Compensatory Body Protein Gain in Newly Weaned Pigs

by

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ABSTRACT

Compensatory body protein gain in newly weaned pigs

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Protein sources used in nursery diets are expensive; there is a need to examine alternative feeding strategies to lower production costs. Experiments were conducted to determine the effects of a short term lysine restriction at weaning on pig growth performance and body composition, and the extent of compensatory growth when pigs are then fed adequate amounts of dietary lysine. Pigs were followed until final market weight of 124kg was attained to assess effects of compensatory growth on carcass and meat quality. Short term lysine restriction at weaning reduced growth performance (gains, feed efficiency) and body protein mass while increasing body lipid mass. However, when fed a diet that was no longer limiting in lysine, pigs were capable of achieving compensatory growth with no effects on carcass or meat quality. Short term nutrient restriction may be an effective approach to reduce diet costs without jeopardizing performance and carcass and meat quality.

DEDICATION

To Dr. Kees de Lange.

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LIST OF ABBREVIATIONS

AA	amino acid
ADFI	average daily feed intake
ADG	average daily gain
ADLysI	average daily lysine intake
BMR	basal metabolic rate
BW	body weight
^{o}C	degrees celsius
Ca	calcium
CP	crude protein
DE	digestible energy
DM	dry matter
DMI	dry matter intake
EBW	empty body weight
FHP	fasting heat production
G:F	feed efficiency
GIT	gastrointestinal tract
HCW	hot carcass weight
IBW	initial body weight
kLys	lysine utilization efficiency
Ld	lipid deposition
Ld:Pd	lipid deposition to protein deposition ratio
LEA	loin eye area

LM	longissimus muscle
L:P	body lipid to body protein ratio
LSW	live slaughter weight
Lys	lysine
MLC II	myosin light chain-2
MLC III	myosin light chain-3
NE	net energy
Pd	protein deposition
Pdmax	upper limit to body protein deposition
P	phosphorus
SAA	sulfur amino acids
SAA:Lys	sulfur amino acids: lysine ratio
SM	semimembranosus muscle
SID	standardized illeal digestibility
SID Lys:Ne	standardized illeal digestibility lysine to net energy ratio
SBM	soybean meal
Target L:P	target whole body lipid to whole body protein ratio
Thr	threonine
Thr:Lys	threonine: Lysine ratio
Trp	tryptophan
Trp:Lys	tryptophan: lysine ratio

VFI	voluntary feed intake
WB	whole body
WBSF	Warner-Bratzler shear force
YD	Yorkshire dams, Duroc sires
YL	Yorkshire dams, Landrace sires
YLD	Yorkshire X Landrace dams, Duroc sires

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CHAPTER 1

1.0 LITERATURE REVIEW

1.1 Introduction

In order to compete in today's market a pork producer must remain profitable. Profitability, to a large extent, is determined by how well a producer can reduce input costs. Feed inputs are often the greatest cost of production and account for up to 70% of total production costs in a swine farrow to finish operation (Statistics Canada, 2015). With recent trends of increasing grain prices, the importance of finding solutions to reduce these costs is becoming greater.

Protein is one of the most expensive nutrients in the diet. More specifically, protein sources used during the nursery phase are relatively expensive compared to other stages of growth due to their high protein concentration and digestibility that is needed by the piglet due to its limited gut capacity and relatively high protein/amino acid (AA) requirements, in contrast to later growth periods. Indeed, by reducing the amount of protein in the diet, feed costs could be substantially reduced. However, reducing protein content in the diet may decrease growth rate and increase the fat content of the body (de Greef, 1992). As a consequence, producers are hesitant to reduce the amount of protein they feed in the diet to their newly weaned pigs.

A reduction in protein content in the diet has been closely associated with increased fat content and reduced protein content in the body (Skiba, 2005). Since more than 50% of protein deposition (Pd) takes place in lean tissue (de Greef and Verstegen, 1993; de Lange et al., 2003), a reduction in lean mass is observed when feeding protein-restricted diets. As a result, producers receive less money for their pigs at market due to the lower amounts of lean and greater amounts of fat present. The latter strategy of reducing dietary protein is therefore not an attractive measure to reduce costs of production. On the other hand, short term restriction of protein in the diet may be cost effective in pig production. It has been well established that following a period of short term protein restriction, pigs can exhibit compensatory growth (Martinez-Ramirez et al., 2008b; Taylor et al., 2015). Compensatory growth can be defined as a phenomenon whereby following a period of nutrient (i.e. protein) or feed restriction (i.e. total quantity of feed available), there is a dramatic increase in growth with animals achieving the same body weight (BW) and body composition in the same amount of time as the unrestricted animals (Hornick et al., 2000). This response may result from improved feed efficiency (G:F) (Chiba et al., 2002) and(or) increased feed intake (Crister et al., 1995) relative to unrestricted animals.

The concept of compensatory growth may be an effective approach to reduce input costs without jeopardizing carcass value. Furthermore, due to the relative immaturity of the digestive tract, and changes in gut structure at the time of weaning, protein digestibility and absorptive capacity may be limited. The latter may result in an increase in available protein for pathogenic bacteria; this may inflict diarrhea and ultimately have a negative influence on performance (e.g. decreased average daily gain (ADG) and G:F) (Pluske et al., 1997). Therefore, reducing protein in the diet during the weaner phase when pigs are highly susceptible to disease, may also reduce the dependency on antibiotics (Wellock et al., 2008). However, research on compensatory growth following a nutrient restriction in nursery pigs is limited and further research is required to confirm its potential to reduce costs of production without affecting animal health and time to market.

1.2 Nutrient Partitioning in Pigs

Nutrients, the building blocks of life can be described as substances that provide essential nourishment for maintenance and(or) growth of an organism to sustain life (Webster's, 1913; Oxford, 1995). As swine nutrition researchers, we strive to meet these nutrient requirements as accurately and economically as possible. In doing so, it is important to understand how nutrients, including energy, are partitioned in the pig.

Particular focus has been placed on the distribution of dietary energy and protein in the pig; this is often referred to as nutrient partitioning in the animal. The latter is often used to determine the extent of fat and lean muscle deposition in the pig, respectively. In addition, energy and protein are often the most expensive components of the diet (OMAFRA, 2017), and therefore it is essential that nutrient requirements are understood in the best possible way. For an extensive review of nutrient requirements and partitioning in pigs, please refer to the Nutrient Requirements of Swine (NRC, 2012).

With the introduction of compensatory growth, meeting the energy and (or) protein requirements of pigs, at least on a short term basis, may not be as essential as previously believed. Nonetheless, understanding the partitioning of energy and protein in the pig is essential to determine the extent of compensatory growth and the factors affecting it.

1.2.1 The Role of Energy in Compensatory Growth

Not a nutrient per se, but rather a component associated with the nutrient content of feeds, energy is often described as the potential capacity to carry out work (Moehn et al., 2005). It is well understood that energy, in terms of nutritional application, is generated from the oxidation of organic compounds (i.e. carbohydrates, lipids, protein).

Carbohydrates in the diet are often the main substrates for oxidation. However, dietary protein and lipids can also be utilized to provide energy for metabolic purposes and growth. Generally speaking, energy can be partitioned into three main categories: heat, product formation (tissues, milk, fetus), and waste products (NRC, 2012). Of particular interest is the partitioning of energy toward lipid and protein deposition in the body, as these are representative of the body composition of the pig (Halas et al., 2004). It is well understood that the level of energy in the diet can influence the extent of protein and lipid growth (de Greef and Verstegen, 1993).

1.2.1.1 Partitioning of Energy

Previously it was stated that energy can be partitioned into three main categories: heat, product formed (tissues, milk, and fetus), and waste products (NRC, 2012). More specifically and for simplicity, energy requirements of pigs are often broken into two categories: maintenance and production (i.e. lipid and protein deposition).

1.2.1.1.1 Maintenance

Biologically, it is dictated that the priority for use of ingested energy is initially given to maintenance (Ferguson, 2006). Simply put, maintenance is the required amount of dietary energy to sustain vital processes within the body so there is no net gain or loss of nutrients in tissue and animal products (ARC, 1981). In terms of energy, maintenance requirements account for approximately 33% of total energy requirements in growing pigs (Black and de Lange, 1995). Therefore, an accurate representation of maintenance requirements is beneficial, when determining the extent of lipid deposition (Ld) and Pd in the body. Multiple methods have been described to determine maintenance requirements, each with their own limitations. The most frequently used method is fasting heat production (FHP) which represents the basal metabolic rate (BMR) of an animal. In other words, the amount of heat that is produced by physiological processes to sustain life when the animal is at rest. The use of the latter method for determining maintenance requirements may be due to its ability to decrease dependency on the level of animal production and nutrient regimen, compared to other methods (de Lange et al., 2006). However, FHP may be influenced by the plane of nutrition and(or) feed composition (Van Milgen et al., 1998). For this reason, various studies have suggested errors in this approach for determining maintenance requirements (Birkett and de Lange, 2001; Van Milgen and Noblet, 2003). A variety of other factors have been known to influence FHP (Van Milgen et al., 1998; Ewan, 2001). Notably, the review by Van Milgen and Noblet (2000), suggested that the main discriminating factor for FHP is BW. Traditionally, the relationship between body surface area and metabolic rate has been described as $BW^{0.75}$ (Van Milgen and Noblet, 2003). However, several studies have suggested that the exponent of 0.75 is too high which leads to underestimating the maintenance requirements for growing pigs (Noblet et al., 1999; Van Milgen and Noblet, 2000). It has been proposed that an exponent of 0.60 may more accurately represent maintenance requirements (Noblet et al., 1999). In addition, several researchers have suggested that maintenance requirements for energy are better defined based on protein content rather than BW (Whittemore, 1983; Schinckel and de Lange, 1996). The rationale behind this is that fat is generally a metabolically inactive tissue, contributing much less to maintenance energy requirements than protein. However, it is important to consider the variation in energy requirements for different pools of protein, in particular viscera and lean muscle. Although the total mass of viscera is much smaller compared to the total mass of lean muscle, the energy expenditure per kilogram of visceral protein often exceeds that of lean muscle (Van Milgen et al., 1998). This may be important to consider, as previous nutritional history significantly influences the weight of metabolically active organs (Koong et al., 1983). Consequently, the organ size of fasted pigs may be smaller than that of the "normal" pig, which has had *ad libitum* access to feed. As such, the energy expenditure of the organs may be lower due to the relative decrease in the size of the organs in fasted pigs (Nyachoti et al., 2000). For this reason, the FHP and thus the maintenance requirements may not accurately reflect the true maintenance requirements for the animal. In addition, one must not forget the effect that heat increment of feeding has on maintenance requirements.

Simply put, heat increment of feeding is the heat produced during the digestion and metabolism of nutrients. The components of heat increment consist of heat of digestion, heat of tissue formation, heat of fermentation, and heat of waste formation (NRC, 2012). Methodology for the estimates of these functions has been described in detail (Baldwin, 1995). These estimates are most commonly influenced by nutrient type, source of nutrients, and the efficiency of nutrient utilization (Van Milgen and Noblet, 2000). With this in mind, consideration of diet composition may be beneficial when determining the contribution of heat increment of feeding to maintenance requirements. For example in poultry management, low protein diets supplemented with crystalline AA will lower the heat increment of feeding; this may be attributed in part to lower heat of waste formation as a result of improved dietary AA balance (Lagana et al., 2007). Together, the FHP and the heat increment of feeding can be used to determine maintenance requirements, and thus the potential energy that may be available for production.

