respectively (Table 4.2). The number of station visits of the feed restricted birds tended to decrease by 36.46 and 30.94 visits for every kilogram increase of BW during wk 26 to 29 (P = 0.088) and 34 to 37 (P = 0.076), respectively (Table 4.2). However, there was no effect of BW at photostimulation on the number of daily station visits during the rearing period (Table 4.2).

When unrestricted birds were included in the analysis, there was a strong reduction in feed seeking behaviour during rearing and toward the end of lay as BW increased. This was expected as the unrestricted birds were not limited to a maximum BW and were able to consume more feed relative to the feed restricted birds during the rearing period, which in turn might have induced satiety and reduced motivation to search for feed. However, this was not observed among the feed restricted birds only. Thus, breeders reared to achieve a BW up to 22.5% above the recommended target were feed restricted to a point that did not appear to reduce hunger, which increased motivation to seek for feed. Inconsistent with the hypothesis, BW increased up to 22.5% above the recommended BW target (lesser degree of feed restriction) did not appear to station visit frequency and therefor reduce hunger during the rearing period

4.4.3 Meal Frequency and Average Daily Feed Intake

In general, the number of meals and ADFI increased as BW increased.

4.4.3.1 All Birds (feed restricted and unrestricted)

The number of meals consumed by all birds increased over a range of 1.8 to 5.8 meals per kilogram increase in BW from 2 to 37 wk of age (Table 4.3). From 2 to 27 wk of age, the range of ADFI increased from 5.5 to 41.5 g per kilogram increase in BW (Table 4.4).

4.4.3.2 Feed Restricted Birds (excluding unrestricted)

Within feed restricted birds, the number of meals consumed increased significantly by 2.4, 1.4, 2.1 and 10.2 meals per kilogram increase in BW from 10 to 13, 14 to 17, 22 to 25 and 26 to 29 wk of age, respectively. In addition, the number of meals consumed by feed restricted birds tended to increase during wk 2 to 5 ($P = 0.069$) and 18 to 21 ($P = 0.062$). Average daily feed intake increased per kilogram increase in BW throughout the rearing and laying periods, with the exception of wk 6 to 9 (Table 4.4).

During rearing, nutrients are allocated toward structural muscle and skeletal development (Kwakkel et al., 1993; Kwakkel et al., 1995). Just prior to sexual maturation, there is a shift in nutrient allocation toward reproductive organ development in preparation of lay (Hadinia et al., 2019). Thus, the number of meals and nutrient intake of all (feed restricted and unrestricted) and feed restricted (excluding unrestricted) broiler breeders in the current study reflected increased BW targets to support pre-pubertal growth during rearing, pubertal growth towards the end of rearing and egg production throughout the laying phase.

4.4.4 Meal Size

From 6 to 25 wk of age, meal size of all birds (feed restricted and unrestricted) decreased significantly over a range of 0.8 to 1.4 g per kilogram increase in BW (Table 4.5). In contrast, there was no effect of BW on meal size of feed restricted (excluding unrestricted) birds (Table 4.5). Including unrestricted birds in the analysis reduced meal size. This suggests unrestricted birds reached a point of satiety during rearing and leading up to peak egg production because they received feed upon every station visit, which in turn decreased motivation to consume large meals. In contrast with the presented hypothesis, increased BW among feed restricted birds (lesser degree of feed restriction) did not reduce hunger and motivation to eat during the rearing period.

4.4.5 Egg Weight

4.4.5.1 All Birds (feed restricted and unrestricted)

Egg weight increased with BW. Specifically, EW increased by 0.7, 1.1, 0.7, 0.5 and 0.6 g per kilogram increase in BW from 22 to 25, 26 to 29, 30 to 33, 34 to 37 and 38 to 42 wk of age, respectively (Table 4.6). Egg weight was not affected by BW during wk 18 to 21 because 2 unrestricted hens that were similar in BW came into lay during that period (Table 4.6).

4.4.5.2 Feed Restricted Birds (excluding unrestricted)

Similarly, EW increased as BW increased during the beginning of lay within the feed restricted birds only. Egg weight increased by 3.1 and 2.5 g per kilogram increase in BW from 22 to 25 and 26 to 29 wk of age, respectively (Table 4.6). There was no effect of BW at photostimulation on EW from 30 to 42 wk of age (Table 4.6).

Egg weight is known to increase with BW over time (McDaniel et al., 1981). In the current study, EW of feed restricted birds increased up to 29 wk of age which coincided with the time BW began to plateau. In contrast, when the unrestricted birds were included with the feed restricted birds in the analysis, EW increased with BW throughout the entire lay period. Literature has reported that heavy BW hens produce heavier eggs pre, post and during peak production compared to medium and light BW hens (Sun and Coon, 2005). Moreover, previous studies that used the PF system reported EW increased with age (van der Klein et al., 2018a; van der Klein et al., 2018b). In the current study, EW may have been similar across feed restricted birds due to frequent meals that provided a sufficient amount of nutrients in small portions throughout the day.

4.4.6 Age at First Egg

4.4.6.1 All Birds (feed restricted and unrestricted)

Age at first egg advanced as BW increased. Age at first egg decreased by 10.8 d (± 1.54 d) per kilogram increase in BW (*P* < 0.001, Figure 4.3).

4.4.6.2 Feed Restricted Birds (excluding unrestricted)

Age at first egg was not advanced as BW at photostimulation increased among feed restricted birds. Age at first egg tended to decrease by 8.8 d (± 5.13 d) per kilogram increase in BW ($R^2 = 0.103$, $P = 0.10$).

Two unrestricted hens came into lay prior to photostimulation on d 141 and 147, during wk 20 and 21, respectively. The remaining unrestricted and feed restricted hens came into lay from d 170 to 181, during wk 24 and 25. Body weight above the recommended targets advanced sexual maturity, which is consistent with Heck et al. (2004) who reported ad libitum-fed broiler breeders came into lay at 20 wk of age before photostimulation. Renema et al. (1999) photostimulated broiler breeder pullets at 21 wk of age, and reported that ad libitum pullets reaching sexual maturity 13.6 d earlier than feed restricted pullets. In contrast, Robinson et al.

(1991) reported that when photostimulated at 22 wk of age, ad libitum broiler breeders reached sexual maturity on d 180.5, which was similar to feed restricted broiler breeders (d 183.3). Notably, one of the CON+12.5% birds weighed 1,981 g at photostimulation which was 593 g less than the average BW of the other birds in the CON+12.5% group. Moreover, the light CON+12.5% bird reached sexual maturity 2 and 10 d prior to the birds that followed the same BW trajectory, and around the same time as birds in the CON+22.5%, CON+20% and CON+17.5% groups (Figure 4.3). This suggests that each bird has a unique optimum BW trajectory and BW threshold to reach sexual maturity.

4.4.7 Egg Production

There was no effect of BW trajectory on cumulative egg production of all birds (feed restricted and unrestricted; data not shown; $R^2 = 0.074$, $P = 0.13$) or within feed restricted (excluding unrestricted) birds (data not shown; $R^2 = 0.011$, $P = 0.60$). On average throughout the laying period, unrestricted hens produced 104.4 eggs/hen and CON hens produced 98.7 eggs/hen. Egg production has been reported to decrease as BW increases (Yu et al., 1992; Heck et al., 2004). Feed restricted broiler breeders produced 29.7% more eggs during the lay period than ad libitum hens (Robinson et al., 1991), however there have been genetic changes to modern breeder birds since this research was reported. More recent literature has demonstrated that high BW hens produced 129.4 eggs/hen from 32 to 55 wk of age, which was 1.39 times more than standard BW hens (van der Klein et al., 2018b). The authors suggest that increased egg production of high BW hens may have been due to strict control of meal size and increased meal frequency through the PF system in combination with recent genetic change to modern breeder lines. Similarly in the current study, controlled feed allocation and increased meal frequency through the PF system may have altered fat deposition and reduced variation in egg production across all birds. Thus, there is potential to increase BW 22.5% above the recommended BW target without affecting egg production of precision-fed hens.

4.5 Conclusion

In conclusion, station visit frequency was a suitable indicator of feed seeking motivation that could be used to describe hunger. Station visit frequency of feed restricted (excluding unrestricted) birds decreased during the laying period as BW increased, however this was not observed during the rearing period. In contrast, when unrestricted birds were included in the analysis, station visits frequency decreased during rearing as BW increased. This means that hunger and motivation to seek for feed was not reduced of birds fed to achieve a BW that ranged of 2.5 to 22.5% above the recommended BW target during rearing, while unrestricted birds that were given feed upon every station visit reached a point of satiety which decreased motivation to seek for feed. Meal frequency, ADFI and meal size more closely reflected an increase in nutrient intake to support growth, maintenance and reproductive requirements. Age at first egg was advanced as BW increased, and cumulative egg production was not significantly affected by increased BW at photostimulation. Notably, 2 unrestricted hens came into lay prior to photostimulation at 20 and 21 wk of age. Thus, there is potential to increase precision-fed broiler breeder BW targets and reduce the degree of feed restriction without reducing reproductive performance. The BW results of the current study indicated that optimal BW trajectories may strongly depend on the individual broiler breeder. Larger future studies are recommended to confirm the effects of increased BW within BW trajectories, and whether genetic potential may influence hunger and feed and feed seeking motivation.

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4.7 References

Aviagen, 2016a. Ross 708 Parent Stock: Performance Objectives. Aviagen, Huntsville, AL.

Aviagen, 2016b. Yield Plus Male Standards - Metric. Aviagen, Huntsville, AL.

Bruggeman, V., O. Onagbesan, E. D'Hondt, N. Buys, M. Safi, D. Vanmontfort, L. Berghman, F. Vandesande, and E. Decuypere. 1999. Effects of timing and duration of feed restriction during rearing on reproductive characteristics in broiler breeder females. Poult. Sci. 78:1424–1434.

CCAC. 2009. CCAC guidelines on: The care and use of farm animals in research, teaching and testing. Canadian Council on Animal Care, Ottawa, ON.

D'Eath, R. B., B. J. Tolkamp, I. Kyriazakis, and A. B. Lawrence. 2009. 'Freedom from hunger' and preventing obesity: The animal welfare implications of reducing food quantity or quality. Anim. Behav. 77:275-288.

Decuypere, E., V. Bruggeman, N. Everaert, Y. Li, R. Boonen, J. de Tavernier, S. Janssens, and N. Buys. 2010. The broiler breeder paradox: Ethical, genetic and physiological perspectives, and suggestions for solutions. Br. Poult. Sci. 51:569–579.

de Jong, I. C., and D. Guémené. 2011. Major issues in broiler breeders. Worlds Poult. Sci. 76:73-82.

de Jong, I. C., and B. Jones. 2006. Feed restriction and welfare in domestic birds. Pages 120-135 in Feeding in Domestic Vertebrates. V. Bels, ed. CABI, Wallingford, United Kingdom.

de Jong, I. C., S. van Voorst, D. A. Ehlhardt, and H. J. Blokhuis. 2002. Effects of restricted feeding on physiological stress parameters in growing broiler breeders. Br. Poult. Sci. 43:157–168.

Girard, T. E., M. J. Zuidhof, and C. J. Bench. 2017. Feeding, foraging, and feather pecking behaviours in precision-fed and skip-a-day-fed broiler breeder pullets. Appl. Anim. Behav. Sci. 188:42–49.

Hadinia, S. H., P. R. O. Carneiro, D. R. Korver, and M. J. Zuidhof. 2019. Energy partitioning by broiler breeder hens in conventional daily-restricted feeding and precision feeding systems. Poult. Sci. 98:6721–6732.

Heck, A., O Onagbesan, K. Tona, S. Metayer, J. Putterflam, Y. Jego, J. J. Trevidy, E. Decuypere, J. Williams, M. Picard and V. Bruggeman. 2004. Effects of ad libitum feeding on performance of different strains of broiler breeders. Br. Poult. Sci. 45:695–703.

Hocking, P. M., M. H. Maxwell, G. W. Robertson, and M. A. Mitchell. 2002. Welfare assessment of broiler breeders that are food restricted after peak rate of lay. Br. Poult. Sci. 43:5–15.

Hocking, P. M., M. H. Maxwell, and M. A. Mitchell. 1996. Relationship between the degree of food restriction and welfare indices in broiler breeder females. Br. Poult. Sci. 37:263–278.

Kwakkel, R. P., J. A. W. van Esch, B. J. Durco, and W. J. Koops. 1995. Onset of lay related to multiphasic growth and body composition in white leghorn pullets provided ad libitum and restricted diets. Poult. Sci. 74:821–832.

Kwakkel, R P., B. J. Ducro, and W. J. Koops, 1993. Multiphasic analysis of growth of the body and its chemical components in White Leghorn pullets. Poult. Sci. 72:1421–1432.

McDaniel, G. R., J. Brake, and M. K. Eckman. 1981. Factors affecting broiler breeder performance. 4. The relationship of some reproductive traits. Poult. Sci. 60:1792–1797.

Merlet, F., J. Puterflam, J. M. Faure, P. M. Hocking, M. S. Magnusson, and M. Picard. 2005. Detection and comparison of time patterns of behaviours of two broiler breeder genotypes fed ad libitum and two levels of feed restriction. Appl. Anim. Behav. Sci. 94:255–271.

Renema, R. A., and F. E. Robinson. 2004. Defining normal: Comparison of feed restriction and full feeding of female broiler breeders. Worlds Poult. Sci. J. 60:508–522.

Renema, R. A., F. E. Robinson, M. Newcombe, and R. I. McKay. 1999. Effects of body weight and feed allocation during sexual maturation in broiler breeder hens. 1. Growth and carcass characteristics. Poult. Sci. 78:619–628.

Renema, R. A., M. E. Rustad, and F. E. Robinson. 2007. Implications of changes to commercial broiler and broiler breeder body weight targets over the past 30 years. Worlds Poult. Sci. J. 63:457–472.

Robinson, F. E., N. A. Robinson, and T. A. Scott. 1991. Reproductive performance, growth rate and body composition of full-fed versus feed-restricted broiler breeder hens. Can. J. Anim. Sci. 71:549–556.

Rodriguez, A. 2017. Effects of daytime and supplemental light spectrum on broiler breeder growth and sexual maturation. MSc. University of Guelph, Guelph, ON.

Rosales, A. G. 1994. Managing stress in broiler breeders: A review. J. Appl. Poult. Res. 3:199–207.

Savory, C. J., and K. Maros. 1993. Influence of degree of food restriction, age and time of day on behaviour of broiler breeder chickens. Behav. Processes. 29:179–190.

Sun, J., and C. N. Coon. 2005. The effects of body weight, dietary fat, and feed withdrawal rate on the performance of broiler breeders. J. Appl. Poult. Res. 14:728–739.

van der Klein, S. A. S., G. Y. Bédécarrats, and M. J. Zuidhof. 2018a. The effect of rearing photoperiod on broiler breeder reproductive performance depended on body weight. Poult. Sci. 97:3286–3294.

van der Klein, S. A. S., G. Y. Bédécarrats, F. E Robinson, and M. J. Zuidhof. 2018b. Early photostimulation at the recommended body weight reduced broiler breeder performance. Poult. Sci. 97:3736–3745.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, and W. H. Hendriks. 2013. Effects of growth patterns and dietary crude protein levels during rearing on body composition and performance in broiler breeder females during the rearing and laying period. Poult. Sci. 92:2091–2100.

Yu, M. W., F. E. Robinson, R. G. Charles, and R. Weingardt. 1992. Effects of feed allowance during rearing and breeding on female broiler breeders. 2. Ovarian morphology and production. Poult. Sci. 71:1750–1761.

Zuidhof, M. J. 2018. Lifetime productivity of conventionally and precision-fed broiler breeders. Poult. Sci. 97:3921–3937.

Zuidhof, M. J., M. V. Fedorak, C. C. Kirchen, E. H. M. Lou, C. A. Ouellette, and I. I. Wenger. 2019. System and method for feeding animals. PrecisionZX, Inc., assignee. US Pat. No. 10,506,793.

Zuidhof, M. J., M. V. Fedorak, C. A. Ouellette, and I. I. Wenger. 2017. Precision feeding: Innovative management of broiler breeder feed intake and flock uniformity. Poult. Sci. 96:2254–2263.

4.8 Tables

Table 4.1 Effect of BW trajectory[1] (W) and age (A) on BW during rearing and lay.