1.2.1.1.2 Production

Theoretically, energy above maintenance can be utilized towards Pd and Ld in the pig. The extent to which this occurs depends on a variety of factors. A major factor to consider is the amount of feed consumed by the pig, or voluntary feed intake (VFI). The VFI ultimately determines nutrient intake levels, and therefore is closely associated with ADG and G:F. Nyachoti et al. (2004) discussed in detail, factors that may influence VFI. However, when other constraints (environment, social, and animal) are not limiting, it is believed that VFI is driven by the pig's requirement for the first limiting nutrient (Ellis and Augspurger, 2001). In most cases, this has been attributed to energy yielding nutrients (Nyachoti et al., 2004). However, as shown by Cole et al. (1971), it appears that pigs are capable of adjusting their feed intake to maintain a constant energy intake. The latter may be compromised when energy density reaches extremes (Cole et al., 1971). In instances where energy density is low, this can most likely be attributed to gut fill (Quiniou et al., 2000). This is especially important to consider in growing pigs, as they often are limited by gut fill, where they are physically unable to consume enough of a low energy diet to meet their growth potential. This inherently will influence the extent of tissue deposition in the pig, and thus our prediction of growth. Nonetheless, these factors are important to consider when determining nutrient intake.

As mentioned, nutrient intake may be the main contributor for the prediction of growth. Growth has been described as an accumulation of protein, fat, ash, and associated energy in the body (Ewan, 2001). The association between energy, protein and fat has been best described by the linear plateau model. The latter was proposed by Whittemore and Fawcett (1976) and has since become the foundation of the relationship between feed intake and Pd and Ld. In this model, the response of Pd and Ld to a change in energy intake for a specific BW range is simulated. Assuming no other nutrients are limiting, this model suggests that as energy intake increases, Pd and Ld increase. For protein, this occurs until a genetic maximum upper limit to Pd (Pdmax) is reached; thereafter, energy consumed goes specifically to Ld (Mohn and de Lange, 1998). The period up to the Pdmax is referred to as the energy dependent phase for Pd, followed by the energy independent phase for Pd. During the energy dependent phase, Pd is thought to be closely associated with the minimum body Ld to body Pd ratio or the minimum Ld:Pd ratio. As described by Whittemore and Kyriazakis (2006), the minimum Ld:Pd ratio refers to the minimum level of body fatness which allows the pig to partition available nutrients to other physiological functions (e.g. lean growth, pregnancy, lactation). In other words, the minimum Ld:Pd ratio is the physiological minimum amount of Ld that must accompany Pd for pigs to grow normally. When pigs are fed a diet that is low enough in energy to restrict their ability to achieve Pdmax, the Ld:Pd ratio will be equal to the minimum Ld:Pd ratio. This ratio was assumed to be constant throughout the energy dependent phase of Pd and therefore independent of energy intake. For this reason, pigs are characterized in this model based on their minimum Ld:Pd ratio and the Pdmax. Since then, the model has been validated by several researchers (Black, 1974; Campbell et al., 1983, 1985; Campbell and Tavener, 1988; de Greef et al., 1992). From past research it is evident that a constant minimum Ld:Pd ratio during the energy dependent phase for Pd may need to be reconsidered. From the studies of Campbell et al. (1983, 1985) and Campbell and Tavener (1988), it is evident that the minimum Ld:Pd ratio increases with increasing energy intake. Similar results were shown by de Greef (1992) where two constant amounts of energy (12.6 and 16.3 MJ DE/day above maintenance) were fed to entire male pigs from 25 to 105 kg BW. The pigs fed the low amount of energy had a Ld:Pd ratio of 0.90 while the pigs fed the high amount of energy had a Ld:Pd ratio of 1.15. In both cases, pigs were believed to be below their genetic maximum for Pd. In addition, this study examined the effects of BW on Ld:Pd ratios. As BW increased, the Ld:Pd ratio increased at both constant energy levels. This suggests that as pigs increase in BW, a larger proportion of energy is partitioned to Ld. However, the authors suggested that an increase in energy causes a much greater effect on the Ld:Pd ratio than an increase in BW. On the other hand, Weis et al. (2004) showed that the effects of BW can be attributed to increases in energy intake. This most likely would be the case in growing pigs, where pigs are commonly fed *ad libitum*.

It is clear that the minimum Ld:Pd ratio is not constant as once believed. As shown, the minimum Ld:Pd ratio can be influenced by nutritional regimen. However, it may be limited in its ability to represent the effects of nutritional history on body composition. For this reason, constraints on energy partitioning may be better expressed as the minimum total body lipid to total body protein ratio (L:P) (Schinckel and de Lange, 1996). The latter is discussed further in section 4.1.2. Nonetheless, the minimum Ld:Pd ratio can still be used as an accurate representation of nutrient partitioning during the energy dependent phase of Pd.

1.2.2 Protein

As previously mentioned, the pig's body can be separated primarily into protein, fat, ash, and water. Protein accounts for approximately 17% of empty body weight (EBW; i.e. the weight of the pig when the gut is empty), but in some cases this figure may be as low as 14% in a market weight pig (approximately 110 kg BW) (de Lange et al., 2003). More specifically, protein can be separated into two major pools: carcass (lean tissue growth) and viscera (organ growth). Particular focus in the literature has been directed towards the carcass as approximately 55% of deposited protein occurs in the lean tissue of the carcass (de Greef and Verstegen, 1993; de Greef, 1994; Bikker 1994). However, the rate and extent to which this occurs in both pools depends on a variety of factors such as feed intake (energy) and BW. The latter has been discussed in detail by Bikker (1994). Furthermore, dietary protein level (or level of AA) and composition can influence the rate of Pd (Campell and Dunkin, 1983; Martinez-Ramirez and de Lange, 2008), and will be discussed further in section 3.2.

Since protein is considered one of the most expensive components of the diet, it is imperative to have a firm understanding of nutritional regimen on protein partitioning in the body. This is especially important to consider as the carcass is often the most valuable portion of the animal.

1.2.2.1 **Maintenance**

Before available amino acids can be used for production, as with energy, priority is given to using AA for maintenance. Amino acid requirements for maintenance arise from the need to replace protein/AA losses due to shedding of skin cells and hair, minimum protein turnover, inevitable catabolism, and basal endogenous gut losses (Moughan, 1999). Traditionally, maintenance requirements for AA have been described as a function of the metabolic BW ($BW^{0.75}$) (NRC, 2012). Although this may be representative for AA losses from the integument, it does not consider basal endogenous AA losses from the gut (de Lange et al., 2012). This is important as basal endogenous gut AA losses are believed to be the main contributor to AA maintenance requirements in the pig (Nyachoti et al., 1997; de Lange, et al., 2013). The main sources of basal endogenous AA losses consist of digestive enzymes, secreted proteins, sloughed intestinal epithelial cells, and mucin protein (Adeola et al., 2016). However, digestive enzymes and secreted proteins are believed to be readily reabsorbed and may contribute little to total endogenous AA losses (Moughan, 1999). Conversely, sloughed mucosal cells and mucin protein are considered to be the main contributor to basal endogenous AA losses as they are relatively resistant to digestion (Moughan, 1999; Williams et al., 2009). The amount of basal endogenous AA losses may be related to the level of dry matter intake (DMI). However, there will always be losses regardless of DMI (Furuya and Kaji, 1992). At higher DMI levels, the degree of cell turnover and mucin secretion may be increased (Moughan, 1999). In theory, on a g/kg DMI basis, basal endogenous AA losses are considered to be constant (Adeola et al., 2016). Moter and Stein (2004) fed pigs at the estimated energy requirement for maintenance, and found that basal endogenous losses may be greater relative to pigs fed *ad libitum.* Adeola et al. (2016) suggested that the latter may be a consequence of the nutrient and energy restriction interfering with the basic metabolism of the pig. Other than DMI (Hees and Seve, 1999), basal endogenous losses appear to be relatively unrelated to the diet (Adeola et al., 2016). On the other hand, specific endogenous losses are considered to be influenced by diet composition such as anti-nutritive factors, dietary fiber content/quality, and protein level/quality, and their effects on Pd should also be considered (Nyachoti et al., 1997).

Maintenance requirements for the growing pig may only represent 10% of total daily AA requirements (Moughan, 1999). Nonetheless, an estimation of AA for maintenance may improve our ability to formulate diets and more accurately predict growth.

1.2.2.2 Production

Amino acid concentrations in the diet above maintenance can be utilized towards protein growth in the pig. While these AA can be used for a variety of functions, a major priority is the utilization of AA for lean deposition in the carcass. Indeed, the amount of energy available in the diet can directly influence the rate and extent of Pd in the carcass (see section 1.2.1.1.2). However, the quality or balance of AA for a protein source fed to pigs may also directly influence Pd (Lewis, 1991). Referred to as the “ideal protein”, the latter represents a protein source that contains the optimum balance of all AA for maintenance and production for a given physiological state (NRC, 2012). In terms of growing pigs, it is believed that the proportions of AA in the muscle and visceral organs largely determine the proportions among the requirements of the AA (Boisen, 1997). More simply, in theory an ideal protein source is a protein source that can provide AA in a ratio that meets but does not exceed the requirements of the pig. In a review by Boisen (1997), the ideal dietary protein AA profile remains relatively constant for pigs between 20 and 100 kg BW. The author’s reasoning was that although the AA patterns for maintenance and protein growth have been determined to be different (Fuller et al., 1989), the contribution of the difference in AA composition for maintenance relative to the "ideal protein" was considered to be minimal. It should be noted, that the pigs referred to in this study weighed approximately 40 kg. As maintenance requirements for protein are often considered to be low in growing pigs, this may suggest why the contribution of the maintenance requirements to the ideal protein were minimal. As pigs grow, the contribution of protein/AA towards maintenance requirements relative to total requirements proportionally becomes greater, and therefore may have more significance on the ideal protein profile. For example, in a study by Hahn and Baker (1995), it was discovered that as the ratio (to Lysine (Lys)) of dietary Threonine (Thr), Tryptophan (Trp), and sulfur AA (SAA) increased (relative to the ideal AA profile for growing pigs), ADG, G:F, and nitrogen retention improved. Although it was not determined if an increase in all three ratios (Thr:Lys, Trp:Lys, and SAA:Lys) are required, it could be speculated that an increase in the Thr:Lys ratio would improve overall performance. As noted by Milgen and Dourmad (2015), endogenous secretions are rich in Thr, and as the amount of their losses increase during growth, the Thr:Lys ratio will also increase. Therefore, by increasing the ratio of dietary Thr:Lys (relative to the ideal AA profile for growing pigs) for finishing pigs, this may increase the level of dietary Thr available for growth. For this reason, the ideal protein ratios suggested for young pigs may not be as applicable in heavier weight pigs, where the contribution of maintenance requirements is greater. In most cases, the AA composition of the ideal protein is expressed relative to Lys. Therefore, if both the ideal ratios and Lys requirements are known, the requirements of the other AA can be calculated (Stein, 2006). The reasoning behind this is that since diets fed to pigs in North America are generally limiting in Lys, the amount of protein that theoretically can be synthesized is limited by the amount of Lys in the diet. The latter is often referred to as the concept of the first limiting AA, based off of "Liebig's law of the minimum". Proposed in 1840 by Justus von Liebig, Liebig's law of the minimum states that the growth and health of an organism are dependent not on the total amount of nutrients available but rather dependent on the most limiting nutrient (Allaby, 2010). Although this was described in relation to plants, it has been widely accepted for use in animal nutrition. Under this theory if one or more AA are limiting, the efficient utilization of other AA will be reduced (NRC, 2012). In turn, a reduction in performance may be observed (Lewis, 1991).

1.3 The Effects of Reducing Protein (Lysine) in the Diet on Various Parameters in the Weaned Pig.

With rising costs for oil, grains, and supplements, feed inputs are one of the greatest costs for pork production. In particular, nursery diets are often the most expensive diets in pork production due to the high level of protein included in these diets (17 to 23% protein) relative to other phases of production. Therefore by reducing protein in these diets, feed costs could be reduced substantially. However it is generally believed that newly weaned pigs must be provided with highly nutritious diets to ensure optimal postweaning growth (Campbell and Dunkin, 1983). Reduced ADG, G:F, and increased back fat thickness have all been noted in nursery pigs fed low protein diets containing 9 to 15% protein (Whang et al., 2003; Martinez-Ramirez et al., 2005; Taylor et al., 2015). Conversely, pigs fed a high protein diet may also have a reduction in ADG and G:F

(O'Connell, et al., 2006). This reduction is often due to high protein diets (17 to 23% protein) increasing the availability of protein to potential enteric pathogens (Nyachoti et al., 2006; Wellock et al., 2008). In addition, high protein diets often increase nitrogen excretion, negatively impacting the environment. For these reasons, it has been suggested that reducing crude protein (CP) while supplementing diets with crystalline AA, may maintain growth performance (ADG, feed intake, G:F) similar to pigs fed high protein diets, while also improving gut health (Kerr et al., 1995). However, when formulating with crystalline AA, it is often required to use multiple crystalline AA, which may become costly. A more economically feasible approach may be to reduce CP in nursery diets for a short period of time. Reducing Lys intake during the nursery phase reduced ADG and G:F in past studies (Wellock et el., 2008; Taylor et al., 2013). This reduction however is often short lived as following a period of AA intake restriction, pigs can exhibit compensatory growth and achieve the same BW and body composition in the same amount of time as unrestricted pigs (Martinez-Ramirez et al., 2008b). One strategy is to reduce Lys intake in weanling pigs when their protein requirements are high and the cost of the protein in the diet is high compared to other phases of production. This approach can reduce feed costs by implementing compensatory growth through re-feeding of lower cost protein sources later in life when protein requirements are lower. However, it is important to thoroughly understand the effects of reducing dietary AA (especially Lys), on various parameters (growth performance, body composition) in the weanling pig. In addition, understanding the potential long term effects of a temporary reduction in dietary protein may be beneficial when looking at the dynamics of compensatory growth.

1.3.1 Effects of Low Protein (Lys) diets on Growth Performance and Carcass Composition

It is well understood that when dietary protein content is below the requirements for the pig for growth, growth performance will be reduced (Lewis, 1991). In most cases, Lys is the first limiting AA in cereal based diets fed to pigs, and thus has been the AA most investigated (Boisen, 1997). Numerous studies have examined the effects of a reduction in dietary Lys on feed intake (Kerr et al., 1995; Chiba et al., 1999; O'Connell et al., 2006; Suarez Belloch et al., 2015; Taylor et al., 2015). In these studies, there were no significant differences in feed intake compared to controls when pig gender, breed, BW, and severity of Lys restriction varied. That being said, Henery (1985) noted in a review that pigs fed diets deficient in Lys or Thr may exhibit an increase in feed intake compared to controls in order to meet their requirements. In agreement with this, Fabian et al. (2002) discovered there was a linear increase in feed intake as the concentration of Lys in isocaloric diets decreased (5.0, 7.0, 9.0, and 11.0 g/kg), when fed to 20-50 kg BW pigs. Although these pigs may have consumed more feed, their Lys consumption along with ADG and G:F were still significantly lower compared to unrestricted pigs. This is in contrast to the NRC (2012) which suggests that an AA deficiency may lead to a reduction in feed intake. The latter may be the case only when other AA are in excess of the limiting AA, and further energy is required for nitrogen excretion. In situations where other AA are balanced relative to the first limiting AA, this may not be the case. D'Mello (2003) suggested that a depression in feed intake may be the result of the lower concentrations of the first limiting AA, initialing a neural signal that causes a change in feed intake. However, these studies were done in rats, and the exact mechanisms are not fully understood. Nonetheless, further research in pigs may be warranted to examine the effects of a low Lys diet on neurotransmitters (e.g. noradrenaline) in the pig.

Indeed, as previously discussed, restricting Lys in pig diets can reduce ADG. This reduction in ADG may be due to a reduction in whole body (WB) Pd and an increase in WB Ld relative to pigs fed diets adequate in Lys (de Greef, 1992). Since the deposition of protein (1 g protein and 4 g water) is heavier relative to Ld (1g fat and 0.2 g water), a decrease in ADG is observed (Ewan, 1991). Consequently, pigs consuming a diet limited in Lys will have increased fat stores and decreased protein stores relative to their unrestricted counterparts. The latter has been described in a review by Skiba (2005) where protein stores decreased and fat stores increased in 9 studies varying in severity and duration of dietary Lys restriction. In addition, these studies reported no significant differences in the size of the viscera. The decrease in ADG and corresponding BW when feeding Lys restricted diets can mainly be attributed to a decrease in the size of the carcass while the viscera remains unchanged. A decrease in the size of the viscera, especially highly metabolic organs such as the liver, kidneys, and large and small intestine, is more commonly observed following a total feed restriction where overall energy intakes are decreased (Bikker, 1994).

A reduction in dietary Lys for pig diets may lead to the repartitioning of energy from protein to fat. The rationale behind this is that energy potentially available for use for Pd is unable to be utilized for Pd due to a lack in AA needed for a given amount of body protein, and consequently this energy is utilized for fat. Furthermore, the reduction in ADG along with increased feed intake will lead to a decrease in overall efficiency (poor G:F) for the pig. Consequently, the time and cost required to reach market weight may increase and producers may be penalized for the increased fat content of the carcass. Use of a compensatory growth strategy may be a means to reduce feed costs and compensate for lost gain, inflicted from a nutrient restriction.

1.4 The Concept of Compensatory Growth

As described by Hornick et al. (2000), compensatory growth or "catch-up" growth refers to a physiological process whereby following a period of nutrient intake restriction, an animal accelerates its growth beyond that of non-restricted animals. This phenomenon can be broken into two phases, a restriction phase and a recovery phase. Most restrictions have involved either a feed intake restriction (limiting the amount of feed available to the animal which ultimately limits energy availability) or a nutrient restriction (e.g. protein restriction). During the recovery phase or compensatory growth period when there are no longer any nutrient restrictions, the animal will respond with an increase in Pd and a decrease in Ld relative to animals that were always fed a nutrient adequate diet (unrestricted animals) (Skiba, 2005; Martinez-Ramirez and de Lange, 2008). Full compensatory growth occurs when previously restricted animals achieve the same BW and body composition in the same overall time as the unrestricted animals.

Compensatory growth has been studied in a variety of animals including: sheep, cattle, and pigs (McMeekan, 1940ab; Ryan et al., 1993;Martinez-Ramirez et al., 2008ab). In the feedlot industry, the concept of compensatory growth is implemented as a part of standard management practices. Cattle are routinely managed on a low plane of nutrition for a period of time where they have undergone a period of nutritional stress with limited total feed intake or intake of high quality diets. These cattle attract premiums from buyers as subsequent growth of cattle is expected to be superior to that of well-fed animals when the restricted animals are placed on a higher plane of nutrition in the recovery phase (Sainz et al., 1995). In pigs, this concept has yet to be put into practice. This can most likely be attributed to the inconsistencies in the literature on the effects of compensatory growth on overall growth performance, body composition, and carcass quality (Campbell and Dunkin 1983; Whang et al., 2003; O'Connell et al., 2006; Martinez-Ramirez et al., 2008ab; Kamalakar et al., 2009). However, examination of the literature shows that studies often vary in type of nutrient restriction, length of restriction, timing of restriction, genotype, and gender, which can possibly explain these inconsistencies in the response to compensatory growth. Thus these studies have highlighted the complexity of achieving full compensatory growth to ensure that previously restricted pigs can achieve the same BW and body composition in the same time as the unrestricted pigs. The mechanisms that regulate compensatory growth are not yet fully understood. Nonetheless, a summary of various proposed theories such as the sizostat theory, the growth plate theory, and peripheral control theory have been summarized in detail by Martinez-Ramirez (2005).

Mechanisms for compensatory growth may not yet be fully understood. However, basic principles of nutrient partitioning in pigs can be used to help understand the phenomenon of compensatory growth.

1.4.1 Basic Principles of Compensatory Growth

A framework to describe the rate and extent of compensatory growth following a period of nutrient or feed restriction has been described in a review by Martinez-Ramirez and de Lange (2008). The authors concluded that compensatory growth is constrained by the Pdmax and is driven by the target whole body lipid to whole body protein ratio (Target L:P). The latter implied that compensatory growth primarily occurs during the energy dependent phase of Pd (see section 1.2.1.1.2). This is believed to be true for both nutrient restrictions and feed restrictions. Description of the various types of restriction will be discussed in detail (see section 1.4.2.1). Experimental evidence for the constraints listed previously will be discussed in terms of a specific nutrient restriction. Nonetheless, the concepts of nutrient partitioning discussed can be used interchangeably between feed and nutrient restrictions.

1.4.1.1 Pdmax

As described previously, Pdmax can be defined as the genetic upper limit for Pd in the pig that can be achieved given that the nutrient supply is adequate, and no other stressors (e.g. environment, disease etc.) are present. Several researchers have reviewed the concept of Pdmax extensively (Schinckel and de Lange, 1996; de Lange et al.,2001; Martinez-Ramirez and de Lange, 2008; de Lange et al., 2012). These authors hypothesized that Pdmax remains relatively constant up to approximately 80-85 kg BW; Pdmax then gradually declines to zero as pigs reach maturity. Furthermore, it was noted that in growing pigs (below approximately 50 kg BW), energy intake will most likely be the limiting factor for Pd. In finishing pigs, the rate of Pd is more likely to be limited by the Pdmax (Schinckel and de Lange, 1996). This can be attributed to BW differences in the pig's physical capacity (gut fill) to ingest and digest food; this physical capacity is often limiting in young growing pigs (Nyachoti et al., 2004). In agreement with this, Mohn and de Lange (1998) showed that at lighter BWs,very high levels of energy intake are required to reach Pdmax. In addition, pork industry pressure to produce leaner pigs has led to improvements in Pdmax, and consequently pigs may be limited in their ability to reach the Pdmax up to heavier BW (de Lange et al., 2001). The latter may increase the opportunity for capitalizing on compensatory growth. In order for pigs to achieve full compensatory growth, they must be able to accelerate their growth beyond that of the unrestricted controls. If Pdmax limits their ability to do so, than compensatory growth will not occur. These concepts were evaluated in two studies by Marinez-Ramirez et al. (2008ab) where intact males and barrows were restricted in standardized illeal digestibility (SID) Lys (30% and 40% below NRC 1998 Lys requirements for growing pigs, respectively) from 15 to 35 kg BW. Compensatory growth was achieved in entire males, but not in barrows. One explanation for this gender effect is that the greater dietary restriction level of Lys fed to barrows limited their ability to compensate. However, during the recovery phase for the barrows, there were no significant differences in Pd or Ld between energy intake treatments. The researchers (Martinez-Ramirez et al., 2008a) evaluated two levels of feed intake (*ad libitum* vs. 75% of dietary energy intake) during the recovery phase for the barrows. An increase in energy intake only increased Ld and not Pd for both control and previously restricted pigs. This suggests that following the restriction phase, both control and restricted barrows were at Pdmax. On the other hand, previously restricted boars achieved a greater Pd (approaching the Pdmax), and used less energy for Ld during the recovery phase compared to the controls. This reduction in Ld and increase in Pd during the recovery phase suggests that a compensatory growth response is strictly a repartitioning of energy between Pd and Ld. However, the ability of pigs to accelerate their Pd beyond that of controls may be limited by their Pdmax. Since barrows had a lower Pdmax compared to boars, Pdmax was achieved at a lower BW in control barrows than it was in control boars (Martinez-Ramirez et al., 2008ab). Therefore, Pdmax may have been one of the major constraints on the rate and extent of compensatory growth.