		BW trajectory										
	Age	CON	CON+2.5%	CON+5%	CON+7.5%	CON+10%	CON+12.5%	CON+15%	CON+17.5%	CON+20%	CON+15%	UNRES
	- wk -						g					
Rearing	2	150	139	141	137	155	135	143	110	152	124	141
	4	368	348	368	297	373	355	349	365	403	309	367
	6	575^{g}	591^{fg}	588^{efg}	551^{defg}	632^{def}	647de	660^{cd}	669^{bcd}	690^{abc}	709^{ab}	789^{a}
	8	796^{fg}	799^{g}	819^{fg}	828^{fg}	856^{ef}	879de	895^{cde}	913^{bcd}	930^{bc}	952^{b}	1,534^{a}
	10	983^{h}	1,002^{gh}	1,031^{fg}	1,049^{f}	1,066^{ef}	1,103^{de}	1,127^{cd}	1,148^{c}	1,167^{bc}	1,195^{b}	2,185^{a}
	12	1,156^{j}	1,192^{ij}	1,218^{hi}	1,240^{gh}	1,275^{fg}	1,306^{ef}	1,332^{de}	1,357^{cd}	1,385^{bc}	1,414^{b}	2,742^{a}
	14	1,323^{j}	1,356^{ij}	1,384^{hi}	1,416^{gh}	1,450^{fg}	1,486^{ef}	1,514^{de}	1,550^{cd}	1,583^{bc}	1,612^{b}	3,139^{a}
	16	1,486^{j}	1,523^{ij}	1,556^{hi}	1,594^{gh}	1,634^{fg}	1,677^{ef}	1,707^{de}	1,745^{cd}	1,778^{bc}	1,820^{b}	3,429^{a}
	18	1,698^{h}	1,739^{gh}	1,779^{fg}	1,819^{f}	1,880^{e}	1,910^{e}	1,953^{d}	1,994^{cd}	2,038^{bc}	2,072^{b}	3,775^{a}
	20	1,977^{j}	2,025^{i}	2,073^{h}	2,119^{g}	2,172^{f}	2,222^{e}	2,273^{d}	2,320^{cd}	2,366^{bc}	2,405^{b}	4,094^{a}
PS[2]	22	2,290^{k}	2,346^{j}	2,400^{i}	2,455^{h}	2,519^{g}	2,576^{f}	2,627^{e}	2,684^{d}	2,742^{c}	2,793^{b}	4,297^{a}
Lay	24	2,587^{k}	2,652^{j}	2,717^{i}	2,788^{h}	2,853^{g}	2,915^{f}	2,973^{e}	3,040^{d}	3,096^{c}	3,163^{b}	4,480^{a}
	26	2,840^{h}	2,929^{g}	2,977^{f}	3,054^{e}	3,140^{d}	3,141^{bcdefgh}	3,261^{c}	3,339^{b}	3,365^{bcdefgh}	3,313^{bcdefgh}	4,447^{a}
	28	3,022^{gh}	3,123^{fh}	3,181^{eg}	3,283^{d}	3,356^{c}	3,377^{c}	3,511^{b}	3,562^{bc}	3,541^{bcde}	3,619^{bcdef}	4,520^{a}
	30	3,155^{def}	3,285^{f}	3,315^{ef}	3,448^{e}	3,528^{d}	3,534^{d}	3,686^{c}	3,754^{b}	3,702^{bcdef}	3,766^{abcdef}	4,591^{a}
	32	3,240^{de}	3,379^{e}	3,440^{de}	3,543^{cd}	3,617^{bcde}	3,656^{bcde}	3,731^{b}	3,866^{bc}	3,777^{abcde}	3,899^{abcde}	4,655^{a}
	34	3,341^{cdef}	3,478^{f}	3,553^{d}	3,657^{c}	3,750^{be}	3,773^{b}	3,855^{abcd}	3,996^{a}	3,971^{abcd}	4,076^{a}	4,642^{a}
	36	3,392^{bcd}	3,511^{d}	3,623^{d}	3,713^{cd}	3,812^{c}	3,838^{c}	3,938^{b}	4,048^{a}	3,984^{abcd}	4,091^{abcd}	4,687^{a}
	38	3,428^{efg}	3,573^{g}	3,647^{df}	3,769^{ce}	3,865^{c}	3,870^{c}	3,997^{b}	4,062^{b}	4,045^{abcd}	4,244$^{a, 3}$	4,797^{ab}
	40	3,501^{fgh}	3,600^{h}	3,686^{eg}	3,788^{df}	3,896^{c}	3,937^{c}	4,051^{b}	4,132^{b}	4,069^{abcde}	4,298$^{a, 3}$	4,780^{a}
Source							Probability					
Rearing	W						< 0.001					
	A						< 0.001					
	W x A						< 0.001					
Lay	W						< 0.001					
	A						< 0.001					
	W x A						< 0.001					

[1] BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) were not limited to a maximum BW.
[2] Photostimulation.
[a – j] Means within rows with no common superscript differ ($P < 0.05$). SEM are shown in the form of a heat map (Figure 4.2).

Table 4.2 Regression analysis of the effect of BW at photostimulation on the daily number of station visits for all birds[1] or feed restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	visits	– visits/kg –				visits	— visits/kg —			
2 to 5	51.0	-8.6	4.14	0.121	0.047	78.6	-19.6	22.32	0.030	0.39
6 to 9	120.4	-23.2	5.57	0.358	< 0.001	63.2	-0.3	29.48	0.000	0.99
10 to 13	130.3	-25.6	4.60	0.499	< 0.001	64.9	0.6	23.58	0.000	0.98
14 to 17	126.6	-25.7	4.66	0.496	< 0.001	120.1	-23.0	24.83	0.033	0.36
18 to 21	136.2	-27.9	5.06	0.495	< 0.001	131.6	-25.9	26.55	0.037	0.34
22 to 25	120.2	-23.3	3.98	0.534	< 0.001	167.1	-41.8	18.77	0.166	0.035
26 to 29	67.6	-11.1	4.26	0.185	0.014	131.7	-36.5	20.51	0.112	0.088
30 to 33	49.6	-7.1	4.31	0.082	0.11	146.1	-45.3	19.42	0.179	0.028
34 to 37	36.8	-5.0	3.44	0.069	0.11	102.2	-30.9	16.67	0.130	0.076
38 to 41	45.8	-8.1	3.36	0.171	0.023	129.9	-41.6	16.60	0.214	0.020

[1] BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2] Excluded unrestricted birds.

Table 4.3 Regression analysis of the effect of BW at photostimulation on the number of meals for all birds[1] or feed restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	meals	– meals/kg –				meals	– meals/kg –			
2 to 5	5.4	1.8	0.62	0.216	0.006	-3.7	5.5	2.87	0.126	0.069
6 to 9	-7.9	5.8	0.60	0.747	< 0.001	8.0	-0.5	2.18	0.002	0.81
10 to 13	-8.4	5.8	0.27	0.935	< 0.001	0.2	2.4	0.82	0.248	0.008
14 to 17	-5.3	4.4	0.31	0.864	< 0.001	2.3	1.4	0.64	0.151	0.045
18 to 21	-2.2	3.8	0.34	0.793	< 0.001	2.2	2.1	1.05	0.132	0.062
22 to 25	-2.6	4.7	0.69	0.611	< 0.001	-9.1	7.4	1.82	0.398	< 0.001
26 to 29	7.2	3.1	1.11	0.201	0.010	-10.6	10.2	3.68	0.236	0.010
30 to 33	-0.3	4.7	1.37	0.284	0.002	0.8	4.4	3.02	0.079	0.15
34 to 37	1.8	3.2	1.17	0.209	0.011	8.9	0.5	2.27	0.002	0.83
38 to 41	6.9	1.2	0.77	0.074	0.15	12.2	-0.9	3.31	0.003	0.78

[1] BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2] Excluded unrestricted birds.

Table 4.4 Regression analysis of the effect of BW at photostimulation on ADFI for all birds[1] or feed restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	— g —	— g/kg —				— g —	— g/kg —			
2 to 5	25.5	5.5	2.11	0.181	0.013	-11.1	20.1	10.44	0.129	0.066
6 to 9	-25.9	35.3	3.96	0.719	< 0.001	68.2	-2.1	19.36	0.000	0.91
10 to 13	-42.7	41.5	1.95	0.936	< 0.001	-19.9	32.3	8.55	0.364	< 0.001
14 to 17	-20.1	32.4	2.17	0.877	< 0.001	9.3	20.5	3.55	0.572	< 0.001
18 to 21	12.7	26.8	2.22	0.825	< 0.001	7.1	29.3	6.23	0.470	< 0.001
22 to 25	46.7	23.4	3.28	0.630	< 0.001	-67.6	69.1	9.76	0.667	< 0.001
26 to 29	128.2	9.8	3.76	0.184	0.014	-4.1	62.7	8.11	0.705	< 0.001
30 to 33	143.9	10.6	3.27	0.260	0.003	32.7	55.1	10.18	0.540	< 0.001
34 to 37	128.0	7.7	3.65	0.137	0.044	42.8	41.9	10.65	0.402	< 0.001
38 to 41	117.0	10.1	2.91	0.300	0.002	58.4	33.8	10.78	0.299	0.005

[1] BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2] Excluded unrestricted birds.

Table 4.5 Regression analysis of the effect of BW at photostimulation on meal size for all birds[1] or feed restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	— g —	— g/kg —				— g —	— g/kg —			
2 to 5	5.6	-0.4	0.29	0.048	0.218	6.3	-0.6	1.48	0.007	0.668
6 to 9	12.1	-1.0	0.47	0.126	0.042	10.1	-0.2	2.43	0.000	0.939
10 to 13	12.0	-0.8	0.33	0.157	0.023	6.6	1.3	1.59	0.027	0.409
14 to 17	13.2	-1.0	0.33	0.206	0.008	8.2	1.1	1.52	0.019	0.491
18 to 21	13.5	-0.9	0.28	0.264	0.002	8.5	1.1	1.32	0.026	0.422
22 to 25	15.0	-1.4	0.37	0.321	< 0.001	12.7	-0.5	1.68	0.003	0.780
26 to 29	12.4	-0.6	0.55	0.042	0.263	15.7	-1.9	2.41	0.025	0.428
30 to 33	18.8	-1.4	0.83	0.090	0.096	16.9	-0.7	3.52	0.002	0.838
34 to 37	16.7	-0.6	0.80	0.017	0.486	10.3	1.9	3.21	0.015	0.554
38 to 41	15.7	-0.2	0.81	0.001	0.854	9.6	2.2	3.68	0.016	0.550

[1] BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2] Excluded unrestricted birds.

Table 4.6 Regression analysis of the effect of BW at photostimulation on egg weight (EW) for all birds[1] or feed restricted birds[2], from 2 to 41 wk of age.

	All birds					Feed restricted birds				
Age (wk)	Intercept	Slope	SEM	R^2	*P*-value	Intercept	Slope	SEM	R^2	*P*-value
	— g —	— g/kg —				— g —	— g/kg —			
18 to 21	61.1	-3.9	8.00	0.105	0.68	-	-	-	-	-
22 to 25	48.6	0.7	0.33	0.022	0.031	42.6	3.1	1.52	0.031	0.044
26 to 29	52.2	1.1	0.26	0.021	< 0.001	48.7	2.5	0.93	0.010	0.008
30 to 33	57.1	0.7	0.28	0.010	0.011	54.8	1.7	1.07	0.004	0.12
34 to 37	60.5	0.5	0.22	0.006	0.033	60.3	0.5	0.89	0.001	0.54
38 to 41	61.7	0.6	0.22	0.011	0.006	61.1	0.9	0.93	0.001	0.35

[1] BW trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted birds (n = 6) were not limited to a maximum BW.
[2] Excluded unrestricted birds.

4.9 Figures

	BW trajectory										
Age (wk)	CON	CON+2.5%	CON+5%	CON+7.5%	CON+10%	CON+12.5%	CON+15%	CON+17.5%	CON+20%	CON+22.5%	UNRES
2	0	-11	-9	-13	5	-15	-7	-40	2	-26	-9
4	0	-20	0	-71	5	-13	-19	-3	35	-59	-1
6	0	16	13	-24	57	72	85	94	115	134	214
8	0	3	23	32	60	83	99	117	134	156	738
10	0	19	48	66	83	120	144	165	184	212	1,202
12	0	36	62	84	119	150	176	201	229	258	1,586
14	0	33	61	93	127	163	191	227	260	289	1,816
16	0	37	70	108	148	191	221	259	292	334	1,943
18	0	41	81	121	182	212	255	296	340	374	2,077
20	0	48	96	142	195	245	296	343	389	428	2,117
22	0	56	110	165	229	286	337	394	452	503	2,007
24	0	65	130	201	266	328	386	453	509	576	1,893
26	0	89	137	214	300	301	421	499	525	473	1,607
28	0	101	159	261	334	355	489	540	519	597	1,498
30	0	130	160	293	373	379	531	599	547	611	1,436
32	0	139	200	303	377	416	491	626	537	659	1,415
34	0	137	212	316	409	432	514	655	630	735	1,301
36	0	119	231	321	420	446	546	656	592	699	1,295
38	0	145	219	341	437	442	569	634	617	816	1,369
40	0	99	185	287	395	436	550	631	568	797	1,279

Figure 4.1 Heat map of differences in BW (g) across BW trajectories from 2 to 40 wk of age, relative to the CON trajectory. Trajectories varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) was not limited to a maximum BW. Red, yellow and blue colours indicate low, intermediate and high values, respectively.

	BW trajectory										
Age (wk)	CON	CON+2.5%	CON+5%	CON+7.5%	CON+10%	CON+12.5%	CON+15%	CON+17.5%	CON+20%	CON+22.5%	UNRES
2	11.1	55.9	15.1	21.4	10.1	12.8	14.0	13.2	8.2	7.3	6.7
4	18.0	23.9	19.3	46.3	28.1	35.1	35.6	27.5	29.6	8.5	13.3
6	6.5	6.8	11.2	27.5	6.8	6.8	6.7	7.5	6.6	8.1	22.1
8	12.9	6.5	6.6	7.4	6.6	6.6	6.6	6.6	6.6	8.0	44.2
10	6.7	6.6	6.9	6.6	10.0	7.2	7.5	6.6	7.0	8.1	46.1
12	6.6	6.7	6.6	6.6	6.8	6.6	7.1	6.6	6.9	8.1	48.7
14	6.6	7.6	6.7	6.6	6.8	6.6	6.7	6.6	6.7	8.1	61.1
16	6.8	6.6	6.9	6.6	6.6	7.7	6.7	8.2	6.9	8.1	45.6
18	6.6	6.6	6.7	6.5	6.8	6.5	6.6	8.2	6.6	8.0	45.3
20	6.6	6.9	6.6	6.6	6.6	6.6	7.3	8.1	6.6	9.7	68.8
22	6.9	8.4	6.6	6.6	6.8	6.6	7.2	8.1	7.7	8.3	59.1
24	2.1	1.3	1.7	1.2	2.0	1.7	2.6	0.1	2.3	0.2	115.5
26	9.2	2.3	6.1	15.6	7.6	78.3	8.0	5.7	134.0	154.4	113.7
28	57.6	1.6	6.4	1.4	5.0	8.9	4.6	47.3	85.7	120.7	144.3
30	91.3	8.9	33.5	5.2	9.4	16.7	9.0	1.9	108.2	154.3	160.0
32	87.2	9.4	32.0	16.9	60.2	83.5	37.5	75.5	166.0	150.5	151.6
34	93.5	8.0	7.8	6.6	2.5	9.6	78.3	3.6	111.2	44.6	162.0
36	144.0	32.7	4.7	48.5	2.8	13.1	16.2	17.7	117.5	134.5	167.0
38	92.8	7.1	5.9	22.1	6.1	14.3	12.4	11.1	98.1	N/A[1]	203.7
40	77.2	16.5	7.4	8.4	14.4	5.4	16.5	9.4	90.9	N/A[1]	146.9

Figure 4.2 Heat map of SEM values (g) for the differences in BW across BW trajectories from 2 to 40 wk of age, relative to Figure 4.1. Trajectories varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) was not limited to a maximum BW. Red, yellow and blue colours indicate low, intermediate and high values, respectively.

[1] An SEM value was not applicable where there was 1 bird remaining in the BW trajectory group.

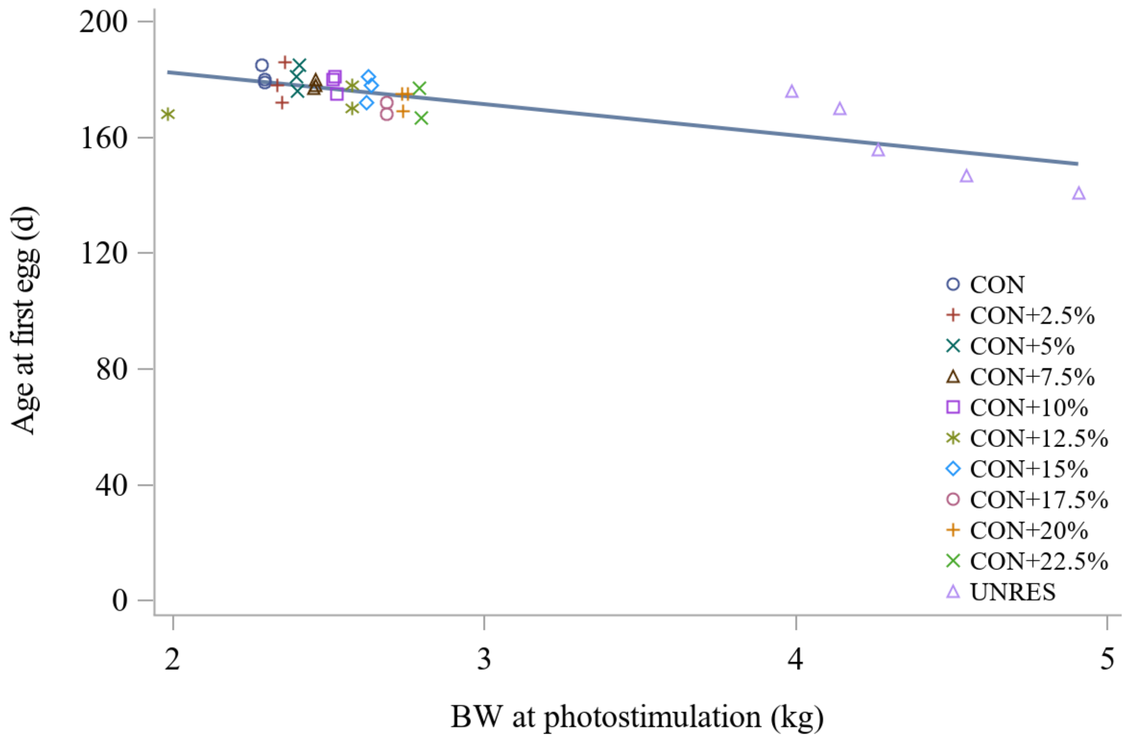

Figure 4.3 Regression analysis of the effect of BW at photostimulation on age at first egg (R^2 = 0.616, $P < 0.001$). Body weight trajectories that varied in pre-pubertal and pubertal phases of growth starting from the Ross 708 recommended BW target (CON) up to 22.5% above CON, in 2.5% increments. An additional group of unrestricted (UNRES) birds (n = 6) was not limited to a maximum BW.