1.4.1.2 Target Body L:P Ratio

It is well understood that physiologically a "minimum" amount of Ld must accompany Pd in normal pig growth. For example, de Greef (1992) fed growing pigs diets that provided 12.6 or 16.3 MJ digestible energy (DE) above maintenance; the increase in level of energy fed increased both protein and fat growth. Whittemore and Kyriazakis (2006) explained this minimum (target) level of body fatness as the genetic level of body fatness that the pigs feel: "physiologically comfortable to partition and prioritizes available nutrients toward lean tissue growth rate and other functions". During the energy dependent phase of Pd, energy intake is insufficient to express both the minimum Ld:Pd ratio and Pdmax (Weis et al., 2004). In other words, energy intake rather than the pig's Pdmax will determine the observed rate of Pd during the energy dependent phase of Pd (Schinckel and de Lange, 1996). Indeed, the minimum Ld:Pd ratio may limit the ability of the pig to achieve its genetic potential. However, as discussed previously, the minimum Ld:Pd may not remain constant and may be influenced by BW, gender, genotype, and the level of energy in the diet (de Greef, 1992, Bikker, 1994, Martinez-Ramirez et al., 2008a). In fact, Kyriazakis and Emmans (1992) showed that when feeding low levels of energy close to maintenance level intakes, Pd remained unchanged while Ld was minimal. The latter provides evidence that the minimum Ld:Pd ratio can be influenced by nutrient level but does not establish how previous nutritional regimens affect the composition of growth (Martinez-Ramirez and de Lange, 2008). For this reason, the effects of previous nutritional regimens (e.g. protein restriction) on body composition may be better represented by the constraints on the minimum L:P ratio or the target WB L:P ratio that the pigs tend to maintain.

It has been well established that following a period of protein restriction, pigs may accelerate their growth beyond that of the unrestricted pigs. As proposed by Schinckel and de Lange (1996), the latter can be explained by the constraints of the target L:P on the partitioning of retained energy between Pd and Ld. As previously discussed, energy intake is insufficient during the energy dependent phase of Pd to fully express both the minimum Ld:Pd ratio and Pdmax. However, when the actual L:P ratio is greater than the target L:P ratio, previously restricted pigs will no longer be in the energy dependent phase of Pd and may be able to accelerate their growth beyond that of the controls to a level similar to Pdmax. Ferguson and Theeruth (2002) fed pigs between 15 and 30 kg BW diets restricted in protein. Restricted pigs had a greater L:P ratio, or in other words were fatter, than the unrestricted pigs. However, when restricted pigs were fed a high protein diet, over time the L:P ratio decreased to a similar level as pigs that had previously not been restricted in dietary protein. Although an increase in Pd is expected (de Greef, 1992), this response will also be accompanied by a reduction in Ld (Ferguson and Theeruth, 2002) or in some cases through the catabolism of excess body fat (Skiba, 2005). This re-distribution between Pd and Ld will occur until the target L:P ratio has been restored (Kyriazakis and Emmans, 1991). During compensatory growth, it appears the composition of growth is driven by the target L:P ratio. However, Martinez-Ramirez and de Lange (2008) noted that previously restricted pigs can only achieve the target L:P ratio when the controls are still in the energy dependent phase of Pd. In other words, if previously restricted pigs are limited by their Pdmax (i.e. the controls are already at the Pdmax) following a protein restriction, they will be unable to achieve the target L:P ratio. For this reason, both the Pdmax and the target L:P should be considered when determining the outcome of compensatory growth.

1.4.2 Factors Influencing Compensatory Growth

The type of restriction, timing of restriction, length of restriction, severity of restriction, and nutrient level during recovery, can influence the extent of compensatory growth. Indeed, it appears that animal and nutritional factors are the main factors influencing compensatory growth (Martinez-Ramirez, 2005). For the purpose of this thesis (except section 1.4.2.1), only nutritional factors influencing compensatory growth are discussed.

1.4.2.1 Type of restriction

The most common type of restrictions imposed in the literature are feed restrictions, which limit total amounts of energy available (Hornick et al; 2000; Martinez-Ramirez and de Lange, 2008; Wiecek et al., 2008), protein or AA restrictions (Wyllie et al., 1969; Zimmerman and Khajaren, 1973; Martinez-Ramirez, 2005; Martinez-Ramirez 2008ab; Taylor et al., 2015), and restrictions caused by a reduction in diet complexity (Skinner et al., 2014; Reinhardt, 2012). Each form of restriction successfully reduced ADG and G:F in pigs. The response in compensatory growth during the recovery phase may however vary. Skiba et al. (2005) attributed these differences to the part of the body that had experienced the greatest reduction in growth during the restriction phase.

When growth has been restricted by a reduction in feed available to the animal, it appears that compensatory growth during the recovery phase primarily occurs in the visceral organs (Bikker, 1994; Skiba et al., 2005; Lovatto et al., 2006). This is in contrast to Therkildsen et al. (2004) where compensatory growth occurred in both the muscle and fat tissue and not just viscera when 28 day old pigs were restricted of feed (fed at 60% of *ad libitum* feed intake) for approximately 7 weeks. At the end of the study, restricted pigs had the same lean muscle content as the pigs fed *ad libitum*, but consumed 5% less feed overall. These results disagree with Hornick et al. (2000) where compensatory gains were achieved by elevated intakes in previously restricted animals compared to controls. However, the latter study observed compensatory growth in ruminants and this may not be the case in pigs.

After a period of protein or AA restriction, pigs are believed to have lower protein stores and greater fat stores compared to controls (Sikba et al., 2001, 2005). The latter can be explained based off the concept of nutrient partitioning described previously (see section 1.2). During the restriction phase, energy that could have been utilized for Pd is instead deposited as fat and this is due to inadequate amounts of protein or AA in the diet, which limits Pd. Consequently, there is an increase in the L:P ratio compared to controls. In a review by Skiba (2005), the latter was seen in 9 studies varying in length and severity of protein or AA restriction at the end of the restriction phase. Contrary to a feed restriction, compensatory growth following a period of protein or AA restriction may be due to an increase in protein gain, closely related to lean tissue gains of the carcass

(Fabian et al., 2002; Reynolds and O'Doherty, 2006; Martinez-Ramirez and de Lange 2008). As previously discussed, in order to correct the nutrition-induced increase in the L:P ratio, pigs are able to reduce their Ld and achieve a Pd rate approaching Pdmax. Consequently, previously restricted pigs will obtain the same L:P ratio as non-restricted controls relative to the target L:P ratio in the same length of time. However, compensatory growth following a protein or AA restriction, has not always been attained on a consistent basis even when tested under similar experimental conditions (e.g. same restriction type, length, severity etc.). Taylor et al. (2013) conducted four similar trials (each 7 months in length) from March 2008 to December 2011 in which nutritionally restricted pigs were fed diets limiting in Lys for a 3 week period. Over these four trials, compensatory growth in pigs occurred during trials 1 and 2, but not in trials 3 and 4. The reasons for this is not understood. Clearly, there appears to be aspects of compensatory growth following a Lys restriction that requires further investigation. Indeed, it may not be as simple as suggesting that the factors listed previously on nutrient partitioning explain why compensatory growth did not occur. Nonetheless, these aspects are still important to consider.

1.4.2.2 Timing of Restriction

In the scientific literature, nutrient or feed restrictions are commonly imposed for a period of time during the grower phase, and to a lesser extent in the nursery phase as feed costs are generally relatively expensive in these phases compared to the other phases of production. Historically, it has been believed that nutritional restrictions in young pigs can cause temporary or permanent damage on subsequent growth in pigs. Such was the case in a study performed by Campbell and Dunkin (1983). Following a period of protein restriction, pigs achieved the same body composition but were significantly older (149 days) than the pigs fed a high protein diet throughout (123 days). The researchers concluded that protein deprivation reduced the amount of DNA in muscle of the pigs, which may have reduced the Pdmax. It is important to note that these pigs were restricted 24 hours after they were born. This is important as the first week of postnatal life is when muscle fibers undergo a period of maturation to establish the highly organized pattern encountered in adult pigs (Lefaucheur et al., 1995). In addition, sow's milk has low amounts of protein relative to energy, limiting the piglet's ability to achieve maximal lean growth (Williams, 1995). Yet, full compensatory growth has been exhibited in pigs restricted immediately postweaning (Campbell and Biden, 1978; Kyriazakis and Emmans, 1991; Taylor et al., 2015). Early nutritional history may therefore not be as important to subsequent growth as previously believed. Unfortunately, studies investigating compensatory growth during the nursery phase are limited. This may be due to the fact that immediately postweaning, piglets undergo a significant amount of environmental and physiological stress; there are concerns that nutrient restrictions at this time may pose problems not only for growth performance, but also animal health.

A substantial amount of research has been conducted on compensatory growth during the grower phase (Chiba et al., 1999, 2002; Fabian et al., 2002; Reynolds and O'Doherty, 2006; Yang et al., 2008). In two studies conducted by Fabian et al. (2004) and O'Connell et al. (2006), full compensatory growth was achieved in finisher pigs following a period of nutrient restriction during the grower phase. In the case of Fabian et al. (2004), pigs were restricted in dietary Lys (5.0 g/kg) from 22 until 51 kg BW, while O'Connell et al.

(2006) fed Lys restricted diets (8.1 g/kg) from 36 to 65 kg BW (35 days). Furthermore, the genders used in the respective studies were different from Fabian et al. (2004) who used barrows, while O'Connell et al. (2006) utilized entire males and gilts. While there were major differences between studies for gender and severity and timing of Lys restriction, full compensatory growth was found in both studies. This further highlights the variability and complexity of compensatory growth, and may explain why compensatory growth has yet to be implemented on commercial operations.