5.0 Chapter 5: Broiler Growth and Efficiency in Response to Relaxed Maternal Feed Restriction

5.1 Abstract

Broiler growth performance can be influenced by maternal body weight (**BW**), maternal age and sex. The current study evaluated broiler growth and efficiency in response to increased maternal BW (relaxed level of maternal feed restriction). It was hypothesized that BW and fatness would increase, and efficiency would be reduced as maternal BW increased. Ten BW trajectories were applied to precision-fed Ross 708 female broiler breeders (n = 30) from 2 to 42 wk of age. Trajectories varied in pre-pubertal and pubertal growth phases from 2.5 to 22.5% above the recommended BW target. Additional unrestricted breeders (n = 6) were not limited to a maximum BW (fed ad libitum). Two 35 d experiments were conducted with precision-fed broilers from these breeders at 35 and 42 wk of age. Two analyses (full and restricted analysis scopes) were performed to evaluate broiler BW, feed conversion ratio (**FCR**) and carcass traits with maternal BW at photostimulation (22 wk of age) as a continuous effect, and maternal age and sex as discrete effects. The full scope included broilers from all hens (feed restricted and unrestricted). The restricted scope excluded broilers from unrestricted hens. Differences were reported at $P \leq 0.05$. For every kilogram increase in maternal BW, cumulative FCR increased by 0.235 g:g in the full scope analysis. Proportional gut weight of broilers from feed restricted hens decreased by 0.8244% per kilogram increase in maternal BW. Males were heavier than females on d 28 and 35, and broilers from 42 wk old breeders were heavier than broilers from 35 wk old breeders on d 0 and 35. Males from all hens were more feed efficient (1.318 g:g) than females (1.335 g:g) from d 29 to 35. Females from all and feed restricted hens had a greater proportional fat pad and breast muscle weight compared to males, and proportional breast muscle yield of

broilers from 42 wk old breeders was on average 1.04 times greater than that of broilers from 35 wk old breeders. Maternal BW did not affect offspring BW, reduced cumulative FCR, and reduced gut weight in the restricted analysis scope.

Key words: precision livestock farming, intergenerational, maternal body weight, maternal age, offspring performance

5.2 Introduction

Over the past few decades, genetic change in the broiler industry has heavily focused on fast and lean growth accompanied by high muscle yield (as reviewed by Tallentire et al., 2016). For example, growth rates of broiler strains used in 2005 increased by 400% compared to broiler strains used in 1957 (Zuidhof et al., 2014). A challenge the industry has faced is that breeder body weight (**BW**) targets have remained relatively constant as growth potential of modern breeder and broiler lines continues to advance (Renema et al., 2007).

Broiler breeders are feed restricted during rearing, and to a lesser extent during lay, to achieve strict BW targets to optimize reproductive performance. Restricted feed intake has been used to control follicular development and to improve reproductive performance in broiler breeders (Katanbaf et al., 1989; Hocking, 1993), which has increased the number of settable eggs for broiler chick production (Yu et al., 1992). However, new research suggests modern broiler breeders have unique optimal growth trajectories, some of which are above the current recommended BW targets, which is clearly emphasized in studies that have used precision feeding (**PF**) systems (Zuidhof, 2018; Hadinia et al., 2019). It was hypothesized that in combination with recent genetic change, some precision-fed broiler breeders with an optimum BW above the current recommended standard did not receive a sufficient amount of nutrients to support high rates of egg production. Thus, there may be a need to increase BW targets to increase nutrient intake for precision-fed broiler breeders. This would not only influence management practices in the hatching egg industry, but address negative welfare issues related to feed restriction such as stress and hunger (D'Eath et al., 2009).

Maternal nutrition can influence offspring growth. Specifically in the context of meat-type chickens, various levels of dietary protein and energy increase egg and chick weights (Enting et al., 2007). In addition, increased maternal dietary protein and energy increased offspring BW and fatness, respectively (Moraes et al., 2014). Multiple studies have focused on intergenerational effects of maternal BW on broiler performance. Broilers from high BW hens (2,400 g at 22 wk of age) gained 2.4% more from 28 to 34 d of age than did broilers from standard BW hens (2,200 g at 22 wk of age; van Emous et al., 2015). Humphreys (2020) reported that broilers from high BW hens (21% above the recommended BW) were 3.9 and 4.1% heavier than broilers from standard BW hens on d 35 and 42, respectively. This research also found that gut and abdominal fat pad weights were 6.4 and 16.0% greater of broilers from high BW hens compared to those from standard BW hens, respectively. Recently, Bowling et al. (2018) assessed stress of feed restricted broiler breeders by measuring yolk corticosterone concentration. The authors found lower maternal BW (greater degree of maternal feed restriction) increased the concentration of yolk corticosterone, which might have reduced growth of male broilers at 42 d of age. Thus, more research is needed to determine the relationship between the degree of maternal BW and broiler growth performance.

In addition to maternal BW, offspring growth is affected by maternal age and sex. Broiler hatch BW increased with maternal age (Peebles et al., 1999; Tona et al., 2004; Iqbal et al., 2016). Male offspring have a greater final BW compared to females (Humphreys, 2020; van der Klein et al., 2017). Moreover, females are documented to have a greater proportion of breast muscle

(Scheuermann et al., 2003; Zuidhof et al., 2014; van der Klein et al., 2017; Moraes et al., 2019) and fat pad (Lippens et al., 2010; Zuidhof et al., 2014; van der Klein et al., 2017; Moraes et al., 2019; Humphreys, 2020) compared to males.

Maternal BW has had no effect on broiler feed efficiency (van Emous et al., 2015; Humphreys, 2020). However, broiler efficiency may be influenced by BW. Chickens with a greater BW have greater maintenance requirements (Yu and Robinson, 1992; Latshaw and Moritz, 2009), therefore feed efficiency may decrease with BW as birds allocate more nutrients to support growth and development requirements.

The main objective of this study was to evaluate offspring growth performance in response to relaxed maternal feed restriction, implemented through various maternal BW trajectories. It was hypothesized that increased maternal BW (lesser degree of maternal feed restriction) would increase broiler BW, breast muscle yield and fatness, and reduce feed efficiency. A second objective was to investigate the effects of maternal age and broiler sex on offspring growth performance. It was additionally hypothesized that BW, breast muscle, liver, gut weights, and fatness would increase, and feed efficiency would decrease as maternal age increased. Further, males would achieve a heavier BW, greater proportional breast weight, lower proportional fat pad weight, and would be more efficient than females.

5.3 Materials and Methods

The animal protocol for the study was approved by the University of Alberta Animal Care and Use Committee for Livestock and followed principles established by the Canadian Council on Animal Care Guidelines and Policies (CCAC, 2009).

5.3.1 Experimental Design

This broiler study was designed as a completely randomized and controlled experiment, and included 2 replicated experiments that differed in maternal age: 35 and 42 wk of age (cohort 1 and 2, respectively). The maternal treatments consisted of 10 unique BW trajectories that were created from a multiphasic Gompertz growth model. The model estimated growth in pre-pubertal, pubertal, and post-pubertal phases. Experimental trajectories varied in pre-pubertal and pubertal growth phases starting from the Ross 708 recommended BW target (CON; Aviagen 2016a) up to 22.5% above the Ross 708 recommended BW target, in 2.5% increments (CON+2.5%, CON+5%, … CON+22.5%). Three female broiler breeders were assigned to each trajectory and were feed restricted to reach their respective target BW. Six additional broiler breeders were assigned to an unrestricted group, meaning they were fed every time they went to the feeding station and were not limited to a maximum BW. Each broiler was considered an experimental unit.

5.3.2 Source Flock

5.3.2.1 Stocks and Management

The source flock consisted of Ross 708 broiler breeder females (n = 36) housed with Yield Plus males (n = 8) in a single environmental chamber with 2 PF stations at a stocking rate of 3.16 birds per m^2. Birds were fed a commercial standard starter crumble diet from 0 to 5 wk (2,726 kcal ME, 21% CP, and 0.993% Ca), a commercial broiler breeder grower mash from 6 to 26 wk (2,799 kcal ME, 15% CP, and 0.79% Ca) and a broiler breeder layer mash from 26 wk to the end of the experiment (2,798 kcal ME, 15% CP, and 3.4% Ca). Females were fed to achieve BW targets specific to their trajectory and males were precision-fed according to the Yield Plus male standard BW profile (Aviagen 2016b). The photoschedule was 24L:0D at 100 lx from d 0 to 3, then reduced to 8L:16D at 15 lx on d 4. Light intensity was reduced to 5 lx on d 26 and remained constant until wk 21 to minimize feather pecking. The females were photostimulated at

22 wk of age by increasing the photoperiod to 11L:13D (20 lx). Day length was further increased to 12L:12D (35 lx) at 23 wk, and 13L:11D (50 lx) at wk 24. Each PF station had green LED lights (2 lx) as minimal illumination to allow birds to navigate through the feeding station during the scotophase. The temperature was set at 34.5°C on d 0 and decreased by 0.5°C daily until d 22 after which the set temperature remained constant at 23.5°C. A neck tag was applied on d 0 for individual identification. A wing tag equipped with a radio frequency identification (**RFID**) transponder was applied to the right wing web of each bird on d 7 to allow the PF stations to identify each individual. All birds were fed individual meals using the PF system (Zuidhof et al., 2019). The source flock females were fed according to their live BW to achieve their trajectory-specific BW targets. If the bird's BW was greater than or equal to the programmed BW target, it was gently ejected from the station without gaining access to feed. If the bird's BW was below the programmed BW target, it was given access to a meal.

5.3.2.2 Egg Collection

Eggs were collected from the source flock over a 7 d period at 35 and 42 wk of age and stored at 18°C prior to incubation. The hen ID, date, and egg weight were recorded on each egg. At the end of each day, eggs were examined and selected for incubation based on egg shape, shell quality, egg weight and cleanliness. Unsettable eggs, defined to include those that were misshapen, thin shelled, weighed less than 52 g or covered with more than 3 mm of dirt, feces or blood were discarded.

5.3.3 Stocks and Management

5.3.3.1 Cohort 1

At 35 wk of age, 167 eggs were collected over 7 d from the broiler breeder source flock, then set in an incubator (37.5°C, 30% relative humidity; **RH**). Eggs were candled on d 7 of incubation and discarded if infertile (n = 12). On d 18 of incubation, eggs were weighed, transferred into pedigree hatching baskets and placed in a hatcher (30% RH, 37.5°C). At hatch, chicks (n = 105) were randomly assigned to 1 of 4 environmental chambers that contained 3 PF stations and ad libitum access to water (n = 1 chamber of 27 chicks; n = 3 chambers of 26 chicks). A wing tag equipped with an RFID transponder was applied to the right wing web of each chick on d 7 for individual identification within the PF stations.

5.3.3.2 Cohort 2

At 42 wk of age, 158 eggs were collected over 7 d from the broiler breeder source flock, then placed in an incubator set at 30% RH and 37.5°C. Eggs were candled on d 7 of incubation and discarded if infertile (n = 12). On d 18, eggs were weighed, transferred into pedigree hatching baskets and placed in a hatcher set at 30% RH and 37.5°C. At hatch, chicks (n = 112) randomly assigned to 1 of 4 environmental chambers with 3 PF stations and ad libitum access to water (n = 26, 29, 23, and 34 chicks per chamber). A wing tag equipped with an RFID transponder was applied to the right wing web of each chick on d 7 for individual identification within the PF stations.

5.3.3.3 Diets, Lighting and Temperature

Birds were fed commercial broiler diets: a starter crumble from d 0 to 10 (3,044 kcal ME, 23% CP, and 1% Ca), a grower crumble from 11 to 24 d (3,091 kcal ME, 20.5% CP, and 0.9% Ca) and a finisher pellet from d 25 to 35 (3,170 kcal ME, 21% CP, and 0.78% Ca). The photoschedule was 23L:1D (16 lx) from d 0 to 3, and decreased by 1 h of light each day until d 7 where the photoperiod remained at 19L:5D (8 lx) for the duration of the experiment. Temperature was set at 34°C on d 0 and decreased by 0.5°C per day until d 28 after which it remained constant at 20.0°C.

5.3.4 Precision Feeding System

The PF system design and function has been described elsewhere (Zuidhof et al., 2019). Briefly, the PF system provided multiple meals to individual broilers throughout the day, based on live BW. Each broiler voluntarily entered the station where it was recognized by its unique RFID. Broilers were fed ad libitum meaning they were given access to feed upon every station visit. The duration of each feeding bout was 60 s. During each feeding bout, broilers had access to 75 g of feed from 0 to 13 d, which was reduced to 65 g from d 14 to 35 to minimize feed wastage. Body weight and feed intake for every feeding bout was recorded in a database along with the RFID.

5.3.5 Data Collection

5.3.5.1 Body Weight and Average Daily Feed Intake

Body weight was manually recorded for each bird daily from d 0 to 11. Body weight was recorded in the PF database upon each station visit beginning on d 12 for the remainder of the experiment (on average, each bird visited the station 417 and 407 times for cohort 1 and 2, respectively). Body weight on d 35 was recorded using a hanging scale. To calculate feed conversion ratio (**FCR**), average daily feed intake (**ADFI**) was recorded in the PF database from d 8 (cohort 1) and 9 (cohort 2) during individual feeding because it was not possible to accurately measure ADFI for each bird prior to individual feeding. During the experiment for cohort 2, there was an unexpected PF system software update on d 7 and 8 which delayed individual feeding mode by 1 day.

5.3.5.2 Carcass Traits

The broilers were euthanized by cervical dislocation and immediately dissected on d 35. Breast muscle (pectoralis major and minor muscles), liver, heart, abdominal fat pad and the gastrointestinal tract (gut; 1 cm above the crop to the end of the colon) weights were recorded. The gastrointestinal tract was not completely emptied, however, all PF stations were closed 12 h prior to euthanasia to ensure the amount of contents in the gastrointestinal tract was low, and consistent among broilers.

5.3.6 Statistical Analysis

All statistical analyses were performed using the MIXED procedure in SAS (Version 9.4. SAS institute, Inc., Cary, NC). Egg weight (**EW**) was evaluated as a one-way ANOVA with maternal age the categorical effect, and maternal BW at photostimulation as a covariate. Maternal BW at photostimulation was used as a proxy for differences in BW across BW trajectories. The day on which eggs were collected was used as the random effect with individual breeder hen as the subject. Body weight, FCR and carcass traits were evaluated under 2 separate analyses with distinct scopes. The first analysis included broilers from all broiler breeders (full scope; including feed restricted and unrestricted broiler breeders), and the second analysis included broilers from feed restricted broiler breeders only (restricted scope; excluded the unrestricted broiler breeders). An ANOVA was conducted with maternal BW at photostimulation as the main effect (regressor), and maternal age and sex as categorical effects on broiler BW, FCR and carcass traits. Similar to the EW analysis, maternal BW at photostimulation was used as a proxy for differences in BW across BW trajectories. Due to convergence issues arising from model complexity, the intercept for each hen (maternal subject) was used as a random effect, rather than pen and individual broiler. Treatment effects on BW were evaluated on d 0, 7, 14, 21, 28 and 35. Feed conversion ratio was analyzed in 4 periods (d 7 to 14, 15 to 21, 22 to 28, and 29 to 35) and from d 7 to 35 (cumulative FCR). Least squares means were adjusting using Tukey's range test and were compared using the DIFF option. Differences were reported when $P \leq 0.05$.

Trends were reported when $0.05 < P \leq 0.10$.

5.4 Results and Discussion

Results are presented separately for each of the 2 analysis scopes. The full scope included broilers from feed restricted and unrestricted breeders. The restricted scope included broilers from feed restricted breeders only, excluding offspring from the unrestricted breeders. Interactions of maternal age, sex and maternal BW were not significant and were therefore removed from the statistical model.

5.4.1 Interpretation of Regression Coefficients

Regression coefficients for maternal BW were reported for offspring BW (Table 5.1), FCR (Table 5.2) and carcass traits (Table 5.3). The regression coefficient explained the effect of each dependent variable (BW, FCR and carcass traits) per kilogram increase in maternal BW. A negative sign of the regression coefficient indicated that the value of the dependent variable decreased with increasing maternal BW. A positive sign of the regression coefficient indicated that the value of the dependent variable increased with increasing maternal BW.

5.4.2 Body Weight

5.4.2.1 Full Scope

There was no effect of maternal BW on broiler offspring BW from 0 to 35 d of age (Table 5.1). On d 0, BW of offspring from 42 wk old breeders was 1.06 times that of offspring from 35 wk old breeders. On d 35, broilers from 42 wk old breeders were 95 g heavier than those from 35 wk old breeders. In contrast, on d 7, offspring from 42 wk old breeders weighed 23 g less than those from the 35 wk old flock. Offspring from the 42 wk old flock tended to be heavier than those from the 35 wk old flock on d 21 ($P = 0.088$, Table 5.1). Males were 95 and 126 g heavier than females on d 28 and 35, respectively (Table 5.1).

5.4.2.2 Restricted Scope

Offspring BW was not affected by maternal BW (Table 5.1). On d 0 and 35, BW of offspring from 42 wk old breeders were heavier (44.9 and 2,131 g) than that of offspring from 35 wk old breeders (42.5 and 2,036 g), respectively. On d 7 however, BW of offspring from 35 wk old breeders was 1.15 times that of offspring from 42 wk old breeders. Offspring from 42 wk old breeders tended to be 1.05 times heavier than those from 35 wk old breeders on d 21. On d 28 and 35, males were 95 and 162 g heavier than females, respectively (Table 5.1).