1.4.2.3 Effects of Severity and Length of Nutrient Restriction

In studies where compensatory growth did not occur, this may be attributed to length or severity of nutrient restrictions inhibiting compensatory growth (Kamalaker et al., 2009). The severity of the protein or AA restriction among studies has varied between 15% and 60% below requirements, with protein or AA restriction lasting in most cases between 14 and 35 days (Wyllie et al., 1969; Zimmerman and Khajarern, 1973; Wellock et al, 2009; Taylor et al., 2015). Unfortunately, experimental design among compensatory growth research is variable; comparing studies in terms of length and severity of nutrient restriction is often difficult due to confounding factors. Furthermore, the timing of the nutrient restriction rather than the length or severity of the nutrient restriction may play a bigger role in the outcome of compensatory growth. For example, pigs receiving a diet 55% below requirements for protein and between 5 to 23 kg BW had reduced growth performance and carcass characteristics during the nutritional restriction but were able to compensate when fed a 16% protein diet in the grower phase (Zimmerman and Khajarern, 1973). Yet, pigs receiving a diet with a similar reduction in dietary protein were unable to compensate when restricted between 20 to 30 kg BW (Whang et al., 2003). In contrast, pigs fed a diet 20% below requirements for Lys between 20 to 50 kg BW had reduced growth performance and carcass characteristics, but were able to compensate thereafter when fed to market weights (Chiba, 1994).

One can speculate that as the severity of the nutrient restriction level increases, restricting pigs later in life may decrease their ability to fully compensate. However, research in this area is rather inconclusive and care should be taken when considering the latter statement. A conclusive conclusion cannot be made because the confounding factors amongst experiments are large and further research is warranted. Determining the effects of the length of the nutrient restriction or the severity of the nutrient restriction on the compensatory growth response may be difficult as these factors often vary together. For this reason, more uniform experiments are required to better understand the effects of the severity or the length of nutrient restriction on the compensatory growth response.

1.4.2.4 Effects of Nutrient Level During the Recovery Period

As previously discussed, accelerated growth following a protein or AA restriction may occur to restore or compensate for the previous loss in growth. In addition, there will be changes in body composition such that growth and body composition in previously restricted pigs will be similar to control pigs that were always fed nutrient adequate diets (Kyriazakis and Emmans, 1991). However, the rate and extent of compensatory growth may be directly impacted by the level of nutrients fed during the recovery phase.

In the past, the common level of protein or AA fed during the recovery phase in compensatory growth studies is either similar to the NRC (1998; 2012) requirements or slightly above (e.g. 20% increase) (Fabian et al., 2002; Martinez-Ramirez el al., 2008; Yang et al., 2008; Kamalaker et al., 2009; Taylor et al., 2015). The duration, length, and timing of dietary protein or AA restrictions have varied among studies; yet compensatory growth has been observed when pigs are fed at or above requirements for dietary protein or Lys in growing pigs. Although, previously restricted pigs may experience an accelerated Pd, it is plausible that they may require more nutrients than their unrestricted counterparts.

In a classical study by Whang et al. (2003), the effects of incremental changes in dietary protein were examined. Between 20 and 30 kg BW, pigs were fed a diet containing either 9% or 18% CP. Following this, all pigs were fed one of 6 experimental diets varying in CP (11.8, 13.1, 14.3, 15.6, 18.8, 21.8%). As CP increased during the recovery phase, ADG increased linearly for both groups of pigs (i.e. 9% and 18% CP). However, pigs previously fed the 9% CP diet grew more efficiently and had greater protein gains then pigs previously fed the 18% CP diet demonstrating compensatory growth. Utilizing the broken line technique pigs previously fed a protein deficient diet required greater levels of dietary protein for maximal protein gain (16.73% vs. 16.23% CP, respectively) as compared to unrestricted fed pigs. Similarly, O' Connell et al. (2006) found that as Lys concentrations in the diet increased during the recovery phase, feed conversion increased linearly for pigs who were previously restricted. On the other hand, with increasing Lys concentrations, feed conversion responded quadratically with pigs who were previously unrestricted. This suggests that at higher concentrations of Lys, pigs who are previously restricted in Lys are more efficient at utilizing Lys during the recovery phase than pigs that were fed Lys adequate diets early on. For both of these studies, there were no significant differences in feed intake between restricted and unrestricted pigs at any point during the experiments. The latter may be a result of limitations in gut capacity, or the isocaloric content of the diets.

Arguably, pigs may not require higher levels of CP or AA during the recovery phase in order to compensate. However, it is possible that feeding higher levels of nutrients during the recovery phase to younger pigs may be beneficial due to their greater potential for Pd relative to older pigs. In other words, the effectiveness of a higher protein diet may depend on the time the recovery is implemented (e.g. nursery vs. grower-finisher). Furthermore, an increase in dietary protein concentration may be beneficial as an increase in feed intake is not expected. This is especially the case in young pigs that are often limited by gut fill. Skiba (2005) suggested that an increase in feed intake during the recovery period is often not expected; the higher body fat content in pigs that were previously restricted may partially lower their appetite due to an inverse correlation between body fat content and feed intake. However, increasing the level of protein during the recovery phase may become counterproductive for reducing overall diet costs. As well, depending on the severity or length of the restriction, increasing protein or AA content may not be necessary. A compensatory growth response often is influenced by multiple factors, and determining whether or not an increase in dietary protein during the recovery phase is required per se, may be difficult to determine.

1.4.3 Effects of Compensatory Growth on Carcass and Meat Quality

Although compensatory growth may be an effective means to reduce diet costs, its effects on carcass and meat quality must be considered. During a protein restriction, elevated Ld relative to the controls is expected (de Greef, 1992; Martinez-Ramirez and de Lange, 2008). Distribution of this fat is of primary interest in terms of carcass quality, as location of this fat may influence the value of the carcass (e.g. subcutaneous vs. intramuscular fat depots). Subcutaneous fat typically is the largest and fastest growing fat pool in a growing pig, followed by intermuscular fat (Farnworth and Kramer, 1987). Earlier studies found that subcutaneous fat is evenly distributed between hind and front quarters; except between 23 and 68 kg BW when there is slight shift in subcutaneous fat content from the front to hind quarters (Richmond and Berg, 1971). In agreement with this, Hammond and Murray (1937) reported that subcutaneous fat is deposited first at the shoulder, then over the rump, and finally over the loin. In a review by Dunshea and D'Souza (2003), the pressure to produce leaner pork (e.g. less back fat) for the industry has led to the redistribution of fat to other parts of the body (e.g. belly). Skinner et al. (2014) found that pigs fed a low complexity diet short term during the nursery phase had an increased belly weight at slaughter (115 kg BW), than pigs fed a high complexity diet throughout the nursery phase. However, this increase was largely attributed to both an increase in total carcass protein and fat content. Other studies have reported increased back fat thickness and marbling relative to controls following a short term reduction in dietary Lys content (Kerr et al., 1995; Martinez-Ramirez and de Lange, 2005; Kamalaker et al., 2009; Taylor et al., 2013). However, when compensatory growth is observed, there are no significant differences in the amount and distribution of fat in the carcass at market slaughter weights ranging from 95 to 110 kg live BW (Martinez-Ramirez and de Lange, 2005, Taylor et al., 2015). The latter has been shown for protein and AA restrictions in both nursery and grower pigs.

Compensatory growth may be an effective means to reduce diet costs without jeopardizing carcass quality, although effects on meat quality should still be considered.

A relationship between meat tenderization and postmortem proteolysis has been described (Anderson et al., 2005; Skiba, 2005). Commonly, it has been hypothesized that the calpain proteolytic system (u-calpain, m-calpain, and calpastatin [calpain inhibiter]) is a key regulator in postmortem proteolysis (Koohmaraie et al., 2002). When calpain concentrations increase in muscle, proteolysis increases which leads to increased meat tenderization. Theoretically, as compensatory growth is expected to increase both protein synthesis and degradation (i.e. protein turnover) beyond that of controls, one would expect that the level of calpains at the time of slaughter would be elevated (Therkildsen et al., 2002; Anderson et al., 2005). However, the effects of compensatory growth on calpain concentrations and meat tenderization are unclear. Lametsch et al. (2006) found compensatory growth increased pork tenderness compared to controls. Yet, there were no dietary treatment effects on calpain activity at the time of slaughter. Rather the intensity of myosin light chain-2 (MLC II) and myosin light chain-3 (MLC III) was increased postmortem. The authors suggested an increase in the intensity of MLC II may be related to tenderness. While some studies have reported increased tenderness at market weight for pigs who were previously restricted in protein and underwent compensatory growth (O'Connell et al., 2006), compensatory growth did not affect pork tenderness in other studies (Martinez-

Ramirez and de Lange, 2008; Taylor et al., 2013). Therkildsen et al. (2002) suggested there may be an optimal point during compensatory growth when protein degradation is greatest although this may not occur at the same time for typical market weights. Nonetheless, it is plausible that compensatory growth may be an effective means not only to reduce diet costs but also to improve meat quality. An improvement in meat quality will lead to an overall better eating experience for the consumer, and improve consumer trust in the producer.

1.5 Conclusion

Compensatory growth may represent a means to reduce feed costs without jeopardizing long term performance, and carcass and meat quality by improving nutrient utilization. However, it is clear that compensatory growth is a complex and dynamic phenomenon and the mechanisms that control it are not fully understood. Furthermore, it appears that the primary focus of compensatory growth research has been directed towards energy restrictions through a reduction in feed intake; however, this may not be the most practical measure in a commercial setting. Research on compensatory growth utilizing a protein or AA restriction is usually conducted using grower-finisher pigs. It may be more beneficial to utilize compensatory growth during the nursery phase as the protein sources used during this phase are often highly expensive relative to other phases of production. However, further research is still required in order to better predict the rate and extent of compensatory growth in various settings. This is needed so that compensatory growth in newly weaned pigs can be implemented into commercial swine operations.

CHAPTER 2

RESEARCH HYPOTHESIS AND OBJECTIVES

The overall hypothesis for the research presented in this thesis is that feeding newly weaned pigs diets deficient in dietary Lys for a 3-week period will result in reduced growth performance (ADG, G:F) and protein growth, while increasing fat growth compared to controls fed nutrient-adequate diets during the same time period. However, when pigs are provided with a diet that is no longer limiting in dietary Lys, both barrows and gilts that were previously restricted in dietary Lys, will undergo compensatory growth and achieve the same BW and body composition in the same amount of time as the unrestricted controls. Furthermore, at market weight (approximately 124 kg BW), pigs previously restricted in dietary Lys will have increased marbling and meat tenderness, but with no other differences in carcass or meat quality compared to controls.

The main objective of this thesis was to determine the effects of a short term dietary Lys restriction at weaning and for 3 weeks in pigs on long term performance and body composition. Second, the thesis will evaluate the effects of a short term dietary Lys restriction immediately postweaning on carcass (fat and muscle deposition) and meat quality traits (colour, marbling, tenderness) in pigs slaughtered at a conventional market weight.

CHAPTER 3: THE EFFECTS OF A TEMPORARY LYSINE RESTRICTION IN NEWLY WEANED PIGS ON SUBSEQUENT GROWTH PERFORMANCE AND BODY COMPOSITION

3.1 Abstract[1]

The concept of compensatory growth represents a means to improve nutrient utilization and decrease costs in pork production. A serial slaughter study was conducted to determine the effects of a Lys restriction immediately following weaning on growth performance and carcass composition. One hundred and forty-four Duroc x Yorkshire x Landrace pigs (initial body weight (IBW) of 6.9 ± 0.21 kg) were randomly allocated to one of three dietary treatments (6 pens/treatment with 8 pigs/pen; 4 barrows, 4 gilts). For three weeks (restriction phase), pigs were fed starter diets that were 110% (Control), 80% (Lys20), or 60% (Lys40) of the estimated SID Lys:NE ratio requirement for nursery pigs according to the Nutrient Requirements of Swine (NRC, 2012). After the restriction phase, all pigs were fed a common grower diet containing 120% of the estimated NRC (2012) requirement for the SID Lys:NE ratio for 6 weeks (recovery phase). During the restriction phase, pig BW gain ($P < 0.01$; 411, 373, and 319 ± 8.2 g/d, respectively for Control, Lys20, Lys40) and G:F ($P < 0.01$; 0.906, 0.805, and 0.711 ± 0.0137, respectively) decreased linearly with decreasing dietary Lys levels. At end of the restriction phase, there was a significant linear decrease ($P < 0.01$) in BW with decreasing dietary Lys levels (15.6, 14.7, and 13.6 ± 0.17 kg, respectively). In addition, there was a linear decrease ($P < 0.01$) in carcass weight (11.6, 11.0, and 10.3 ± 0.30 kg, respectively), and carcass CP content as a % of hot carcass weight (HCW) (16.47, 16.14, and 15.36 ± 0.193 %, respectively) with decreasing dietary Lys levels in pigs slaughtered at the end of the restriction phase. Following completion of the recovery phase, there was a trend for a linear increase (P < 0.06) in BW gain (863, 870, and 892 ± 11.0 g/d, respectively) and a linear increase (P < 0.01) in G:F (0.612, 0.640, and 0.654 ± 0.0112, respectively) with decreasing dietary Lys levels. Carcass weight (40.5, 40.3, and 39.6 ± 0.81 kg, respectively) and carcass CP content as a % of HCW (16.79, 17.41, and 17.14 ± 0.224%, respectively) were similar (P > 0.10) across dietary treatments in pigs slaughtered at the end of the recovery phase. At the end of the study, BW (average of 50.5 ± 0.63 kg) were similar (P > 0.10) across dietary treatments. In conclusion, newly weaned pigs previously fed a diet restricted in Lys for 3 weeks, achieved full compensatory growth after a 6 week recovery period.

Key words: weaned pigs, SID Lys, compensatory growth, growth performance, carcass composition

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3.2 Introduction

Traditionally, it was believed that feeding high protein diets to pigs early in life was essential to ensure optimal lifelong performance (Campbell and Dunkin, 1983). However, the feeding of high protein diets has often been associated with increased incidence of postweaning diarrhea, due to increased proliferation of pathogenic bacteria, which limits growth (Ball and Aherne, 1987; Wellock et al., 2008). In addition, protein is frequently considered one of the most expensive nutrients in the diet. Consequently, a reduction in dietary protein may reduce diet costs and improve overall gut health. However, it is well understood that reducing CP in the diet may cause adverse effects on growth performance and body composition. Researchers have suggested using feeding strategies employing the use of synthetic AA in low CP diets to reduce these effects (Kerr et al., 1995). However, Nyachoti et al. (2006) noted there are discrepancies in the literature on the effectiveness of synthetic AA supplementation in low CP diets. Foremost, synthetic AA currently are relativity expensive, and an increase in their use may not be practical on an economic basis. Therefore, alternative feeding strategies are required which lower feed costs without jeopardizing nutrient utilization.

As discussed in Chapter 1, compensatory growth may be an effective means to improve nutrition utilization and decrease feed costs. It has been well established that following a period of AA restriction pigs can achieve compensatory growth (Whang et al., 2003; Martinez-Ramirez et al., 2008b; Taylor et al., 2015). Notably, the primary focus has been given to research examining protein and(or) AA restrictions in the growing phase and not the nursery phase per se. Feed costs could be reduced using an approach to decrease protein intake during the nursery phase when feed protein is expensive; this would be followed by increasing protein intake during later periods of growth where compensatory growth can occur. The objective of this study was to determine the effects of a temporary dietary Lys restriction immediately postweaning, followed by feeding a high Lys diet in the recovery phase on subsequent growth performance and carcass composition. We hypothesize that: 1) pigs receiving the low Lys diet will have reduced growth performance (ADG, G:F), Pd, and increased fat gain during the restriction period, and 2) following the restriction period, pigs will achieve full compensatory growth when fed a high Lys diet.

3.3 Materials and Methods

3.3.1 Animals and general management

The current study was conducted at the University of Guelph's Arkell Swine Research Station in Guelph, Ontario, Canada. The experimental protocol was approved by the University of Guelph Animal Care committee prior to the commencement of the study. Additionally, all pigs were cared for according to the Canadian Council on Animal Care (CCAC) guidelines on the care and use of farm animals (CCAC, 2009).

One hundred and forty-four, Duroc x Yorkshire x Landrace mixed sex pigs (Yorkshire x Landrace dams, Duroc sires) (YLD) from 26 different litters were utilized for the experiment. For the first 4 weeks of the experiment, pigs (IBW of 6.9 ± 0.22 kg (mean ± SE)) were housed in two environmentally controlled rooms (26^{o}C). Each room contained 9 pens with plastic coated, expanded metal, floors (1.2 m x 3.0 m). To ensure growing pigs had sufficient space, all pigs were relocated from their respective rooms and pens at the beginning of week 5 to two different rooms in the barn. Each room was environmentally controlled (21^{o}C) with fully slatted pens (1.5 m x 4.0 m). Pig space allowance and feeder space met the recommendations of the Canadian Code of Practice for the Care and Handling of Pigs (NFACC, 2014).

For the duration of the experiment, all pigs were fed *ad libitum* and had free access to water via a nipple drinker. Feed refusals were collected and weighed (Defender 3000 bench scale, OHAUS Corporation, Parsippany, NJ, USA) weekly for calculation of average daily feed intake (ADFI). At the same time, individual pig BW were recorded (Week 1-4: Defender 3000 bench scale, OHAUS Corporation, Parsippany, NJ, USA; Week 4-9: Model 450 floor scale, GSE, Livonia, MI, USA) for calculation of ADG.

3.3.2 Experimental Design

At weaning, pigs were removed from the sow and randomly allocated based on BW to one of three dietary treatments which included: 1) Control: diet formulated to be 10% above the estimated NRC (2012) requirements for the SID Lys:NE ratio in nursery pigs, 2) Lys20: diet formulated to be 20% below the estimated NRC (2012) requirements for the SID Lys:NE ratio in nursery pigs, 3) Lys40: diet formulated to be 40% below the estimated NRC (2012) requirements for the SID Lys:NE ratio in nursery pigs. Each treatment consisted of 6 replicate pens, with 8 pigs per pen (4 barrows, 4 gilts). Pigs were fed their designated experimental diet for a total period of 3 weeks; this was the restriction phase for pigs fed the Lys20 and Lys40 diets. Following this, all pigs were fed common grower diets for a 6-week period; this was the recovery phase for pigs fed the Lys20 and Lys40 diets. In addition, at the end of weeks 3, 6, and 9, 2 pigs (1 barrow, 1 gilt) per pen were slaughtered and utilized for chemical body composition analysis.

Due to the variability in weights of pigs that were available for the experiment at weaning, pigs were split equally into two rooms based on low and high BW allocations (average of 6.3 kg and 7.6 kg, respectively). Each room had the same number of treatment replicates, while littermates were delegated to separate pens to reduce the potential for confounding factors.

3.3.3 Experimental Diets

All diets fed during the experiment were prepared and pelleted at the University of Guelph Arkell Feed Mill. Ingredient inclusion level, calculated nutrient composition, and analyzed nutrient composition of the diets are presented in Table 3.1. During bagging, subsamples of feed from each bag were taken and pooled per diet and batch. Samples were homogenized and sent to SGS Agrifood Laboratories (Guelph, ON) for dry matter (DM), calcium (Ca), phosphorus (P), and nitrogen analyses. For individual AA analysis, samples were sent to Evonik laboratories (Hanau, Germany) to verify accuracy of feed mixing. The total nitrogen content of feed samples was determined using the total combustion method according to the AOAC (1997), and AA concentrations were determined according to Llames and Fontaine (1994). All diets were formulated to ensure the intake of vitamins and minerals exceeded requirements for growing pigs according to the NRC (2012).

For the first 3 weeks of the experiment, pigs were fed 2 phases (I: week 1, II: weeks 2-3) which were either 10% above (control), 20% below (Lys20), or 40% below (Lys40) the NRC (2012) estimated requirements for the SID Lys:NE ratio in nursery pigs. Diets for the Lys20 treatment were prepared by blending the control and Lys40 diets at a ratio of 40:60. Following this, all pigs were fed 2 phases (grower I: weeks 4-6, grower II: weeks 7-9) which were 20% above the NRC (2012) estimated requirements for the SID Lys: NE ratio for growing pigs.

With the exception of corn and soybean meal (SBM), the inclusion level of the main ingredients used in all dietary treatments remained relatively constant. In doing so, variability caused by differences in diet composition may have been reduced. However, due to the high inclusion level of corn relative to SBM in the Lys restricted diets, the energy content across treatments was not isocaloric. This was why diets were formulated on the basis of the SID Lys:NE ratio, and not simply on the dietary Lys content, per se.

3.3.4 Serial Slaughter Procedure

As previously stated, 2 pigs (1 barrow, 1 gilt) from every pen were slaughtered at the end of weeks 3, 6, and 9. One day prior to slaughter, all pigs were weighed to calculate the average BW for each pen. This was done to select pigs closest in BW to the average BW of the pen, to slaughter for physical and chemical body composition. All pigs had free access to water and feed directly before slaughter. At slaughter, pigs were reweighed and live BW was recorded prior to electrical stunning for rendering the pig insensible. Pigs were then exsanguinated via severing major blood vessels in the neck; blood was collected and weighed. Following this, visceral organs (heart, lungs, kidneys, liver, spleen, pancreas, bladder, and reproductive tract) were removed, and weighed as a whole. The full gastrointestinal tract (GIT) was weighed separately, washed to remove gut contents, and then reweighed for calculation of gut fill. After weighing, the visceral organs including the GIT were bagged and stored at -20^{o}C for a minimum of 2 weeks before grinding. The empty carcass was also weighed, put into a plastic bag, and frozen at -20^{o}C for two weeks before grinding.

At the beginning of the experiment, 8 pigs (4 barrows, 4 gilts) were slaughtered and processed as discussed above for use in calculation of Pd and Ld for the pigs on trial.

3.3.5 Sample Preparation and Chemical Body Composition Analysis

Once frozen, carcass (including head, skin, hair, feet, and hooves) and viscera were removed from the freezer and reweighed separately, directly before grinding. Whole carcass and viscera were ground individually 3 times using a commercial meat grinder (model B-801, Autio Company, Astoria, OR, USA) using a 12.5 mm die and a 6 mm die, respectively. After the final grinding, 2 subsamples (approximately 200 g each) from each carcass and viscera were taken, weighed, and stored in the freezer at -20ºC. One of the 2 subsamples was freeze dried, and then reweighed to determine the water content of whole carcass and viscera. Following this, freeze dried samples were utilized for determination of DM, ash, fat, and nitrogen contents.