Body weight, independent of the analysis scope, was not affected by maternal BW, which does not support the original hypothesis that BW would increase as maternal BW increased. Thus, broiler breeders reared to achieve BW targets from 2.5 to 22.5% above the recommended targets or fed ab libitum produced offspring that had similar BW over a 35 d grow cycle. This is inconsistent with Humphreys (2020) who reported that offspring from hens reared 21% above the recommended BW target (high BW) were 3.9% heavier than offspring from hens reared on a standard BW on d 35. Moreover, van Emous et al. (2015) observed that broilers from high BW hens (200 g above standard BW curve) weighed 1.4% more than those from standard BW hens on d 35. Similar to the current study, Humphreys (2020) and van Emous et al. (2015) found that broiler hatch weight did not differ between high and standard BW hens. Egg and chick weights are positively correlated (Wilson, 1991; Tona et al., 2004; Lourens et al., 2006; Iqbal et al., 2016). Moreover, EW increased with hen BW (McDaniel et al., 1981). Reproductive performance of the broiler breeders in the current study was reported by Zukiwsky et al. (2020). Consistent with previous literature, the authors found that EW increased with BW. In the current study, eggs from the 42 wk old breeders on average weighed 65.0 g, which was 3.3 g heavier than those from the 35 wk old breeders ($P < 0.001$). Thus, greater hatch BW of offspring from 42 wk old breeders might have been due to greater EW.

Similar effects of maternal age and sex were observed between both analysis scopes, which was consistent with the hypotheses that BW would increase with maternal age, and males would be heavier than females. Specifically on d 0 and on 35, offspring from the 42 wk old breeders were heavier than those from 35 wk old breeders. This was expected as hatch weight (Peebles et al., 1999; Tona et al., 2004; Ulmer-Franco et al., 2010; El Sabry et al., 2013; Iqbal et al., 2016) and final BW (Ulmer-Franco et al., 2010; El Sabry et al., 2013) are reported to increase with maternal age. Further, male offspring from both analysis scopes were heavier than females on d 28 and 35. Bowling et al. (2018) evaluated growth performance of broilers from feed restricted hens with low (3.4), medium (3.5) or high (3.9 kg) BW. The authors found no difference in offspring BW from 0 to 35 d of age, however, male offspring from high BW hens were 227.4 g heavier than those from high BW hens on d 42. The authors reported that yolks from low BW hens had a corticosterone concentration 1.21 times greater than that of medium BW hens, and hypothesized that maternal feed restriction-induced stress might have reduced male offspring BW on d 42. It is possible that in the current study, sex-dependent differences in BW at the end of the growing cycle might have been due to the reduced stress as a result of increased maternal BW and concomitant relaxed levels of feed restriction.

5.4.3 Feed Efficiency

5.4.3.1 Full Scope

Feed efficiency was not affected by maternal BW during the 7 to 14, 15 to 21, 22 to 28 and 29 to 35 d of age periods (Table 5.2). However, cumulative FCR over the whole study (7 to 35 d) increased by 0.235 g:g/kg of maternal BW ($R^2 = 0.208$, $P < 0.001$). From d 29 to 35, FCR tended to be lower of offspring from 35 wk old breeders (1.319) compared to those from 42 wk old breeders (1.334 g:g; $P = 0.071$). Males had a significantly lower FCR (1.318) compared to females (1.335 g:g) from 29 to 35 d of age.

5.4.3.2 Restricted Scope

For every kilogram increase of maternal BW, offspring FCR decreased by 0.081 g:g from 15 to 21 d of age ($R^2 = 0.171$, $P = 0.026$). In addition, cumulative FCR increased by 0.471 g:g/kg of maternal BW ($R^2=0.048$, $P = 0.010$). Offspring FCR tended to decrease by 0.0910 and 0.0460 g:g per kilogram increase in maternal BW from d 7 to 14 ($P = 0.076$) and 22 to 28 ($P = 0.10$), respectively. There were no significant effects of maternal age and sex on FCR (Table 5.2), however, from d 29 to 35, offspring from 35 wk old breeders tended to be 1.29% more efficient than those from 42 wk old breeders ($P = 0.071$).

Cumulative FCR of offspring from both analysis scopes increased as maternal BW increased. This suggests that offspring from heavier BW hens were less efficient than those from heavy BW hens over a 7 to 35 d growth period, which is consistent with the hypothesis. Cumulative FCR might have been influenced by individual broiler variation in ADFI and motivation to seek feed within the PF system might have also influenced FCR. Feed conversion ratio of offspring from the restricted scope analysis decreased from 15 to 21 d of age as maternal BW increased. In other words from d 15 to 21, in the range of restricted maternal BW trajectories that were studied, offspring from heavy BW hens were less efficient than those from lighter BW hens.

5.4.4 Carcass Traits

5.4.4.1 Full Scope

There were no significant effects of maternal BW on the proportions of breast muscle, liver, heart, fat pad and gut weights (Table 5.3). The proportion of breast muscle weight tended to decrease by 0.4090%/kg of maternal BW ($R^2 = 0.190$, $P = 0.073$). Proportional breast weight of offspring from 42 wk old breeders was 1.04 times that of offspring from 35 wk old breeders. Similarly, proportional liver weight of offspring from 42 wk old breeders was 1.06 times greater than that of offspring from 35 wk old breeders. Proportional breast muscle weight of females was 1.05 times that of males, and the proportional weight of fat pad for females was 1.15 times greater than that of males (Table 5.3). Proportional heart weight was 1.20 times greater in males compared to females. Proportional gut weight of males tended to be 1.05 times greater than that of females ($P = 0.06$).

5.4.4.2 Restricted Scope

Proportional gut weight decreased by 0.8244%/kg of maternal BW ($R^2 = 0.114$, $P = 0.022$), while proportional breast muscle, liver, heart and fat pad weights were not affected by maternal BW (Table 5.3). The proportion of breast muscle yield was 1.03 times greater in offspring from 42 wk old breeders compared to that of 35 wk old breeders. Similar to the full scope analysis, various proportional organ weights were affected by sex (Table 5.3). Specifically, proportional breast and fat pad weights of females were 1.04 and 1.14 times that of males, respectively. Proportional heart and gut weights in males were 1.05 times greater than those in females, respectively.

There were minimal effects of maternal BW on carcass traits of offspring from both the full and restricted analysis scopes. Among offspring in the restricted analysis scope, gut weight decreased as maternal BW increased. A large gut is associated with increased nutrient absorption (Jackson and Diamond, 1996; further reviewed by Tallentire et al., 2016) and was also associated with increased average daily gain (Humphreys, 2020). In the restricted analysis scope of the current study, offspring from low BW hens had larger guts than those from high BW hens, which could have resulted in a lower FCR (Table 5.2). Thus, a smaller gut weight as a result of increased maternal BW may reduce broiler efficiency. The proportion of fat pad weight was not influenced by maternal BW of offspring from the full and restricted analysis scopes (Table 5.3). This was interesting to note since other literature reported the proportion of fat in broilers increased as a result of increased maternal BW (Humphreys, 2020; van der Waaij et al., 2011).

In both analysis scopes, offspring from 42 wk old breeders had greater proportional breast muscle yield compared to those from 35 wk old breeders. This may be explained by the natural allometric growth of breast muscle in broilers. Previous literature has reported that breast muscle weight increased with BW (Scheuermann et al., 2003; Zuidhof et al., 2014; van der Klein et al., 2017), which is consistent with the current results as offspring from 42 wk old breeders were heavier than those from 35 wk old breeders on d 35. In addition, proportional liver weight increased with maternal age in offspring from the full analysis scope, however, this was not observed in offspring from the restricted analysis scope. The liver is an important metabolic organ that supports growth and development. A heavy BW broiler might have a larger liver to support greater maintenance requirements compared to a lighter BW broiler. Thus, greater proportional liver weight might be related to greater BW on d 35 of broilers from 42 wk old breeders than those from 35 wk old breeders in the full analysis scope.

A primary result of decades of genetic selection has increased breast muscle yield and decreased the proportion of carcass fat. Females in both analysis scopes had greater proportional weight of breast muscle and abdominal fat pad compared to males. Moreover, proportional heart weight of males was greater than that for females. These results were expected because it is well established that females have a larger proportion of breast muscle (Grey et al., 1982; Young et al., 2001; Moraes et al., 2014; Zuidhof et al., 2014; Moraes et al., 2019) and abdominal fat pad

(Brake et al., 1993; Moraes et al., 2014; Zuidhof et al., 2014; Humphreys, 2020) compared to males, while males have a greater proportional heart weight compared to females (Brake et al., 1993; Zuidhof et al., 2014; Humphreys, 2020). In the restricted scope analysis, males had a greater proportional gut weight compared to females, which is consistent with van der Klein et al. (2017) and Humphreys (2020). The gut is responsible for nutrient absorption, which plays a key role in metabolism to support growth and muscle development. Specific to the restricted analysis scope, males were heavier than females on d 35. Thus, males might have had a greater proportional gut weight than females to support maintenance requirements associated with a greater BW.

5.5 Conclusion

In conclusion, there were several notable effects of maternal age and sex on BW, FCR and carcass traits. Consistent with previous literature and the current hypotheses, BW increased with maternal age, and males were heavier than females. Moreover, females had a greater proportion of breast muscle yield and abdominal fat compared to males. In the range of restricted maternal BW trajectories that were studied, relaxed maternal feed restriction and unrestricted feed intake did not affect broiler offspring BW during the entire growth cycle. Consistent with the hypothesis, cumulative FCR from d 7 to 35 decreased as maternal BW increased among broilers from the full and restricted analysis scopes. This reduction in offspring feed efficiency may have been due to increased maintenance requirement as BW increased. In the range of maternal BW trajectories studied, the impact on offspring carcass traits was less than expected. Notably, proportional gut weight of broiler offspring in the restricted scope analysis decreased with increasing maternal BW, which might have contributed to reduced feed efficiency. Overall, it was concluded that increased maternal BW up to 22.5% above the recommended BW and unrestricted growth had little impact on broiler growth performance. This suggests that increasing female broiler breeder BW targets to lower the severity of feed restriction would reduce gut weight and increase feed efficiency in broiler offspring.

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5.7 References

Aviagen, 2016a. Ross 708 Parent Stock: Performance Objectives. Aviagen, Huntsville, AL.

Aviagen, 2016b. Yield Plus Male Standards - Metric. Aviagen, Huntsville, AL.

Bowling, M., R. Forder, R. J. Hughes, S. Weaver, and P. I. Hynd. 2018. Effects of restricted feed intake in broiler breeder hens on their stress levels and the growth and immunology of their offspring. Transl. Anim. Sci. 2: 263-271.

Brake, J., G. B. Havenstein, S. E. Scheideler, P. R. Ferket and D. V. Rives. 1993. Relationship of sex, age, and body weight to broiler carcass yield and offal production. Poult. Sci. 72:1137–1145.

CCAC. 2009. CCAC guidelines on: The care and use of farm animals in research, teaching and testing. Canadian Council on Animal Care, Ottawa, ON.

D’Eath, R. B., B. J. Tolkamp, I. Kyriazakis, and A. B. Lawrence. 2009. ‘Freedom from hunger’ and preventing obesity: The animal welfare implications of reducing food quantity or quality. Anim. Behav. 77:275–288.

El Sabry, M. I., S. Yalçin, and G. Turgay-Izzetoglu. 2013. Interaction between breeder age and hatching time affects intestine development and broiler performance. Livest. Sci. 157:612–617.

Enting, H., W. J. A. Boersma, J. B. W. J. Cornelissen, S. C. L. van Winden, M. W. A. Verstegen, and P. J. van der Aar. 2007. The effect of low-density broiler breeder diets on performance and immune status of their offspring. Poult. Sci. 86:282–290.

Grey, T. C., D. Robinson, and J. M. Jones. 1982. Effect of age and sex on the eviscerated yield, muscle and edible offal of a commercial broiler strain. Br. Poult. Sci. 23:289–298.

Hadinia, S. H., P. R. O. Carneiro, D. R. Korver and M. J. Zuidhof. 2019. Energy partitioning by broiler breeder hens in conventional daily-restricted feeding and precision feeding systems. Poult. Sci. 98:6721–6732.

Hocking, P. M. 1993. Roles of body weight and feed intake in ovarian follicular dynamics in broiler breeders at the onset of lay and after a forced molt. Poult. Sci. 83:2044–2050.

Humphreys, K. D. 2020. Implications of altering maternal feed availability and feeding system on offspring performance. MSc. Thesis. University of Alberta, Edmonton, Alberta, Canada.

Iqbal, J., S. H. Khan, N. Mukhtar, T. Ahmed, and R. A. Pasha. 2016. Effects of egg size (weight) and age on hatching performance and chick quality of broiler breeder. J. Appl. Anim. Res. 44:54–64.

Jackson, S., and J. Diamond. 1996. Metabolic and digestive responses to artificial selection in chickens. Evolution. 50:1638–1650.

Katanbaf, M. N., E. A. Dunnington, and P. B. Siegel. 1989. Restricted feeding in early and late-feathering chickens. Poult. Sci. 68:352–358

Latshaw, J. D., and J. S. Moritz. 2009. The partitioning of metabolizable energy by broiler chickens. Poult. Sci. 88:98–105.

Lippens, M., G. Room, D. De Groote, and E. Decuypere. 2010. Early and temporary quantitative food restriction of broiler chickens. 1. Effects on performance characteristics, mortality and meat quality. Br. Poult. Sci. 41:343–354.

Lourens, A., R. Molenaar, H. van den Brand, M. J. W. Heetkamp, R. Meijerhof, and B. Kemp. 2006. Effect of egg size on heat production and the transition of energy from egg to hatchling. Poult. Sci. 85:770-776.

McDaniel, G. R., J. Brake, and M. K. Eckman. 1981. Factors affecting broiler breeder performance. 4. The relationship of some reproductive traits. Poult. Sci. 60:1792–1797.

Moraes, T. G. V., A. Pishnamazi, E. T. Mba, I. I. Wenger, R. A. Renema, and M. J. Zuidhof. 2014. Effect of maternal dietary energy and protein on live performance and yield dynamics of broiler progeny from young breeders. Poult. Sci. 93:2818–2826.

Moraes, T. G. V., A. Pishnamazi, I. I. Wegner, R. A. Renema, and M. J. Zuidhof. 2019. Energy and protein dilution in broiler breeder pullet diets reduced offspring body weight and yield. Poult. Sci. 98:2555–2561.

Peebles, E. D., S. M. Doyle, T. Pansky, P. D. Gerard, M. A. Latour, C. R. Boyle, and T. W. Smith. 1999. Effects of breeder age and dietary fat on subsequent broiler performance. 1. Growth, mortality, and feed conversion. Poult. Sci. 78:505–511.

Renema, R. A., M. E. Rustad, and F. E. Robinson. 2007. Implications of changes to commercial broiler and broiler breeder body weight targets over the past 30 years. Worlds Poult. Sci. J. 63:457–472.

Scheuermann, G. N., S. F. Bilgili, J. B. Hess, and D. R. Mulvaney. 2003. Breast muscle development in commercial broiler chickens. Poult. Sci. 82:1648–1658.

Tallentire, C. W., I. Leinonen, and I. Kyriazakis. 2016. Breeding for efficiency in the broiler chicken: A review. Agron. Sustain. Dev. 36:66. https://doi.org/10.1007/s13593-016-0398-2.

Tona, K., O. Onagbesan, B. De Ketelaere, E. Decuypere, and V. Bruggeman. 2004. Effects of age of broiler breeders and egg storage on egg quality, hatchability, chick quality, chick weight, and chick posthatch growth to forty-two days. J. Appl. Poult. Res. 13:10–18.

Ulmer-Franco, A. M., G. M. Fasenko, and E. E. O'Dea Christopher. 2010. Hatching egg characteristics, chick quality, and broiler performance at 2 breeder flock ages and from 3 egg weights. Poult. Sci. 89:2735–2742.

van der Klein, S. A., F. A. Silva, R. P. Kwakkel, and M. J. Zuidhof. 2017. The effect of quantitative feed restriction on allometric growth in broilers. Poult. Sci. 96:118–126.

van der Waaij, E. H., H. van den Brand, J. A. M. van Arendonk, and B. Kemp. 2011. Effect of match or mismatch of maternal–offspring nutritional environment on the development of offspring in broiler chickens. Animal. 5:741–748.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, H. van den Brand, and W. H. Hendriks. 2015. Effects of growth patterns and dietary protein levels during rearing of broiler breeders on fertility, hatchability, embryonic mortality, and offspring performance. Poult. Sci. 94:681-691.

Wilson, H. R. 1991. Interrelationship of egg size, chick size, posthatching growth and hatchability. Worlds Poult. Sci. J. 47:5-20.

Young, L. L., J. K. Northcutt, R. J. Buhr, C. E. Lyon, and G. O. Ware. 2001. Effects of age, sex, and duration of post-mortem aging on percentage yield of parts form broiler chicken carcasses. Poult. Sci. 80:376–379.

Yu, M. W., and F. E. Robinson. 1992. The application of short-term feed restriction to broiler chicken production: A review. J. Appl. Poult. Res. 1:147–153.

Yu, M. W., F. E. Robinson, R. G. Charles, and R. Weingardt. 1992. Effect of feeding allowance during rearing and breeding on female broiler breeders. 2. Ovarian morphology and production. Poult. Sci. 71:1750–1761.

Zuidhof, M. J. 2018. Lifetime productivity of conventionally and precision-fed broiler breeders. Poult. Sci. 97:3921–3937.

Zuidhof, M. J., M. V. Fedorak, C. C. Kirchen, E. H. M. Lou, C. A. Ouellette, and I. I. Wenger. 2019. United states patent: System and method for feeding animals. PrecisionZX, Inc., assignee. Pat. No. US 10,506,793 B2.

Zuidhof, M. J., B. L. Schneider, V. L. Carney, D. R. Korver, and F. E. Robinson. 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. Poult. Sci. 93:2970–2982.

Zukiwsky, N. M., M. Afrouziyeh, F. E. Robinson, and M. J. Zuidhof. 2020. Feeding, feed seeking behavior and reproductive performance of broiler breeders under conditions of relaxed feed restriction. Manuscript PSJ-S-20-01326. Submitted to Poult. Sci. August 12, 2020.

5.8 Tables

Table 5.1 Body weight of broiler offspring on d 0, 7, 14, 21, 28 and 35 according to the full[1] and restricted[2] scope analyses. The regression coefficient was reported for maternal BW at photostimulation (PS) as a continuous effect, and LSMeans were reported for categorical effects maternal age (MA) and sex.

				Age (d)											
Scope	Effect	MA	Sex	0	SEM	7	SEM	14	SEM	21	SEM	28	SEM	35	SEM
Full	Continuous			g/kg											
	BW at PS			0.484	0.667	-1.811	2.309	-8.692	7.255	-17.339	17.075	-32.281	27.712	-36.987	35.042
	Categorical			g											
	MA (wk)	35		42.5^{b}	0.4	164^{a}	2.0	424	6.5	860	13.8	1,479	24.0	$2{,}022^{b}$	30.4
		42		45.1^{a}	0.4	141^{b}	2.0	424	5.9	895	14.6	1,531	24.6	$2{,}117^{a}$	32.4
	Sex		M	43.9	0.4	152	2.0	430	6.4	895	16.3	$1{,}552^{a}$	28.6	$2{,}151^{a}$	36.6
			F	43.6	0.4	152	2.0	419	5.9	860	11.9	$1{,}457^{b}$	19.2	$1{,}989^{b}$	25.2
	Source of variation			Probability											
	BW at PS			0.47		0.44		0.24		0.32		0.25		0.30	
	MA			< 0.001		< 0.001		0.99		0.088		0.13		0.033	
	Sex			0.60		0.92		0.21		0.083		0.006		< 0.001	
Restricted	Continuous			g/kg											
	BW at PS			0.327	2.830	11.088	7.734	34.186	26.054	76.415	63.726	95.928	100.640	96.099	125.100
	Categorical			g											
	MA (wk)	35		42.5^{b}	0.4	164^{a}	2.1	426	7.2	865	15.16	1,489	26.0	$2{,}036^{b}$	32.0
		42		44.9^{a}	0.5	142^{b}	2.1	430	5.9	905	15.50	1,545	25.5	$2{,}131^{a}$	34.6
	Sex		M	43.9	0.5	152	2.1	432	6.8	900	17.4	$1{,}561^{a}$	30.0	$2{,}160^{a}$	39.0
			F	43.5	0.4	154	2.1	424	6.4	870	12.9	$1{,}472^{b}$	20.6	$2{,}007^{b}$	26.5
	Source of variation			Probability											
	BW at PS			0.91		0.16		0.20		0.24		0.35		0.45	
	MA			< 0.001		< 0.001		0.62		0.066		0.13		0.047	
	Sex			0.52		0.61		0.37		0.16		0.016		0.002	

[1] Full scope analysis included broiler offspring from feed restricted and unrestricted hens. Feed restricted hens were reared according to 10 unique BW trajectories as maternal treatments that varied in pre-pubertal and pubertal phases of growth up to 22.5% above the recommended Ross 708 BW target, in 2.5% increments. Six additional hens were unrestricted (not limited to a maximum BW).

[2] Restricted scope analysis excluded broiler offspring from unrestricted broiler breeders.

[a, b] LSMeans within analysis scope, column, and effect with no common superscript differ (*P* < 0.05).

Table 5.2 Cumulative FCR and FCR over four periods from 7 to 35 d of age of broiler offspring according to the full[1] and restricted[2] scope analyses. The regression coefficient was reported for maternal BW at photostimulation (PS) as a continuous effect, and LSMeans were reported for categorical effects maternal age (MA) and sex.

				Age (d)									
				7 to 14		15 to 21		22 to 28		29 to 35		Cumulative FCR	
Scope	Effect	MA	Sex	FCR	SEM	FCR	SEM	FCR	SEM	FCR	SEM	FCR	SEM
Full	Continuous			g:g/kg									
	BW at PS			0.003	0.013	0.006	0.009	0.005	0.007	0.004	0.007	0.235	0.065
	Categorical			g:g									
	MA (wk)	35		0.901	0.014	1.059	0.008	1.225	0.006	1.319	0.006	1.489	0.066
		42		0.929	0.013	1.068	0.008	1.231	0.006	1.334	0.005	1.529	0.064
	Sex		M	0.912	0.014	1.060	0.008	1.223	0.006	1.318[b]	0.006	1.484	0.066
			F	0.919	0.013	1.067	0.009	1.233	0.006	1.335[a]	0.005	1.534	0.064
	Source of variation			Probability									
	BW at PS			0.81		0.55		0.46		0.52		< 0.001	
	MA			0.14		0.43		0.48		0.071		0.67	
	Sex			0.71		0.57		0.23		0.040		0.59	
Restricted	Continuous			g:g/kg									
	BW at PS			-0.091	0.051	-0.081	0.034	-0.046	0.027	-0.003	0.028	0.471	0.181
	Categorical			g:g									
	MA (wk)	35		0.900	0.016	1.053	0.009	1.221	0.006	1.317	0.008	1.420	0.063
		42		0.926	0.014	1.066	0.009	1.229	0.006	1.334	0.005	1.457	0.058
	Sex		M	0.913	0.016	1.059	0.009	1.222	0.006	1.319	0.007	1.443	0.056
			F	0.913	0.015	1.060	0.009	1.228	0.006	1.332	0.006	1.434	0.056
	Source of variation			Probability									
	BW at PS			0.076		0.026		0.10		0.93		0.010	
	MA			0.23		0.31		0.36		0.071		0.67	
	Sex			0.99		0.95		0.49		0.14		0.92	

[1] Full scope analysis included broiler offspring from feed restricted and unrestricted hens. Feed restricted hens were reared according to 10 unique BW trajectories as maternal treatments that varied in pre-pubertal and pubertal phases of growth up to 22.5% above the recommended Ross 708 BW target, in 2.5% increments. Six additional hens were unrestricted (not limited to a maximum BW).

[2] Restricted scope analysis excluded broiler offspring from unrestricted broiler breeders.

[a, b] LSMeans within analysis scope, column, and effect with no common superscript differ ($P < 0.05$).

Table 5.3 Breast, liver, heart, abdominal fat pad and gut weight as a percentage of live BW of 35 d old broiler offspring according to the full[1] and restricted[2] scope analyses. The regression coefficient was reported for maternal BW at photostimulation (PS) as a continuous effect, and LSMeans were reported for categorical effects maternal age (MA) and sex.

Scope	Effect	MA	Sex	Breast	SEM	Liver	SEM	Heart	SEM	Fat pad	SEM	Gut	SEM
Full	Continuous			% yield/kg									
	BW at PS			-0.4090	0.2217	0.0209	0.0236	-0.0023	0.0104	-0.0008	0.0368	0.0974	0.1161
	Categorical			% of live BW									
	MA (wk)	35		20.93^{b}	0.20	1.80^{b}	0.02	0.56	0.01	1.33	0.03	6.20	0.10
		42		21.70^{a}	0.22	1.85^{a}	0.02	0.58	0.01	1.40	0.03	6.06	0.10
	Sex		M	20.83^{b}	0.23	1.83	0.02	0.60^{a}	0.01	1.23^{b}	0.03	6.26	0.09
			F	21.81^{a}	0.18	1.82	0.02	0.55^{b}	0.01	1.45^{a}	0.03	5.99	0.12
	Source of variation			Probability									
	BW at PS			0.073		0.38		0.83		0.98		0.41	
	MA			0.009		0.047		0.17		0.15		0.33	
	Sex			0.001		0.54		< 0.001		< 0.001		0.06	
Restricted	Continuous			% yield/kg									
	BW at PS			0.9186	0.8514	-0.1167	0.0843	-0.0518	0.0396	-0.0068	0.1525	-0.8244	0.3394
	Categorical			% of live BW									
	MA (wk)	35		21.11^{b}	0.22	1.80	0.02	0.56	0.01	1.35	0.03	6.15	0.10
		42		21.78^{a}	0.24	1.85	0.02	0.58	0.01	1.38	0.04	6.01	0.11
	Sex		M	21.00^{b}	0.20	1.83	0.02	0.59^{a}	0.01	1.27^{b}	0.04	6.24^{a}	0.13
			F	21.90^{a}	0.25	1.81	0.02	0.55^{b}	0.01	1.45^{a}	0.03	5.93^{b}	0.08
	Source of variation			Probability									
	BW at PS			0.29		0.18		0.20		0.96		0.022	
	MA			0.038		0.13		0.27		0.57		0.35	
	Sex			0.005		0.46		0.004		< 0.001		0.039	

[1] Full scope analysis included broiler offspring from feed restricted and unrestricted hens. Feed restricted hens were reared according to 10 unique BW trajectories as maternal treatments that varied in pre-pubertal and pubertal phases of growth up to 22.5% above the recommended Ross 708 BW target, in 2.5% increments. Six additional hens were unrestricted (not limited to a maximum BW).

[2] Restricted scope analysis excluded broiler offspring from unrestricted broiler breeders.

[a, b] LSMeans within analysis scope, column, and effect with no common superscript differ (*P* < 0.05).

6.0 Chapter 6: Synthesis

6.1 General Discussion

The research conducted as part of this thesis investigated broiler breeder management, and in particular, manipulation of body weight (**BW**) and relaxed feed restriction using a precision feeding (**PF**) system (Zuidhof et al., 2019). The PF system allows for various BW trajectories to be assigned to individual birds. As such, it is possible to evaluate hunger and reproductive performance as a result of increased BW and relaxed feed restriction, and further investigate the consequence of maternal BW on broiler growth performance. However, as outlined in Chapter 2.3, there are challenges associated with the PF system, specifically with training chicks how to eat from the PF stations to set them up for success later in life.

6.1.1 Aggression in Broiler Breeder Chicks

The first experiment in this thesis (Chapter 3) focused on the outcomes of using an automated marking system (**AMS**) prototype in a PF station during the first 3 wk of life, otherwise described as the training period. The PF system has reduced variance in BW for broiler breeders, specifically by a CV of less than 2% by 19 wk of age (Zuidhof et al., 2017). However, Zuidhof (2018) demonstrated that BW CV of broiler breeder chicks fluctuated between 5 to 10% for the first 5 wk of age. Chicks undergo training during the first 2 to 3 weeks of life to learn how to successfully eat from stations individually. Without proper training, chicks might not achieve their target BW from a young age. An automated marking system (**AMS**) prototype was implemented into a single PF station which marked chicks that ate from the feeder with dye. Chicks with minimal to no dye markings could be identified as chicks that need additional training to learn how to successfully eat from the PF system. Artificial dye markings have stimulated aggressive behaviours such as pecking and aggressive encounters between pen mates

(Estevez et al., 2003; Dennis et al., 2008). However, there is limited literature that associates dye markings with aggression performed by broiler breeder chicks. Thus, it was essential to determine whether the dye markings used as an identification method during the first 3 wk of life would stimulate aggression among breeder chicks. The results reported in Chapter 3 demonstrated there was a significant increase in aggressive pecking of chicks that were marked with the AMS at 26 d of age, but this is beyond the time at which it is recommended to use to the AMS during the training period. This suggests that there is potential to implement an AMS prototype in future PF studies to assist with identifying chicks that need additional assistance learning how to eat from the system, without stimulating aggression.

6.1.2 Optimizing Broiler Breeder BW and the Degree of Feed Restriction

Broiler breeder management can be a challenge. In the past, broiler breeder pullets have been severely feed restricted to control BW and optimize reproductive performance. Broiler breeder BW targets have seen little change while the genetic potential of the pullets and their offspring has increased (Renema et al., 2007). This also means that the severity of feed restriction for broiler breeders has remained constant to achieve the recommended BW targets. Welfare has become an important focus of modern livestock production. Feed restriction leads to hunger and stress, which is a clear welfare issue (D'Eath et al., 2009; Tolkamp and D'Eath 2016). For the first time, Zuidhof (2018) suggested that there is a need to increase BW targets to support egg production of precision-fed broiler breeders, which would in turn relax the degree of feed restriction to address welfare concerns. This was the foundation of the objectives and hypotheses in Chapter 4, which implemented various BW trajectories to evaluate hunger and reproductive performance as a result of increased BW and concomitant levels of relaxed feed restriction. The results of Chapter 4 demonstrated that broiler breeders reared on a range of BW trajectories from the recommended BW up to 22.5% above the recommended target had similar reproductive performance, which was evidence that led to reject the hypothesis that reproductive performance would decrease with increased BW at photostimulation. Notably, unrestricted feeding advanced age at first egg, and there were no differences in egg production as BW targets increased or between unrestricted versus feed restricted hens. Moreover, feed seeking behaviour was not significantly reduced across feed restricted birds during rearing, which suggested a 22.5% increase above BW targets did not reduce hunger. These results provide insight that BW targets of precision-fed birds can be increased without negatively effecting reproductive performance, but also in attempt to reduce hunger by allowing birds to consume more feed to achieve greater BW targets.

6.1.3 Broiler Growth Performance

The primary goal of broiler breeder management is to produce efficient and high-yielding offspring for meat consumption. This is a challenge as the growth potential of broilers has increased tremendously over the past 60 years (Zuidhof et al., 2014), while little change has been implemented to broiler breeder management, specific to BW targets (Renema et al., 2007). It is crucial for both the hatching egg and broiler industries to understand the potential repercussions of increased broiler breeder BW on offspring performance before making recommendations and considering implementation of changes in industry broiler breeder BW targets. Maternal BW has affected hatch weight and long term growth performance of broiler offspring (van der Waaij et al., 2011; van Emous et al., 2015; Bowling et al., 2018; and Humphreys, 2020). However, growth performance is also affected by maternal age (Peebles et al., 1999; Tona et al., 2004; Iqbal et al., 2016) and broiler sex (Brake et al., 1993; Young et al., 2001; Moraes et al., 2014; Zuidhof et al., 2014). Thus, there is a complex relationship between broiler breeder management and the effects of offspring performance. The primary purpose of the experiment in Chapter 5 was to investigate broiler growth performance in response to increased maternal BW. As reported in Chapter 5, there were few significant effects of increased maternal BW on offspring BW, efficiency and carcass traits. Notably, cumulative feed efficiency decreased as maternal BW increased, which suggests offspring from high BW hens are less efficient than those from low BW hens. In addition, offspring gut weight decreased as maternal BW increased, which may have contributed toward the reduced feed efficiency. Overall, it was concluded that broiler offspring performance was greatly influenced by maternal age and broiler sex, similar to findings of previous literature.

6.2 Novelty of Research

Chapter 3 of this thesis was the first experiment to evaluate whether artificial dye markings from an AMS prototype implemented in the PF system promoted aggression among chicks. It was determined that the dye markings from the AMS prototype promoted aggressive pecking at 26 d of age, however as previously summarized in Chapter 3, this was beyond the age at which the AMS would be used as an identification method during the training phase. Thus, there is potential to implement the AMS into individual PF stations for the first 3 wk of life to assist with identifying chicks that need additional training to learn how to eat from the PF station feeder. Further, to our knowledge, there is no literature on chick aggression and behaviour between 7 to 26 d of age. The experiment in Chapter 3 discovered that chicks performed a great amount of feather pecking from 7 to 26 d of age, which is interpreted as an exploratory behaviour to familiarize themselves with their surroundings rather than aggression. These findings provide insight on chick behaviour and welfare, and suggest broiler breeders perform few, if any, aggressive behaviours such as aggressive pecks, threats or fights at a very young age.

The experiment conducted in Chapter 4 was the first study in which a large range of BW trajectories were preassigned to broiler breeders using the PF system. Previous works had implemented two trajectories to broiler breeders to achieve target BW of 22% above the recommended BW targets (van der Klein, et al., 2018a; van der Klein et al., 2018b), however the current thesis included the first experiment that implemented 10 different BW trajectories. The BW trajectories were created from a multi-phase growth model which estimated and manipulated growth in pre-pubertal and pubertal phases, rather than a single target BW which has been the common method of modeling growth for poultry in the past (Zuidhof, 2020). The experiment in Chapter 4 was also the first time broiler breeders were fed ad libitum using the PF system. It was hypothesized that unrestricted feeding would reduce reproductive performance. However, there was no severe negative effect ad libitum precision-fed broiler breeders on reproductive performance other than age at first egg was advanced prior to photostimulation (22 wk of age); 2 of the 6 unrestricted hens came into lay during 20 and 21 wk of age while the remaining hens in the experiment laid their first egg from 24 to 25 wk of age. Initially it was of concern that the unrestricted birds would become too heavy, and their legs would not be able to support their BW when ejected from the PF stations. One unrestricted bird had a concerning leg injury and was culled at 24 wk of age, while the other unrestricted birds (n = 5) lived for the remainder of the experiment with no leg injuries that resulted in mortality.

In extension of Chapter 4, Chapter 5 similarly presented novel research in which offspring growth performance was evaluated in response to a large range in maternal BW and concomitant levels of relaxed feed restriction. Previous research had investigated broiler BW and carcass traits in response to maternal BW, however, compared offspring from standard BW hens to hens that were reared 9.1 (van Emous et al., 2015) and 21% (Humphreys, 2020) above the standard BW.

6.3 Study Limitations

The PF system was developed in 2014, and has been used in focus of multiple research experiments since that time. Over years of work and studies, limitations of the feeding technology have been identified and corrective actions have been taken to improve the overall system. The current PF system and experiments were highly successful, however like many new technologies some limitations were identified over the course of the research presented in this thesis.

The AMS prototype (Chapter 3) was implemented as part of the PF system. One AMS prototype was available for use in the current experiment, and was previously tested in a pilot study conducted in 2018. During the current research, a novel method of manually marking the chicks with dye was created to replicate the dye markings from the AMS. Some challenges arose while creating the manual marking method since it had not been performed in the previous pilot study. For example, the method was tested on frozen, culled chicks prior to the first day of manual marking. However, the frozen feathers did not absorb the dye effectively. It was additionally observed that the dye on the manually marked chicks would fade over the week before they were re-marked 7 d later, while the chicks marked by the AMS received new dye markings each day if they visited and ate from the feeder. There were also challenges with programming the AMS prototype to continuously run during the beginning of the experiment from d 5 to 11. As such, it was required to check the AMS prototype multiple times throughout the day to monitor activity and reset the system as needed to ensure it was continuously running. In future studies, it is recommended that an additional AMS prototype is used to create a replicated treatment group to increase the power of statistical analysis. Alternatively, a new manual marking method could be developed and tested prior to the beginning of the next experiment in which the AMS is used. The new method could include more frequent marking throughout the weeks when the AMS is used.