All analyses for carcass and viscera samples were done in duplicate. For DM and ash analyses, 2 g of sample were used, while 0.5 g of sample were used for fat analysis. To ensure proper standardization of the various analytical methods to a DM basis, DM content was determined via forced air oven drying (Model 737F, Fisher Scientific, Hampton, New Hampshire, United States) at 100ºC for 24 h. After drying, samples were ashed in a muffle furnace (Model 650-126 Fisher Scientific, Hampton, New Hampshire, United States) at 500ºC for 12 h for determination of ash content. Fat content was determined via the high-temperature solvent extraction method (AOCS, 2017), using the ANKOM XT20 (ANKOM TECHNOLOGY, Macedon, NY, USA) fat extractor. For protein determination, samples were sent to SGS Agrifood Laboratories (Guelph, ON) and analyzed for nitrogen content using the total combustion method according to the AOAC (1997).

3.3.6 Calculations and Statistical Analysis

Crude protein mass, fat mass, and ash mass for the carcass and viscera were all calculated as the proportion of CP, fat, or ash mass of the freeze dried sample, and the dry carcass or viscera weight, respectively. Daily Pd and Ld were calculated as the difference in protein or fat mass of the pigs at the end of the given period (e.g. weeks 1 to

3, weeks 4 to 9), and the average protein or fat mass of the pigs (per treatment) at the beginning of the given period, divided by the period length, respectively. In addition, the Ld:Pd ratio of the carcass or viscera was calculated as the Ld (g/d) divided by the Pd (g/d), while the L:P ratio was calculated as the fat mass (kg) divided by the protein mass (kg) of the carcass or viscera, respectively. All WB calculations for protein, fat, ash, and water are described as the sum of the specific carcass, viscera, and blood measures. The chemical composition of blood used for calculations was based on values from Mitruka and Rawnsley (1981). Furthermore protein, fat, ash, and water contents for the carcass, viscera, and WB are presented as a percentage of the carcass, viscera, and WB weight, respectively.

The apparent efficiency of dietary SID Lys utilization (kLys) for WB protein retention was calculated. In this equation, it was assumed that the Lys content of protein gain was 7.10 g/100 g of WB protein gain (NRC, 2012). Total SID Lys consumed was calculated based on feed intake, analyzed dietary Lys content, and the estimated SID Lys digestibility values according to the NRC (2012). Furthermore, Lys losses (g/d) from the intestine, skin and hair, relative to DM intake and metabolic weight ($BW^{0.75}$) were considered (NRC, 2012). A detailed description of this equation has been described elsewhere (Mansilla, 2017).

All data were analyzed as a randomized complete block design using the PROC GLIMMIX function of SAS (v.9.4, SAS Institute Inc., Cary, NC), with pen as the experimental unit. In this model, dietary treatment and block (room) were considered fixed effects, and pen as a random effect. For growth performance data, IBW was used as a covariate while week (of the experiment) was treated as a repeated measure. In addition, gender was considered a fixed effect when analyzing physical and chemical body composition data. Interactive effects between treatment, block, week, and gender were also tested when applicable. When interactive effects were not significant, a reduced model was used. Differences among least square treatment means were assessed using the Tukey Honest Significance Test. Furthermore, linear and quadratic contrasts were conducted to determine response trends to changes in dietary SID Lys intake. Differences between least squared means were considered significant when $P < 0.05$ and a trend when $0.05 \leq P \leq 0.10$.

Table 3.1

Ingredient composition and nutrient levels of experimental diets fed from weeks 1-9 (% as-fed basis).

	Diet[1]							
	Control I	Lys20 I	Lys40 I	Control II	Lys20 II	Lys40 II	Grower I	Grower II
Ingredient (%)								
Corn	6.92	20.62	29.76	30.13	41.92	49.78	40.65	64.96
Soybean Meal	22.90	9.16	-	23.30	11.60	3.80	30.1	28.50
Barley	25.00	25.00	25.00	25.00	25.00	25.00	20.00	-
Oat Groats	10.00	10.00	10.00	-	-	-	-	-
Whey	20.00	20.00	20.00	8.00	8.00	8.00	-	-
Fish Meal	5.00	5.00	5.00	3.00	3.00	3.00	-	-
Blood Plasma	4.50	4.50	4.50	2.00	2.00	2.00	-	-
Blood Meal	-	-	-	2.00	2.00	2.00	2.00	-
Mono/Dicalcium Phosphate	0.37	0.56	0.68	0.83	0.99	1.10	1.09	1.34
Vitamin and Mineral Premix[2]	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.6
Limestone	0.83	0.86	0.88	0.80	0.82	0.84	1.10	1.25
Salt	0.10	0.12	0.13	0.40	0.42	0.43	0.73	0.21
Fat, animal/vegetable blend	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Lysine	0.28	0.18	0.12	0.35	0.22	0.14	0.47	0.39
Methionine	0.15	0.07	0.02	0.17	0.07	0.01	0.20	0.14
Threonine	0.05	0.02	-	0.12	0.05	-	0.16	0.11
Calcium Formate	0.40	0.40	0.40	0.40	0.40	0.40	0.20	-
Calcium Propionate	0.40	0.40	0.40	0.40	0.40	0.40	0.20	-
Calculated Nutrient Composition[3]								
NE (kcal/kg)	2486	2557	2605	2462	2510	2557	2438	2533
CP (%)	25.1	19.5	15.78	23.1	18.2	15.0	22.4	19.5
Total Lys (%)	1.78	1.33	1.03	1.66	1.24	0.96	1.62	1.31

SID Lys (%)	1.59	1.18	0.90	1.49	1.10	0.84	1.46	1.18
SID Thr (%)	0.92	0.70	0.56	0.88	0.65	0.50	0.85	0.70
SID Trp (%)	0.30	0.23	0.18	0.26	0.19	0.15	0.25	0.20
SID Met + Cys (%)	0.88	0.68	0.55	0.82	0.62	0.49	0.79	0.67
SID Lys/Ne	6.38	4.63	3.46	6.04	4.38	3.28	5.99	4.65
Ca (%)	0.90	0.90	0.90	0.84	0.84	0.84	0.79	0.77
P (%)	0.67	0.65	0.63	0.64	0.62	0.61	0.62	0.65
Analyzed Nutrient Composition[4] (%)								
DM	89.0	88.8	89.3	89.1	88.3	88.18	86.81	87.30
CP	23.9	18.4	16.3	23.2	18.2	15.6	21.3	18.8
Total Lys	1.69	1.31	1.16	1.69	1.28	1.12	1.62	1.30
Ca	1.04	1.04	1.22	0.86	1.06	1.26	0.98	0.81
P	0.74	0.76	0.73	0.74	0.73	0.73	0.70	0.69

[1] Control I, Lys20 I, and Lys40 I, fed for week 1; Control II, Lys20 II, and Lys40 II, fed from weeks 2-3; Grower I fed from weeks 4-6 and Grower II fed from weeks 7-9.

[2] Supplied per kg of diet: vitamin A, 12,000 IU as retinyl acetate; vitamin D3, 1,200 IU as cholecalciferol, vitamin E, 48 IU as D,L-α-tocopherol acetate; vitamin K, 3 mg as menadione; vitamin B12, 0.03 mg; d-pantothenic acid, 18 mg; riboflavin, 6 mg; choline, 600 mg; folic acid, 2.4 mg; niacin, 30 mg; thiamine, 18 mg; pyridoxine, 1.8 mg; biotin, 200 µg; Cu, 18 mg as $CuSO_4 \cdot 5H_2O$; Fe, 120 mg as $FeSO_4$; Mn, 24 mg as $MnSO_4$; Zn, 126 mg as ZnO; Se, 0.36 mg as $FeSeO_3$; I, 0.6 mg as KI (DSM Nutritional Products Canada Inc., Ayr, ON, Canada).

[3] Calculated using ingredient values on an as-fed basis according to the NRC (2012).

[4] Values represent the means of 1 batch for Control I, Lys20, and Lys40, respectively; 1 batch for Control II, Lys20 II, and Lys40 II, respectively; 3 batches for Grower I; and 3 batches for Grower II.

3.4 Results and Discussion

3.4.1 General Observations and Health

According to the nutrient analysis of experimental diets, nutrient values were within acceptable range of calculated values (Table 3.1). However for Lys40 diets, total Lys content was 12% and 14% greater than anticipated for Lys40 I and Lys40 II, respectively. These errors may reflect an underestimation of Lys content in some of the dietary ingredients used, and/or analytical errors. Furthermore, Ca concentrations in most diets were much greater than formulated. The latter may be attributed to the Ca contribution of the feed ingredients,

Ca propionate and Ca formate used in the diets. Nonetheless, the discrepancies noted did not appear to influence the relative response of the pigs to the dietary treatments.

Although blood was collected and weighed during the serial slaughter, there appeared to be inconsistencies in collection of blood among pigs. For this reason, the blood volume used for whole body calculations (e.g. Pd) was assumed to be 6% of EBW (Upton, 2008).

During weeks 4 to 9, one pig from the control treatment and one pig from the Lys20 treatment, were removed from the trial due to *Streptococcus suis* infection. Based on subjective visual observations, the remaining pigs appeared to be in good health, with no evident treatment effects on health (e.g. rough hair coat).

3.4.2 Growth Performance

Growth performance results for the restriction phase, recovery phase, and overall trial (restriction + recovery) are presented in Table 3.2; results for the first and second half of the recovery phase are presented in Table 3.3.

Initial BW did not differ ($P > 0.98$) across dietary treatments confirming appropriate piglet allocation on the basis of BW (Table 3.2). During the restriction phase, ADG and G:F decreased linearly ($P < 0.01$) with decreasing dietary Lys levels (Table 3.2). Consequently at the end of the restriction phase (end of week 3), there was a linear decrease ($P < 0.01$) in final BW with decreasing dietary Lys levels (Table 3.2). These results are consistent with numerous studies where pigs have been fed diets limited in Lys (Chiba et al., 1999; Martinez-Ramirez, 2005; Reynolds and O'Doherty, 2006; Brestensky et al., 2014; Taylor et al., 2015). Although there were no differences ($P = 0.94$) in ADFI, average daily Lys intake (ADLysI) decreased linearly ($P < 0.01$) and quadratically ($P = 0.03$) with decreasing dietary Lys levels. In contrast, Fabian et al. (2002) suggested that when pigs are fed isocaloric diets limiting in Lys, they will consume more feed in an attempt to meet their AA requirements. Although in the latter study, grower pigs (from 20 to 50 kg BW) were used for the duration of the experiment as compared to newly weaned pigs in the present study. With this in mind, Nyachoti et al. (2004) proposed that pigs up to about 20 kg BW will be limited in their ability to meet their desired nutrient intake due to their small physical gut capacity (gut fill). Since the pigs used in the current experiment were restricted in Lys directly at weaning, their ability to compensate in terms of feed intake may have been limited by their small physical gut capacity. Similar results to ours have been observed in previous studies (Yang et al.,2008; Taylor et al., 2015).

For the first half of the recovery period (weeks 4-6) (Table 3.3), ADG increased linearly ($P < 0.05$) with decreasing dietary Lys levels. Previously it has been suggested that an increase in ADG after a nutrient restriction (or compensatory growth increase) may be the result of increased feed intake during the recovery phase (Critser et al., 1995).