There was a notable increase in feather pecking and feather licking that occurred from d 19 to 26 in the experiment outlined in Chapter 3. The feather pecking was initially observed to be directed at the new white chick plumage growing in on the tail, wings and body. By 20 d of age the feather licking and pecking reached a point where feathers were completely removed and the tails were bare and bleeding in the most severe cases. Initially, the increased frequency of feather pecking and feather licking began in a single chamber which contained 2 pens; one pen of manually marked birds and one pen of control birds with no dye. A few days later, the feather pecking and feather licking increased in a second chamber that contained 2 replicated pens of manually marked and control chicks. After the experiment ended, the frequency of feather pecking and feather licking increased in the single pen of chicks marked by the AMS prototype, however, it was not as severe compared to the other chambers. The increased frequency of feather pecking and feather licking that occurred over the last 2 days of behaviour observations undoubtedly contributed toward the frequency of gentle and severe feather pecks.

There were some unexpected issues that occurred with the PF system design and software. Software updates are important to improve features of the PF system. During experiment 2 (Chapter 5) a software update occurred during the training period on d 7. As a result, multiple stations in all pens ceased activity because multiple errors occurred after the software update, meaning the chicks did not have access to the PF stations. Unfortunately, this happened after routine barn checks occurred in the afternoon, and the errors were discovered over the online application that allowed personnel and staff to monitor the stations remotely. Some stations appeared as though they were unaffected by the software update error, however when checking the barn the next day, the online application was not accurate and more stations were inactive compared to what the online application reported. Because most of the stations were inactive, the majority of chicks lost BW and required an additional day of training to give the chicks a chance to reach their daily BW target and learn how to eat successfully from the station. The BW loss during this time did not appear to affect the overall growth performance in comparison to the broilers in experiment 1, which might be because the restriction occurred for a short period of time at a young age.

During the training period for each experiment in Chapters 3 to 5, there was a software issue that occurred during individual feeding mode. Specifically, the issue did not allow a bird to progress from the sorting to feeding stage, which would result in the station being inactive for 5 to 10 minutes. Not being allowed to advance to the feeding stage could have created a negative experience for the particular chick that was not able to advance. The feed located in the feeding stage acted as a reward for chicks which motivated them to enter the station. However, if not able to proceed to the feeding stage, they would not receive a reward for entering the station. Ultimately, this might have made chicks hesitant to enter the station, and they would not receive a meal and lose BW. Thus, those chicks required additional training to learn how to successfully eat from the station as described in Chapter 3. It is important to note that even with the software issue, all chicks were successfully trained in Chapters 3 through 5 and learned how to eat within the stations individually.

6.4 Direction of Future Research

There are many opportunities for future studies based on the current research. Chapter 4 evaluated hunger through assessing feeding and feed seeking behaviours of precision-fed birds, and two new questions originated from the results of that experiment. It appeared as though station visit frequency was an appropriate feed seeking behaviour to evaluate hunger because during rearing, the number of station visits of feed restricted broiler breeders (excluding the unrestricted birds) was not affected by increased BW at photostimulation. This means that even though BW increased up to 22.5% above the recommended BW, and feed restriction was relaxed to achieve a greater BW, birds experienced hunger during rearing. This poses the first question of what is the optimal BW trajectory and concomitant level of feed restriction in which hunger is reduced? In contrast to station visit frequency, the number of meals, meal frequency and ADFI on the other hand reflected nutrient intake to achieve trajectory-specific BW targets. Thus, a second question is what other behaviours can be used to evaluate and better reflect hunger of precision-fed birds? There are various behaviours related to activity level (sitting, standing and foraging) and stereotypical oral behaviours (drinker pecking and feeder pecking) that have been used to evaluate hunger in other broiler breeder research that could be applied in future PF studies (D'Eath et al., 2009; Arrazola et al., 2019a; Arrazola et al., 2019b). As such, there is potential for future studies to evaluate hunger through various behaviours in attempt to determine an optimal BW trajectory that reduces hunger.

In addition, there is potential to collaborate with behaviour and welfare specialists, or include detailed welfare assessment of poultry in future PF-focused studies. Specifically, future PF research could include physiological measures of stress to assess the welfare of feed restricted broiler breeders. An example of a physiological measure include blood samples to assess the heterophil:lymphocyte ratio (as reviewed by D'Eath et al., 2009). There is also potential to compare physiological welfare parameters of precision-fed and conventionally fed birds.

The inspiration for experiments in Chapters 4 and 5 originated from previous works conducted by Dr. Zuidhof's research team that suggested future PF research evaluate broiler breeder performance as a result of increased BW and relaxed levels of feed restriction (Zuidhof, 2018; Hadinia et al., 2019; van der Klein et al., 2018a; van der Klein et al., 2018b). The research presented in this thesis explored various maternal BW trajectories, however the optimal BW trajectory for broiler breeders remains unknown. Results from Chapter 4 suggested BW targets of precision-fed breeders could be increased without negatively effecting reproduction, and further did not affect offspring BW with minimal impact on carcass composition and efficiency (Chapter 5). Growth modeling has been used to predict growth in meat and egg-type chickens, but there has been limited work to model broiler breeder growth. Over the past 25 years, growth modeling has advanced from using single to multiphasic growth models to better estimate development according to pre-pubertal and pubertal growth (Kwakkel et al., 1993; Kwakkel et al., 1995). However, these models were developed in the 1990s and there has been little development in growth modeling since that research (Zuidhof, 2020). A recently proposed growth model includes 3 phases (pre-pubertal, pubertal and post-pubertal growth) in attempt to more closely predict and alter broiler breeder BW targets as pressures from genetic change continue to evolve (Zuidhof, 2020). Hence, there are opportunities for future growth modeling research to better understand and predict BW of modern broiler breeders, which can be carried out efficiently using the PF system.

It would also be of great value to conduct future broiler breeder and offspring studies in which broiler breeder and broiler offspring performance is evaluated in response to manipulated broiler breeder BW. Prior to the presented research, one additional broiler breeder – broiler life-time study using the PF system was conducted (van der Klein et al., 2018a; van der Klein et al., 2018b; Humphreys, 2020). Humphreys (2020) had a more general focus on epigenetics of maternal BW on broiler growth. The current experiments (Chapter 5) did not focus on epigenetics in particular, however, there was a collaboration with epigenetic researchers that evaluated the effect of various BW trajectories on female broiler breeder hepatic gene expression, and consequent effects on reproductive hormone regulation and lipid metabolism. The researchers further evaluated if differences in maternal gene expression were passed onto their offspring. Ultimately, epigenetics studies might provide additional insight to the results outlined in Chapter 5.

6.5 Overall Implications

To date, the PF system has been solely used in a research setting. However, there is potential to implement precision feeding on commercial breeder farms. Findings in Chapter 3 helped advance the progress of commercialization as it was determined that the dye markings from the AMS prototype did not stimulate aggression in precision-fed broiler breeder chicks for the first 3 wk of training. Thus, the AMS has potential to serve as a valid identification system on farms which will allow producers to visually identify chicks, as they conduct barn checks. Further, this allows producers to be able to easily identify chicks that need additional training to learn how to eat from the PF stations.

One of the overarching findings in this thesis was that BW targets of precision-fed broiler breeders can be increased without negatively affecting reproductive performance and have minimal impact on broiler offspring growth performance (Chapter 4 and Chapter 5, respectively). Even though these results are specific to the PF system, it provides some valuable insight for the hatching egg and broiler industries in combination with previous PF research. Zuidhof (2018) hypothesized that the main reasons as to why BW targets can be increased is because the PF system allows for precise feed allocation over multiple meals throughout the day. This was thought to influence body composition, specifically the proportion of carcass fat (Hadinia et al., 2019; Zuidhof, 2018). In turn, precision-fed broiler breeders did not have a sufficient amount of fat to support high rates of egg production. By increasing BW targets, the birds would have access to more feed and nutrients that could be allocated toward growth, maintenance and fat deposition leading up to sexual maturity, and egg production. The current research demonstrated increased BW would not negatively affect reproduction and offspring growth performance. Therefore generally speaking, the hatching egg industry could use these results to adjust feeding programs on farms to increase BW and nutrient intake. This could be achieved through using a PF system, or possibly increasing the number of meals per day. However, increased meal frequency in a conventional system would need to be evaluated in a research setting before adjustments were made.

6.6 Conclusions

This thesis investigated the challenge of how to identify precision-fed chicks that required additional training to successfully learn how to eat from the PF stations. Previous work in 2018 successfully implemented a marking system prototype as part of a PF station, and the current research demonstrated that the dye markings from the AMS prototype did not stimulate aggression between broiler breeder chicks for the first 21 d of life. Thus, the AMS prototype can successfully serve as an identification method without promoting aggression during the training phase of precision-fed birds.

The current research was consistent with van der Klein (2018a, 2018b) confirming that broiler breeder BW can be increased up to 22.5% above the current recommended BW targets without negatively affecting reproductive performance. In addition, hunger was not completely eliminated as BW increased (Chapter 4), specifically among feed restricted birds. This leads to the hypothesis that BW targets might need to be increased above 22.5% to reduce hunger. Importantly, implementation of these findings would reduce the degree of feed restriction and welfare concerns associated with severe feed restriction, which is characterized in conventional broiler breeder management. The current research also demonstrated increased maternal BW had little effect on offspring growth performance. Rather, differences in broiler offspring BW, efficiency and carcass traits varied depending on maternal age and broiler sex. Specifically, offspring feed efficiency decreased as maternal BW increased, which might have been related to the reduction in gut weight. There is therefore potential to increase maternal BW targets without negative effects on broiler growth performance using a PF system.

6.7 References

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2019a. The effect of alternative feeding strategies for broiler breeder pullets: 1. Welfare and performance during lay. Poult. Sci. 98:6205–6216.

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2019b. The effect of alternative feeding strategies for broiler breeder pullets: 1. Welfare and performance during rearing. Poult. Sci. 98:3377–3390.

Bowling, M., R. Forder, R. J. Hughes, S. Weaver, and P. I. Hynd. 2018. Effects of restricted feed intake in broiler breeder hens on their stress levels and the growth and immunology of their offspring. Transl. Anim. Sci. 2: 263-271.

Brake, J., G. B. Havenstein, S. E. Scheideler, P. R. Ferket and D. V. Rives. 1993. Relationship of sex, age, and body weight to broiler carcass yield and offal production. Poult. Sci. 72:1137–1145.

D'Eath, R. B., B. J. Tolkamp, I. Kyriazakis, and A. B. Lawrence. 2009. 'Freedom from hunger' and preventing obesity: The animal welfare implications of reducing food quantity or quality. Anim. Behav. 77:275-288.

Dennis, R. L., R. C. Newberry, H. W. Cheng, and I. Estevez. 2008. Appearance matters: Artificial marking alters aggression and stress. Poult. Sci. 87:1939–1946.

Estevez, I., L. J. Keeling, and R. C. Newberry. 2003. Decreasing aggression with increasing group size in young domestic fowl. Appl. Anim. Behav. Sci. 84:213-218.

Hadinia, S. H., P. R. O. Carneiro, D. R. Korver and J. M Zuidhof. 2019. Energy partitioning by broiler breeder hens in conventional daily-restricted feeding and precision feeding systems. Poult. Sci. 98:6721-6732.

Humphreys, K. D. 2020. Implications of altering maternal feed availability and feeding system on offspring performance. MSc. Thesis. University of Alberta, Edmonton, Alberta, Canada.

Iqbal, J., S. H. Khan, N. Mukhtar, T. Ahmed, and R. A. Pasha. 2016. Effects of egg size (weight) and age on hatching performance and chick quality of broiler breeder. J. Appl. Anim. Res. 44:54–64.

Kwakkel, R P., B. J. Ducro, and W. J. Koops, 1993. Multiphasic analysis of growth of the body and its chemical components in White Leghorn pullets. Poult. Sci. 72:1421-1432.

Kwakkel, R. P., J. A. W. van Esch, B. J. Durco, and W. J. Koops. 1995. Onset of lay related to multiphasic growth and body composition in white leghorn pullets provided ad libitum and restricted diets. Poult. Sci. 74:821-832.

Moraes, T. G. V., A. Pishnamazi, E. T. Mba, I. I. Wenger, R. A. Renema, and M. J. Zuidhof. 2014. Effect of maternal dietary energy and protein on live performance and yield dynamics of broiler progeny from young breeders. Poult. Sci. 93:2818–2826.

Peebles, E. D., S. M. Doyle, T. Pansky, P. D. Gerard, M. A. Latour, C. R. Boyle, and T. W. Smith. 1999. Effects of breeder age and dietary fat on subsequent broiler performance. 1. Growth, mortality, and feed conversion. Poult. Sci. 78:505–511.

Renema, R. A., M. E. Rustad, and F. E. Robinson. 2007. Implications of changes to commercial broiler and broiler breeder body weight targets over the past 30 years. Worlds Poult. Sci. J. 63:457-472.

Tolkamp, B. J., and R. B. D'Eath. 2016. Hunger associated with restricted feeding systems. Pages 11-27 in Nutrition and the Welfare of Farm Animals. Phillips, C. J. C., ed. Springer, Switzerland.

Tona, K., O. Onagbesan, B. De Ketelaere, E. Decuypere, and V. Bruggeman. 2004. Effects of age of broiler breeders and egg storage on egg quality, hatchability, chick quality, chick weight, and chick posthatch growth to forty-two days. J. Appl. Poult. Res. 13:10–18.

van der Klein, S. A. S., G. Y. Bédécarrats, F. E. Robinson, and M. J. Zuidhof. 2018a. Early photostimulation at the recommended body weight reduced broiler breeder performance. Poult. Sci. 97:3736-3745.

van der Klein, S. A. S., G. Y. Bédécarrats, and M. J. Zuidhof. 2018b. The effect of rearing photoperiod on broiler breeder reproductive performance depended on body weight. Poult. Sci. 97:3286-3294.

van der Waaij, E. H., van den Brand, J. A. M. van Arendonk, and B. Kemp. 2011. Effect of match or mismatch of maternal-offspring nutritional environment on the development of offspring in broiler chickens. Animal. 5:741-748.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, H. van den Brand, and W. H. Hendriks. 2015. Effects of growth patterns and dietary protein levels during rearing of broiler breeders on fertility, hatchability, embryonic mortality, and offspring performance. Poult. Sci. 94:681-691.

Young, L. L., J. K. Northcutt, R. J. Buhr, C. E. Lyon, and G. O. Ware. 2001. Effects of age, sex, and duration of post-mortem aging on percentage yield of parts form broiler chicken carcasses. Poult. Sci. 80:376–379.

Zuidhof, M. J. 2018. Lifetime productivity of conventionally and precision-fed broiler breeders. Poult. Sci. 97:3921-3937.

Zuidhof, M. J. 2020. Multiphasic poultry growth models: Method and application. Poult. Sci. doi https://doi.org/10.1016/j.psj.2020.08.049.

Zuidhof, M. J., M. V. Fedorak, C. A. Ouellette, and I. I. Wenger. 2017. Precision feeding: innovative management of broiler breeder feed intake and flock uniformity. Poult. Sci. 96:2254-2263.

Zuidhof, M. J., M. V. Fedorak, C. C. Kirchen, E. H. M. Lou, C. A. Ouellette, and I. I. Wenger. 2019. System and method for feeding animals. PrecisionZX, Inc., assignee. US Pat. No. 10,506,793.

Zuidhof, M. J., B. L. Schneider, V. L. Carney, D. R. Korver, and F. E. Robinson. 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. Poult. Sci. 93:2970-2982.

References

Andretta, I., C. Pomar, J. Rivest, J. Pomar, and J. Radünz. 2016. Precision feeding can significantly reduce lysine intake and nitrogen excretion without compromising the performance of growing pigs. Animal. 10:1137–1147.

Angove, J. L., and R. E. A. Forder. 2020. The avian maternal environment: Exploring the physiological mechanisms driving progeny performance. Worlds Poult. Sci. J. 76:100-118.

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2019a. The effect of alternative feeding strategies for broiler breeder pullets: 1. Welfare and performance during rearing. Poult. Sci. 98:3377-3390.

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2019b. The effect of alternative feeding strategies for broiler breeder pullets: 1. Welfare and performance during rearing. Poult. Sci. 98:3377–3390.

Arrazola, A., E. Mosco, T. M. Widowski, M. T. Guerin, E. G. Kiarie, and S. Torrey. 2020. The effect of alternative feeding strategies during rearing on the behaviour of broiler breeder pullets. Appl. Anim. Behav. Sci. 224:104929.

Aviagen, 2016a. Ross 708 Parent Stock Performance Objectives. Aviagen, Huntsville, AL.

Aviagen, 2016b. Yield Plus Male Standards - Metric. Aviagen, Huntsville, AL.

Aviagen, 2018. Ross 708 Parent Stock Handbook. Aviagen, Huntsville, AL.

Aviagen, 2019. Ross 708 Broiler Performance Objectives. Aviagen, Huntsville, AL.

Banhazi, T. M., H. Lehr, J. L. Black, H. Crabtree, P. Schofield, M. Tscharke, and D. Berckmans. 2012. Precision livestock farming: An international review of scientific and commercial aspects. Int. J. Agric. Biol. Eng. 5:1-9.

Basarab, J. A., M. A. Price, J. L. Aalhus, E. K. Okine, W. M. Snelling, and K. L. Lyle. 2003. Residual feed intake and body composition in young growing cattle. Can. J. Anim. Sci. 83:189-204.

Bédécarrats, G. Y. 2015. Control of the reproductive axis: Balancing act between stimulatory and inhibitory inputs. Poult. Sci. 94:810–815.

Bédécarrats, G. Y, M. Baxter, and B. Sparling. 2016. An updated model to describe the neuroendocrine control of reproduction in chickens. Gen. Comp. Endocrinol. 227:58–63.

Bédécarrats, G. Y., H. McFarlane, S. R. Maddineni, and R. Ramachandran. 2009. Gonadotropininhibitory hormone receptor signaling and its impact on reproduction in chickens. Gen. Comp. Endocrinol. 163:7–11.

Bessei, W. 2006. Welfare of broilers: A review. Worlds Poult. Sci. J. 62:455-466.

Borchers, M. R., Y. M. Change, I. C. Tsai, B. A. Wadsworth, and J. M. Bewley. 2016. A validation of technologies monitoring dairy cow feeding, ruminating, and lying behaviors. J. Dairy Sci. 99:7458-7466.

Bowling, M., R. Forder, R. J. Hughes, S. Weaver, and P. I. Hynd. 2018. Effects of restricted feed intake in broiler breeder hens on their stress levels and the growth and immunology of their offspring. Transl. Anim. Sci. 2: 263-271.

Brake, J., G. B. Havenstein, S. E. Scheideler, P. R. Ferket and D. V. Rives. 1993. Relationship of sex, age, and body weight to broiler carcass yield and offal production. Poult. Sci. 72:1137–1145.

Bruggeman, V., O. Onagbesan, E. D'Hondt, N. Buys, M. Safi, D. Vanmontfort, L. Berghman, F. Vandesande, and E. Decuypere. 1999. Effects of timing and duration of feed restriction during rearing on reproductive characteristics in broiler breeder females. Poult. Sci. 78:1424-1434.

Buckley, L. A., V. Sandilands, P. M. Hocking, B. J. Tolkamp, and R. B. D'Eath. 2015. Feed-restricted broiler breeders: State-dependent learning as a novel welfare assessment tool to evaluate their hunger state? Appl. Anim. Behav. Sci. 165:124-132.

Buis, R. B. 2016. Development and application of a precision feeding program using electronic sow feeder and effect on gestation primiparous sow performance. MSc. Thesis. University of Guelph, Ontario, Canada.

Campderrich, I., G. Liste, and I. Estevez. 2017. Group size and phenotypic appearance: Their role on the social dynamics in pullets. Appl. Anim. Behav. Sci. 189:41–48.

Canadian Council on Animal Care. 2009. CCAC guidelines on: The care and use of farm animals in research, teaching, and testing. Canadian Council on Animal Care, Ottawa, ON.

Cobb-Vantress. 2016. Cobb Breeder Management Guide. Cobb-Vantress, Siloam Springs, AR.

Cobb-Vantress. 2018. Cobb 500 Broiler Performance and Nutrition Supplement. Cobb-Vantress, Siloam Springs, AR.

Corkery, G., S. Ward, C. Kenny, and P. Hemmingway. 2013. Incorporating smart sensing technologies into the poultry industry. J. Worlds Poult. Res. 3:106-128.

Council Directive. 1998. No. 98/58/EC. Concerning the protection of animals kept for farming purposes. Official journal L221, p. 23. Amended as council regulation (EC) No. 806/2003 Apr. 14, 2003. Official journal L122, p. 1.

Culbertson M. M., S. E. Speidel, R. K. Peel, R. R. Cockrum, M. G. Thomas, and R. M. Enns. 2015. Optimum measurement period for evaluating feed intake traits in beef cattle. J. Anim. Sci. 93:2482-2487.

Dalton, H. A., B. J. Wood, T. M. Widowski, M. T. Guerin, and S. Torrey. 2018. Comparing the behavioural organization of head pecking, severe feather pecking, and gentle feather pecking in domestic turkeys. Appl. Anim. Behav. Sci. 204:66-71.

David, S. A., M. Mersch, S. Foissac, A. Collin, F. Pitel, and V. Coustham. 2017. Genome-wide epigenetic studies in chicken: A review. Epigenomes. 1:20. doi:10.3390/epigenomes1030020.

D'Eath, R. B., B. J. Tolkamp, I. Kyriazakis, and A. B. Lawrence. 2009. 'Freedom from hunger' and preventing obesity: The animal welfare implications of reducing food quantity or quality. Anim. Behav. 77:275-288.

Decuypere, E., P. M. Hocking, K. Tona, O. Onagbesan, V. Bruggeman, E. K. M. Jones, S. Cassy, N. Rideau, S. Metayer, Y. Jego, J. Putterflam, S. Tesseraud, A. Collin, M. Duclos, J. J. Trevid, and J. Williams. 2006. Broiler breeder paradox: A project report. Worlds Poult. Sci. J. 62:443-453.

de Jong, I. C., H. Enting, S. Van Voorst, E. W. Ruesink, and H. J. Blokhuis. 2005. Do low density diets improve broiler breeder welfare during rearing and laying? Poult. Sci. 84:194-203.

de Jong, I. C., and D. Guémené. 2011. Major issues in broiler breeders. Worlds Poult. Sci. J. 76:73-82.

de Jong, I. C., and B. Jones. 2006. Feed restriction and welfare in domestic birds. Pages 120-135 in Feeding in Domestic Vertebrates. V. Bels, ed. CABI, Wallingford, United Kingdom.

de Jong, I. C., A. S. van Voorst, and H. J. Blokhuis. 2003. Parameters for qualification of hunger in broiler breeders. Phys. Behav. 78:773-783.

Dennis, R. L., R. C. Newberry, H. W. Cheng, and I. Estevez. 2008. Appearance matters:

Artificial marking alters aggression and stress. Poult. Sci. 87:1939–1946.

DeVries, T. J., M. A. G. von Keyserlingk, D. M. Weary, and K. A. Beauchemin. 2003. Technical note: validation of a system for monitoring feeding behaviour of dairy cows. J. Dairy Sci. 86:3571-3574.

Dixon, L. M., S. Brocklehurts, V. Sandilands, M. Bateson, B. J. Tolkamp, and R. B. D'Eath. 2014. Measuring motivation for appetite behaviour: Food-restricted broiler breeder chickens cross a water barrier to forage in an area of wood shavings without food. Plos One. 9:1-11. E102322.

Duncan, I. J. H. 1998. Behavior and behavioral needs. Poult. Sci. 77:1766-1772.

Dunn, I. C., and P. J. Sharp. 1990. Photoperiodic requirements for LH release in juvenile broiler and egg-laying strains of domestic chickens fed ad libitum or restricted diets. J. Reprod. Fertil. 90:329-335.

Eastwood, C., M. Trotter, and N. Scott. 2015. Understanding the user: Learning from on-farm application of precision farming technologies in the Australian livestock sector. Aust. J. Multi-disciplinary Eng. 10:41-50.

Ekmay, R. D., C. Salas, J. England, S. Cerrate, and C. N. Coon. 2012. The effects of pullet body weight, dietary nonpyhtate phosphorus intake, and breeder feeding regimen on production performance, chick quality, and bone remodeling in broiler breeders. Poult. Sci. 91:948-964.

El Sabry, M. I., S. Yalçin, and G. Turgay-Izzetoglu. 2013. Interaction between breeder age and hatching time affects intestine development and broiler performance. Livest. Sci. 157:612–617.

Emmans, G. C. 1981. A model of the growth and feed intake of ad libitum fed animals, particularly poultry. Pages 103– 110 in Computers in Animal Production. G. M. Hillyer, C.

T. Whittemore, and R. G. Gunn, ed. Occasional Publication No. 5. British Society of Animal Science (formerly British Society of Animal Production), Penicuik, Midlothian, UK.

Enting, H., W. J. A. Boersma, J. B. W. J. Cornelissen, S. C. L. van Winden, M. W. A. Verstegen, and P. J. van der Aar. 2007. The effect of low-density broiler breeder diets on performance and immune status of their offspring. Poult. Sci. 86:282–290.

Estevez, I., I. L. Andersen, and E. Nævdal. 2007. Group size, density and social dynamics in farm animals. Appl. Anim. Behav. Sci. 103:185-204.

Estevez, I., L. J. Keeling, and R. C. Newberry. 2003. Decreasing aggression with increasing group size in young domestic fowl. Appl. Anim. Behav. Sci. 84:213-218.

Estevez, I., R. C. Newberry, and L. J. Keeling. 2002. Dynamics of aggression in the domestic fowl. Appl. Anim. Behav. Sci. 76:307-325

Fontana, I., E. Tullo, A. Butterworth, and M. Guarino. 2015. An innovative approach to predict the growth in intensive poultry farming. Comput. Electron. Agric. 119:178-183.

Fournel, S., A. N. Rousseau, and B. Laberge. 2017. Rethinking environment control strategy of confined animal housing systems through precision livestock farming. Biosyst. Eng. 155:96-123.

Fraser, D. 2008. Understanding animal welfare: The science and its cultural context. 1 ed. Wiley Blackwell, the United Kingdom.

Frésard, L., M. Morisson, J. M. Brun, A. Collin, B. Pain, F. Minvielle, and F. Pitel. 2013. Epigenetics and phenotypic variability: some interesting insights from birds. Genet. Sel. Evol. 45:16.

Frost, A. R. 2001. An overview of integrated management systems for sustainable livestock production. Integrated management systems for livestock. BSAP Occasional Publication. 28:45-50.

Girard, T. E., M. J. Zuidhof, and C. J. Bench. 2017a. Aggression and social rank fluctuations in precision-fed and skip-a-day broiler breeder pullets. Appl. Anim. Behav. Sci. 187:38-44.

Girard, T. E., M. J. Zuidhof, and C. J. Bench. 2017b. Feeding, foraging, and feather pecking behaviours in precision-fed and skip-a-day-fed broiler breeder pullets. Appl. Anim. Behav. Sci. 188:42-49.

Gompertz, B. 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of Life Contingencies. Trans. R. Philos. Soc. 115:513–585.

Gous, R. M., E. T. Moran Jr., H. R. Stilborn, G. D. Bradford, and G. C. Emmans. 1999. Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. Poult. Sci. 78:812-821.

Grey, T. C., D. Robinson, and J. M. Jones. 1982. Effect of age and sex on the eviscerated yield, muscle and edible offal of a commercial broiler strain. Br. Poult. Sci. 23:289–298.

Groothuis, T. G., W. Muller, and N. von Engelhardt. 2005. Maternal hormones as a tool to adjust offspring phenotype in avian species. Neurosci. Biobehav. Rev. 29:329–352.

Grossman, M., and W. J. Koops. 1988. Multiphasic analysis of growth curves in chickens. Poult. Sci. 67:33-42.

Hadinia, S. H., P. R. O. Carneiro, C. J. Fitzsimmons, G. Y. Bédécarrats, and M. J. Zuidhof. 2020. Post-photostimulation energy intake accelerated pubertal development in broiler breeder pullets. Poult. Sci. 99:2215-2229.

Hadinia, S. H., P. R. O. Carneiro, D. R. Korver and J. M Zuidhof. 2019. Energy partitioning by broiler breeder hens in conventional daily-restricted feeding and precision feeding systems. Poult. Sci. 98:6721-6732.

Hayward, L. S., D. G. Satterlee, and J. C. Wingfield. 2005. Japanese quail selected for high plasma corticosterone response deposit high levels of corticosterone in their eggs. Physiol. Biochem. Zool. 78:1026-1031.

Heck, A., O Onagbesan, K. Tona, S. Metayer, J. Putterflam, Y. Jego, J. J. Trevidy, E. Decuypere, J. Williams, M. Picard and V. Bruggeman. 2004. Effects of ad libitum feeding on performance of different strains of broiler breeders. Br. Poult. Sci. 45:695–703.

Hocking, P. M. 1993. Roles of body weight and feed intake in ovarian follicular dynamics in broiler breeders at the onset of lay and after a forced molt. Poult. Sci. 83:2044-2050.

Hocking, P. M. 2004. Roles of body weight and feed intake in ovarian follicular dynamics in broiler breeders at the onset of lay and after a forced molt. Poult. Sci. 82:2044-2050.

Hocking, P. M., R. Bernard, and G. W. Robertson. 2002a. Effects of low dietary protein and different allocations of food during rearing and restricted feeding after peak rate of lay on egg production, fertility and hatchability in female broiler breeders. Br. Poult. Sci. 43:94-103.

Hocking, P.M., and S. R. I. Duff. 1989. Musculo-skeletal lesions in adult male broiler breeder fowls and, their relationships with body weight and fertility at 60 weeks of age. Br. Poult. Sci. 30: 777-784.

Hocking, P. M., A. B. Gilbert, M. Walker, and D. Waddington. 1987. Ovarian follicular structure of white leghorns fed ad libitum and dwarf and normal broiler breeders ad libitum or restricted until point of lay. Br. Poult. Sci. 28:493-506.

Hocking, P. M., M. H. Maxwell, and M. A. Mitchell. 1996. Relationship between the degree of food restriction and welfare indices in broiler breeder females. Br. Poult. Sci. 37:263–278.

Hocking, P.M., M. H. Maxwell, G. W. Robertson, and M. A. Mitchell. 2001. Welfare assessment of modified rearing programmes for broiler breeders. Br. Poult. Sci. 42:424-432.

Hocking, P. M., M. H. Maxwell, G. W. Robertson, and M. A. Mitchell. 2002b. Welfare assessment of broiler breeders that are food restricted after peak rate of lay. Br. Poult. Sci. 43:5–15.

Hocking, P.M., V. Zaczek, E. K. M. Jones, and M. G. McLeod. 2004. Different concentrations and sources of dietary fibre may improve the welfare of female broiler breeders. Br. Poult. Sci. 45: 9-19.

Hornick, J. L., C. Van Eanaeme, O. Gerard, I. Dufrasne, and L. Istasse. 2000. Mechanisms of reduced and compensatory growth. Domest. Anim. Endocrinol.19:121-132.

Hu, Y., Y. Ni, and L. Ren. 2008. Leptin is involved in the effects of cysteamine on egg laying of hens, characteristics of eggs, and posthatch growth of broiler offspring. Poult. Sci. 87:1810-1817.

Humphreys, K. D. 2020. Implications of altering maternal feed availability and feeding system on offspring performance. MSc. Thesis. University of Alberta, Edmonton, Alberta, Canada.

Hutchison, T. W. S., and C. Riddell. 1990. A study of hepatic lesion in broiler chickens at processing plants in Saskatchewan. Can. Vet. J. 31:20–25.

Iqbal, J., S. H. Khan, N. Mukhtar, T. Ahmed, and R. A. Pasha. 2016. Effects of egg size (weight) and age on hatching performance and chick quality of broiler breeder. J. Appl. Anim. Res. 44:54-64.

Jackson, S., and J. Diamond. 1996. Metabolic and digestive responses to artificial selection in chickens. Evolution. 50:1638–1650.

John, A. J., C. E. F. Clark, M. J. Freeman, and K. L. Kerrisk. 2016. Review: Milking robot utilization, a successful precision livestock farming evolution. Anim. 10:1484-1492.

Katanbaf, M. N., E. A. Dunnington, and P. B. Siegel. 1989. Restricted feeding in early and late-feathering chickens. Poult. Sci. 68:352-358.

Kwakkel, R P., B. J. Ducro, and W. J. Koops, 1993. Multiphasic analysis of growth of the body and its chemical components in White Leghorn pullets. Poult. Sci. 72:1421-1432.

Kwakkel, R. P., J. A. W. van Esch, B. J. Durco, and W. J. Koops. 1995. Onset of lay related to multiphasic growth and body composition in white leghorn pullets provided ad libitum and restricted diets. Poult. Sci. 74:821-832.

Latshaw, J. D., and J. S. Moritz. 2009. The partitioning of metabolizable energy by broiler chickens. Poult. Sci. 88:98–105.

Lees, J. J., C. Lindholm, P. Batakis, M. Busscher, and J. Altimiras. 2017. The physiological and neuroendocrine correlates of hunger in the Red Junglefowl (Gallus gallus). Scientific reports. 7:17984. doi:10.1038/s41598-017-17922-w.

Leeson, S. 2007. Metabolic challenges: Past, present, and future. J. Appl. Poult. Res. 16:121-125.

Leeson, S., and T. Walsh. 2004. Feather in commercial poultry. 2. Factors influencing feather growth and feather loss. Worlds Poult. Sci. J. 60:52-63.

Lesuisse, J., C. Li, S. Schallier, J. Leblois, N. Everaert, and J. Buyse. 2017. Feeding broiler breeders reduced balanced protein diet during the rearing and laying period impairs reproductive performance but enhances broiler offspring performance. Poult. Sci. 96:3949-3959.

Lewis, P. D. 2006. A review of lighting for broiler breeders. Br. Poult. Sci. 47:393-404.

Lippens, M., G. Room, D. De Groote, and E. Decuypere. 2010. Early and temporary quantitative food restriction of broiler chickens. 1. Effects on performance characteristics, mortality and meat quality. Br. Poult. Sci. 41:343–354.

Lourens, A., R. Molenaar, H. van den Brand, M. J. W. Heetkamp, R. Meijerhof, and B. Kemp. 2006. Effect of egg size on heat production and the transition of energy from egg to hatchling. Poult. Sci. 85:770-776.

McDaniel, G. R. 1983. Factors affecting broiler breeder performance. 5. Effects of preproduction feeding regimens on reproductive performance. Poult. Sci. 62:1949-1953.

McDaniel, G. R., J. Brake, and M. K. Eckman. 1981. Factors affecting broiler breeder performance. 4. The relationship of some reproductive traits. Poult. Sci. 60:1792-1797.

Mellor, E., B. Brilot, and S. Collins. 2018. Abnormal repetitive behaviours in captive birds: A tinbergian review. Appl. Anim. Behav. Sci. 198:109-120.

Melnychuk, V. L., J. D. Kirby, Y. K. Kirby, D. A. Emmerson, and N. B. Anthony. 2004. Effect of strain, feed allocation program, and age at photostimulation on reproductive development and carcass characteristics of broiler breeder hens. Poult. Sci. 83:1861-1867.

Mench, J. A. 1988. The development of aggressive behavior in male broiler chicks: A comparison with laying-type males and the effects of feed restriction. Appl. Anim. Behav. Sci. 21:233-242.

Mench, J. A. 2002. Broiler breeders: feed restriction and welfare. Worlds Poult. Sci. J. 58:23-29.

Merlet, F., J. Puterflam, J. M. Faure, P. M. Hocking, M. S. Magnusson, and M. Picard. 2005. Detection and comparison of time patterns of behaviours of two broiler breeder genotypes fed ad libitum and two levels of feed restriction. Appl. Anim. Behav. Sci. 94:255–271.

Mohiti-Asli, M., M. Shivazad, M. Zaghari, M. Rezaian, S. Aminzadeh, and G. G. Mateos. 2012. Effects of feeding regimen, fiber inclusion, and crude protein content of the diet on performance and egg quality and hatchability of eggs of broiler breeder hens. Poult. Sci. 91:3097–3106.

Moraes, T. G. V., A. Pishnamazi, E. T. Mba, I. I. Wenger, R. A. Renema, and M. J. Zuidhof. 2014. Effect of maternal dietary energy and protein on live performance and yield dynamics of broiler progeny from young breeders. Poult. Sci. 93:2818–2826.

Moraes, T. G. V., A. Pishnamazi, I. I. Wegner, R. A. Renema, and M. J. Zuidhof. 2019. Energy and protein dilution in broiler breeder pullet diets reduced offspring body weight and yield. Poult. Sci. 98:2555–2561.

Moran, E. T. Jr. 2007. Nutrition of the developing embryo and hatchling. Symposia: managing the embryo for performance. Poult. Sci. 86:1043-1049.

Morrissey, K. L. H., T. Widowski, S. Leeson, V. Sandilands, A. Arnone, and S. Torrey. 2014. The effect of dietary alterations during rearing on growth, productivity, and behaviour in broiler breeder females. Poult. Sci. 93:285–295.

Mortensen, A. K., P. Lisouski, and P. Ahrendt. 2016. Weight prediction of broiler chickens using 3D computer vision. Comp. Elect. Agric. 123:319-326.

Mottram, T. 2016. Animal board invited review: precision livestock farming for dairy cows with a focus on oestrus detection. Anim. 10:1575-1584.

Nicol, C. J., M. Bestman, A. M. Gilani, E. N. de Haas, I. C. de Jong, S. Lambton, J. P. Wagenaar, C. A. Weeks, and T. B. Rodenburg. 2013. The prevention and control of feather pecking: Application to commercial systems. Worlds Poult. Sci. J. 69:775-788.

Nicol, C. J., N. G. Gregory, T. G. Knowles, I. D. Parkman, and L. J. Wilkins. 1999. Differential effects of increased stocking density, mediated by increased flock size, on feather pecking and aggression in laying hens. Appl. Anim. Behav. Sci. 65:137–152.

Peebles, E. D., S. M. Doyle, T. Pansky, P. D. Gerard, M. A. Latour, C. R. Boyle, and T. W. Smith. 1999. Effects of breeder age and dietary fat on subsequent broiler performance. 1. Growth, mortality, and feed conversion. Poult. Sci. 78:505–511.

Pishnamazi, A., R. A. Renema, M. J. Zuidhof, and F. Robinson. 2014. Effect of age at photostimulation on sexual maturation in broiler breeder pullets. Poult. Sci. 93:1274-1281.

Pomar, C., J. Pomar, F. Dubeau, E. Joannopoulos, and J. P. Dussault. 2014. The impact of daily multiphase feeding on animal performance, body composition, nitrogen and phosphorus excretions, and feed costs in growing-finishing pigs. Anim. 8:704–713.

Pomar, C., and A. Remus. 2019. Precision pig feeding: A breakthrough toward sustainability. Anim. Front. 9:52-59.

Rao, K., J. Xie, X. Yang, L. Chen, R. Grossmann, and R. Zhao. 2009. Maternal low-protein diet programs offspring growth in association with alterations in yolk-sac membrane, hypothalamus and muscle of developing Langshan chicken. Br. J. Nutr. 102:848-857.

Renema, R. A., and F. E. Robinson. 2004. Defining normal: Comparison of feed restriction and full feeding of female broiler breeders. Worlds Poult. Sci. J. 60:508-522.

Renema, R. A., F. E. Robinson, P. R. Goerzen, and M. J. Zuidhof. 2001. Effects of altering growth curve and age at photostimulation in female broiler breeders. 2. Egg production parameters. Can. J. Anim. Sci. 81:477–486.

Renema, R. A., F. E. Robinson, J. A. Proudman, M. Newcombe, and R. I. McKay. 1999. Effects of body weight and feed allocation during sexual maturation in broiler breeder hens. 2. Ovarian morphology and plasma hormone profiles. Poult. Sci. 78:629–639.

Renema, R. A., M. E. Rustad, and F. E. Robinson. 2007. Implications of changes to commercial broiler and broiler breeder body weight targets over the past 30 years. Worlds Poult. Sci. J. 63:457-472.

Richards, M. P., and M. Proszkowiec-Weglarz. 2007. Mechanisms regulating feed intake, energy expenditure, and body weight in poultry. Poult. Sci. 86:1478–1490.

Richards, M. P., R. W. Rosebrough, C. N. Coon, and J. P. McMurtry. 2010. Feed intake regulation for the female broiler breeder: In theory and in practice. J. Appl. Poult. Res. 19:182-193.

Riedstra, B., and T. G. G. Groothuis. 2002. Early feather pecking as a form of social exploration: The effect of group stability on feather pecking and tonic immobility in domestic chicks. Appl. Anim. Behav. Sci. 77:127-138.

Robinson, F. E., N. A. Robinson, and T. A. Scott, 1991. Reproductive performance, growth rate and body composition of full-fed versus feed-restricted broiler breeder hens. Can J. Anim. Sci. 71:549–556.

Rodriguez, A. 2017. Effects of daytime and supplemental light spectrum on broiler breeder growth and sexual maturation. MSc. University of Guelph, Guelph, ON.

Rosales, A. G. 1994. Managing stress in broiler breeders: A review. J. Appl. Poult. Res. 3:199-207.

Sandilands, V., B. J. Tolkamp, and I. Kyriazakis. 2005. Behaviour of food restricted broilers during rearing and lay—effects of an alternative feeding method. Physio. Behav. 85:115–123.

Sandilands, V., B. J. Tolkamp, C. J. Savory, and I. Kyriazakis. 2006. Behavior and welfare of broiler breeders fed qualitatively restricted diets during rearing: are there viable alternatives to quantitative restriction? Appl. Anim. Behav. Sci. 96: 53-67.

Savory, C. J. 1995. Feather pecking and cannibalism. Worlds Poul. Sci. J. 51:215-219.

Savory, C. J., P.M. Hocking, J. S. Mann, and M. H. Maxwell. 1996. Is broiler breeder welfare improved by using qualitative rather than quantitative food restriction to limit growth rate? Anim. Welf. 5:105-127.

Savory, C. J., and K. Maros. 1993. Influence of degree of food restriction, age and time of day on behaviour of broiler breeder chickens. Behav. Processes. 29:179-190.

Savory, C. J., K. Maros, and S. M. Rutter. 1993. Assessment of hunger in growing broiler breeders in relation to a commercial restricted feeding programme. Anim. Welf. 2:131-152.

Saccone, V., and P. L. Puri. 2010. Epigenetic regulation of skeletal myogenesis. Organogenesis. 6:48–53.

Scheuermann, G. N., S. F. Bilgili, J. B. Hess, and D. R. Mulvaney. 2003. Breast muscle development in commercial broiler chickens. Poult. Sci. 82:1648–1658.

Scholtz, M. M., J. P. van Zyl, and A. Theunissen. 2014. The effect of epigenetic changes on animal production. Appl. Anim. Husb. Rural Dev. 7:7-10.

Shariatmadari, F. 2012. Plans of feeding broiler chickens. Worlds Poult. Sci. J. 68:21-30.

Shao, W., R. Wawakami, R. Yoshihashi, S. You, H. Kawase, and T. Naemura. 2020. Cattle detection and counting in UAV images based on convolutional neural networks. Int. J. Remote Sens. 41:31-52.

Shea, M. M., J. A. Mench., and O. P. Thomas. 1990. The effect of dietary tryptophan on aggressive behavior in developing and mature broiler breeder males. Poult. Sci. 69:1664-1669.

Shi, L., Y. Sun, H. Xu, Y. Liu, Y. Li, Z. Huang, A. Ni, C. Chen, D. Li, P. Wang, J. Fan, H. Ma, and J. Chen. 2020. Effect of age at photostimulation on sexual maturation and egg-laying performance of layer breeders. Poult. Sci. 99:812-819.

Sun, J., and C. N. Coon. 2005. The effects of body weight, dietary fat, and feed withdrawal rate on the performance of broiler breeders. J. Appl. Poult. Res. 14:728-739.

Tallentire, C. W., I. Leinonen, and I. Kyriazakis. 2016. Breeding for efficiency in the broiler chicken: A review. Agron. Sustain. Dev. 36:66.

The Welfare of Farmed Animals (England) Regulations. 2007. No. 2078 in general conditions under which farmed animals must be kept in feed, water and other substances. Accessed on Mar. 20, 2020. http://www.legislation.gov.uk/uksi/2007/2078/schedule/1/made.

The Welfare of Farmed Animals (Wales) Regulations. 2007. No. 3070 in general conditions under which farmed animals must be bred or kept in feed, water and other substances. Accessed on Mar. 20, 2020. http://www.legislation.gov.uk/wsi/2007/3070/made.

The Welfare of Farmed Animals (Scotland) Regulations. 2010. No. 388 in general conditions under which farmed animals must be bred kept. Accessed on Mar. 20, 2020. http://www.legislation.gov.uk/ssi/2010/388/schedule/1/made.

The Welfare of Farmed Animals Regulations (North Ireland). 2012. No. 156 in general conditions under which farmed animals must be kept. Accessed on Mar. 20, 2020. https://www.legislation.gov.uk/nidsr/2012/9780337986475/schedule/1.

Tolkamp, B. J., and R. B. D'Eath. 2016. Hunger associated with restricted feeding systems. Pages 11-27 in Nutrition and the Welfare of Farm Animals. Phillips, C. J. C., ed. Springer, Switzerland.

Tompić, T., J. Dobša, S. Legen, N. Tompić, and H.Medić. 2011. Modeling the growth pattern of in-season and off-season Ross 308 broiler breeder flocks. Poult. Sci. 90:2879-2887.

Tona, K., O. Onagbesan, B. De Ketelaere, E. Decuypere, and V. Bruggeman. 2004. Effects of age of broiler breeders and egg storage on egg quality, hatchability, chick quality, chick weight, and chick posthatch growth to forty-two days. J. Appl. Poult. Res. 13:10-18.

Ulmer-Franco, A. M., G. M. Fasenko, and E. E. O'Dea Christopher. 2010. Hatching egg characteristics, chick quality, and broiler performance at 2 breeder flock ages and from 3 egg weights. Poult. Sci. 89:2735–2742.

Uni, Z., L. Yadgary, and R. Yair. 2012. Nutritional limitations during poultry embryonic development. J. Appl. Poult. Res. 21:175-184.

USDA, 2020. USDA, Economic Research Service. Food availability (per capita) data system: Poultry (chicken and turkey). Accessed Jan. 23, 2020. https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/.

van der Klein, S. A. S., G. Y. Bédécarrats, F. E. Robinson, and M. J. Zuidhof. 2018a. Early photostimulation at the recommended body weight reduced broiler breeder performance. Poult. Sci. 97:3736-3745.

van der Klein, S. A. S., G. Y. Bédécarrats, and M. J. Zuidhof. 2018b. The effect of rearing photoperiod on broiler breeder reproductive performance depended on body weight. Poult. Sci. 97:3286-3294.

van der Klein, S. A., F. A. Silva, R. P. Kwakkel, and M. J. Zuidhof. 2017. The effect of quantitative feed restriction on allometric growth in broilers. Poult. Sci. 96:118–126.

van der Klein, S. A. S., M. J. Zuidhof, and G. Y. Bédécarrats. 2020. Diurnal and seasonal dynamic affecting egg production in meat chickens: A review of mechanisms associated with reproductive dysregulation. Anim. Reprod. Sci. 213:106257.

van der Waaij, E. H., van den Brand, J. A. M. van Arendonk, and B. Kemp. 2011. Effect of match or mismatch of maternal-offspring nutritional environment on the development of offspring in broiler chickens. Animal. 5:741-748.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, H. van den Brand, and W. H. Hendriks. 2015. Effects of growth patterns and dietary protein levels during rearing of broiler breeders on fertility, hatchability, embryonic mortality, and offspring performance. Poult. Sci. 94:681-691.

van Emous, R. A., R. P. Kwakkel, M. M. van Krimpen, and W. H. Hendriks. 2013. Effects of growth patterns and dietary crude protein levels during rearing on body composition and performance in broiler breeder females during the rearing and laying period. Poult. Sci. 92:2091-2100.

van Hierden, Y. M., S. M. Korte, E. W. Ruesink, C. G. van Reenen, B. Engel, J. M. Koolhaas, and H. J. Blokhuis. 2002. The development of feather pecking behaviour and targeting of pecking in chicks from a high and low feather pecking line of laying hens. Appl. Anim. Behav. Sci. 77:183-196.

van Middelkoop, J. H. 1978. Types of eggs produces in white plymouth rock hens. Worlds Poult. Sci. J. 34:69–80.

Vranken, E., and D. Berckmans. 2017. Precision livestock farming for pigs. Anim. Frontiers. 7:32-37.

Wathes, C. M., H. H. Kristensen, J. M Aerta, and D. Berckmans. 2008. Is precision livestock feeding an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? Comput. Electron. Agric. 64:2-10.

Wang, Z, J. D. Nkrumah, C. Li, J. A. Basarab, L. A. Goonewardene, E. K. Okine, D. H. Crews Jr., and S. S. Moore. 2006. Test duration for growth, feed intake, and feed efficiency in beef cattle using the GrowSafe System. J. Anim. Sci. 84:2289-2298.

Wang, Z., and M. J. Zuidhof. 2004. Estimation of growth parameters using a nonlinear mixed Gompertz model. Poult. Sci. 83:847-852.

Welberg, L. A. M., and J. R. Seckl. 2001. Prenatal stress, glucocorticoids and the programming of the brain. J. Neuroendocrinol. 13:113-128.

Werkheiser, I. 2018. Precision livestock farming and farmers' duties to livestock. J. Agric. Environ. Ethics. 31:181-195.

Wilson, H. R. 1991. Interrelationship of egg size, chick size, posthatching growth and hatchability. Worlds Poult. Sci. J. 47:5-20.

Wilson, H. R. 1997. Effects of maternal nutrition on hatchability. Poult. Sci. 76:134-143.

Wilson, C. M., and F. M. McNabb. 1997. Maternal thyroid hormones in Japanese quail eggs and their influence on embryonic development. Gen. Comp. Endocrinol. 107:153-165.

Young, L. L., J. K. Northcutt, R. J. Buhr, C. E. Lyon, and G. O. Ware. 2001. Effects of age, sex, and duration of post-mortem aging on percentage yield of parts form broiler chicken carcasses. Poult. Sci. 80:376–379.

Yu, M. W., and F. E. Robinson. 1992. The application of short-term feed restriction to broiler chicken production: A review. J. Appl. Poult. Res. 1:147–153.

Yu, M. W., F. E. Robinson, R. G. Charles, and R. Weingardt. 1992. Effect of feeding allowance during rearing and breeding on female broiler breeders. 2. Ovarian morphology and production. Poult. Sci. 71:1750-1761.

Zajonc, R. B., W. R. Wilson, and D. W. Rajecki. 1975. Affiliation and social discrimination produced by brief exposure in day-old domestic chicks. Anim. Behav. 23:131-138.

Zimmerman, P. H., A. C. Lindberg, S. J. Pope, E. Glen, J. E. Bolhuis, and C. J. Nicol. 2006. The effect of stocking density, flock size and modified management on laying hen behaviour and welfare in a non-cage system. Appl. Anim. Behav. Sci. 101:111–124.

Zubair, A. K., and S. Leeson. 1996. Compensatory growth in the broiler chicken: a review. Worlds Poult. Sci. J. 52:189-201.

Zuidhof, M. J. 2018. Lifetime productivity of conventionally and precision-fed broiler breeders. Poult. Sci. 97:3921-3937.

Zuidhof, M. J. 2020. Multiphasic poultry growth models: Method and application. Poult. Sci. doi https://doi.org/10.1016/j.psj.2020.08.049.

Zuidhof, M. J., M. V. Fedorak, C. C. Kirchen, E. H. M. Lou, C. A. Ouellette, and I. I. Wenger. 2019. System and method for feeding animals. PrecisionZX, Inc., assignee. US Pat. No. 10,506,793.

Zuidhof, M. J., M. V. Fedorak, C. A. Ouellette, and I. I. Wenger. 2017. Precision feeding: innovative management of broiler breeder feed intake and flock uniformity. Poult. Sci. 96:2254-2263.

Zuidhof, M. J., D. E. Holm, R. A. Renema, M. A. Jalal, and F. E. Robinson. 2015. Effects of broiler breeder management on pullet body weight and carcass uniformity. Poult. Sci. 94:1389-1397.

Zuidhof, M. J., B. L. Schneider, V. L. Carney, D. R. Korver, and F. E. Robinson. 2014. Growth, efficiency, and yield of commercial broilers from 1957, 1978, and 2005. Poult. Sci. 93:2970-2982.