However, there were no differences (P > 0.28) in feed or Lys intakes during this period; an increase in growth compared to controls was solely due to an improvement in G:F (Table 3.3). Feed efficiency increased linearly (P < 0.01) with decreasing dietary Lys levels. More commonly, an increase in feed intake has been found in the past following a period of feed restriction (Donker et al., 1986; Heyer and Lebret, 2007). On the other hand, our results are supported by past studies which state that no significant differences in feed intake are expected following a protein restriction (Skiba, 2005; Wellock et al., 2009). In fact, de Greef (1992) reported a reduction in feed intake following a period of protein restriction. The latter may be correlated with a reduction in appetite related to the fat content of the body (Skiba, 2005). Although previously restricted pigs were more efficient and gained more during the first half of the recovery period, there was a slight linear decrease (P = 0.01) in final BW at the end of week 6 (Table 3.3). However, by the end of week 9 in the recovery phase, there were no differences (P = 0.45) in final BW across treatments (Table 3.3). It appears that the main compensatory growth response may have occurred primarily in the first three weeks of the recovery phase (weeks 4-6), as there were no differences (P > 0.16) in ADG, daily feed or Lys intakes, or G:F during the second half of the recovery phase (weeks 7-9) (Table 3.3). In agreement, Reynolds & O' Doherty (2006) observed that the majority of the compensatory growth response occurred in the first two weeks of the recovery phase when grower pigs previously restricted in Lys, were fed a diet no longer limiting in Lys in similar proportions to the current study.

Overall there were no differences in ADG and ADFI (P > 0.41) for the entire duration of the experiment (combined restriction & recovery data; Table 3.2). However, there was a linear decrease ($P < 0.01$) in ADLysI with decreasing dietary Lys levels (Table 3.2). This can be attributed to the lower dietary Lys content in the Lys20 and Lys40 diets fed during the restriction phase. Since there were no differences ($P = 0.45$) in BW at the end of the recovery phase, this suggests that pigs were fully able to compensate with respect to ADG and BW following a 3 week Lys restriction period (Table 3.2). However, a linear decrease ($P < 0.01$) in G:F with decreasing Lys levels was observed overall (Table 3.2). To the author's knowledge, no significant differences in G:F overall for an entire compensatory growth experiment have been observed in previous studies where compensatory growth occurred. In the current study, it is unclear why overall G:F was lower in the previously restricted pigs; this decrease may be related to the large decrease in G:F during the restriction period. Nonetheless, previously restricted pigs were able to fully compensate in terms of ADG and BW following a temporary Lys restriction.

3.4.3 Physical and Chemical Body Composition

All physical and chemical body composition data for pigs slaughtered at the end of weeks 3, 6, and 9 are presented in Tables 3.4, 3.5, and 3.6, respectively. Furthermore, all protein, fat, water, and ash contents of the carcass, viscera, and WB are expressed on a % of carcass, viscera, and WB basis, respectively.

At the end of the restriction phase, cold carcass weight decreased linearly ($P < 0.01$) with decreasing dietary Lys level (Table 3.4). This was accompanied by linear decreases ($P < 0.01$) in carcass protein and water content, and linear increases ($P \leq 0.03$) in carcass fat and ash content, as dietary Lys levels decreased (Table 3.4). The decrease in water content of the carcass can be attributed to the close association between the water and protein content of muscle (Weis, 2001; de Lange et al., 2003). From our results, it appears that a temporary Lys restriction can alter the partitioning of energy between protein and fat in the carcass. This repartitioning of energy can be attributed to the low level of dietary Lys in the restricted diets limiting the pigs ability to maximize Pd; energy that could have been utilized for Pd with adequate Lys available instead is utilized towards Ld when Lys is deficient. As previously mentioned in Table 3.2, Lys intakes during the restriction phase decreased linearly ($P < 0.01$) and quadratically ($P = 0.03$) with decreasing dietary Lys levels. Furthermore, kLys increased linearly ($P < 0.03$) during the restriction and was 64.8, 75.8, and 74.6 $\pm$ 2.87 %, respectively for the control, Lys20, and Lys40 pigs (Table 3.7). This suggests that the restricted pigs were indeed limited in dietary Lys, as the maximum efficiency of Lys for protein retention is assumed to be 75% (NRC, 2012). The effects of a dietary Lys restriction on the carcass in the current study are consistent with past trials evaluating protein and Lys restrictions for both nursery and grower pigs (Zimmerman and Khajarern, 1973; de Greef, 1992; Chiba et al., 1999; Taylor et al., 2015). Although dietary Lys restrictions are known to have effects on the carcass, the effects on the viscera in terms of size and composition are variable. In the current study, while dietary Lys did not affect ($P > 0.30$) the amount of the total viscera present on a kg basis, there was a linear increase ($P < 0.01$) in the size of the empty GIT as a % of the total viscera with decreasing dietary Lys levels (Table 3.4). To the author's knowledge, very few studies have observed such an effect on the GIT following a dietary Lys restriction. However, Skinner et al. (2014) reported that when pigs were fed a low complexity diet (primarily corn and soybean meal), this was accompanied by an increase in the size of the empty GIT relative to pigs fed a high complexity diet (inclusion of high quality protein sources). This contrasts to the current study where there was a linear decrease ($P < 0.01$) in the size of the remaining viscera (pooled viscera excluding the GIT) as a % of total viscera weight with decreasing dietary Lys levels (Table 3.4). While water content in the viscera was not affected ($P > 0.94$) by dietary Lys levels, there were linear decreases ($P < 0.01$) in the protein and ash contents of the total viscera, and a linear increase ($P < 0.01$) in the fat content of the total viscera as dietary Lys levels decreased (Table 3.4). Since individual organ weights were not recorded in the present study, it is unclear which organ(s) were influenced by dietary Lys content. More commonly, it is believed that a decrease in the size of the viscera (e.g. kidneys, liver, and small intestine) is seen following feed restriction (Bikker, 1994; Skiba 2005). Prolonged exposure to a low CP diet may lead to a reduction in the size of the kidneys and liver. In the past, some studies have reported a reduction in the size of kidneys and liver with decreasing dietary protein content when feeding low CP diets (Kerr et al., 1995, 2003; Chiba et al., 1999; Ruusunen, et al., 2007). From these studies, it was hypothesized that an increase in liver and kidney size may have been due to increased urea production and excretion of excess protein in pigs fed unrestricted diets. With all this said, the inconsistencies among studies on the effects of a reduced protein or AA diet on organ size and composition are not well understood; varying responses have been found in past trials using similar sample numbers, and duration and severity of protein or AA restriction as the present study (Kamalakar et al., 2009, Taylor et al., 2013, 2015).

While there was a linear decrease ($P = 0.01$; Table 3.4) in carcass weight (kg basis) as dietary Lys levels decreased, it is not surprising that this was accompanied by a linear decrease ($P = 0.01$) in EBW (kg basis; Table 3.4). In addition, as a result of the lower protein content and the greater fat content of both the carcass and viscera at the end of the restriction, linear decreases ($P < 0.01$) in WB protein and WB water contents, and a linear increase ($P < 0.01$) in WB fat content were observed (Table 3.4). Whole body ash content was not affected ($P \geq 0.06$) by dietary Lys level (Table 3.4). These results indicated that the effort to induce WB composition differences thru feeding of a low Lys diet was successful.

Some nutrition induced differences in body composition observed at the end of the restriction phase were still present at the end of week 6 (middle of recovery phase) when all pigs were fed a common diet. In particular, WB protein content decreased linearly ($P < 0.01$) with decreasing dietary Lys content (Table 3.5). The differences in WB protein content amongst restriction phase dietary treatments can be attributed to the linear decrease ($P < 0.01$) in the protein content of the carcass with decreasing dietary Lys levels (Table 3.5). The appearance of limited compensatory growth for Lys20 and Lys40 pigs is responsible for the trend ($P < 0.10$) for a linear decrease in carcass weight in the middle of the recovery phase as dietary Lys levels decreased (Table 3.5). However, there were no differences ($P = 0.25$) in EBW across dietary treatments. Furthermore, there were no differences ($P > 0.14$) in fat, water, or ash contents in the carcass, viscera, and subsequently the WB as dietary Lys levels decreased (Table 3.5).

It is well understood that pigs become fatter than a given “desired” body composition due to a previous nutritional restriction; once this restriction is removed, pigs will attempt to correct this deviation by altering the composition of growth (Whittemore and Kyriazakis, 2006). Since there were no differences (P > 0.30) in feed intake across dietary treatments for the first half of the recovery phase (Table 3.3), compensatory growth appears to be due to a redistribution of energy between protein and fat and not as a reduction in intake. In the present study, it appears that the majority of compensation of protein content to this point may have occurred primarily in the viscera, as there were no differences (P > 0.50) in the body composition of the viscera at the middle of the recovery phase (Table 3.5). The latter is in agreement with Martinez-Ramirez et al. (2008a) but not Therkildsen et al. (2004). It is unclear why the difference in protein content of the carcass between the control pigs and previously restricted pigs remained relatively unchanged. Earlier research has suggested that an increase in protein growth may occur almost immediately following the removal of the nutrient restriction (Therkildsen et al., 2002). Furthermore, as there were no differences (P > 0.36) in WB fat, ash, and water contents at the middle of the recovery phase, this may highlight further discrepancies in carcass protein content (Table 3.5). As previously discussed, previous research has found a close association between WB protein content and WB water content (de Lange et al., 2003). This implies that no significant differences in protein content would be expected, given that no significant differences in water content were observed. However, Whang et al. (2003) found that in pigs who underwent a previous protein restriction, a previous protein restriction did have an affect on body water content for pigs slaughtered immeditly following the restricition at the same BW. However, body protein content was not affected by a previous protein restriction, but the reason for this is not well understood. It is possible that the treatment differences in protein values observed at the end of week 6 in the present study were influenced by experimental error and require further investigation.

Previous differences in physical and chemical body composition as a result of a Lys restriction were no longer present at the end of the recovery phase (week 9), where there were no differences ($P > 0.09$) for any carcass, viscera, or WB traits across dietary treatments (Table 3.6). This is generally in agreement with growth performance data observed in the current study (Table 3.2).

While data on compensatory growth in newly weaned pigs is limited, our findings are similar to past studies conducted in newly weaned pigs (Zimmerman and Khajarern, 1973; Skinner et al., 2014; Taylor et al., 2015). Limited work in this area is most likely due to our past understanding that young pigs require high protein diets to optimize long term performance (Campbell and Dunkin, 1983). The rationale behind this may be related to the postweaning stress and physiological changes that occur in newly weaned pigs (Campbell et al., 2013). While grower pigs in theory have time to "acclimatize" to their new environment, compensatory growth has not always been observed. Failure to achieve compensatory growth may be related to a variety of factors such as timing of restriction, severity of restriction etc., and highlights the complexity of compensatory growth (see Chapter 1, section 1.4.2). In fact, in 4 similar trials conducted by Taylor et al. (2013), pigs in only 2 of the 4 trials achieved compensatory growth. The authors concluded that compensatory growth was not achieved when feed intake for previously restricted pigs decreased relative to the control pigs during the recovery period, which limited their ability to compensate. It is plausible that the greater fat content of the previously restricted pigs may have lowered their intake as previously discussed (see section 1.3.1)

(Skiba, 2005). Since compensatory growth did not occur in 2 of the trials by Taylor et al. (2013), the authors suggested there appears to be an intervening factor(s) preventing compensatory growth in the previously restricted pigs which requires further investigation. However, in the present study, newly weaned pigs were able to fully compensate for nutrition induced differences in body composition. The significance of early protein (AA) nutrition in newly weaned pigs on lifetime performance warrants further investigation.

3.4.4 Protein and Lipid Deposition Parameters

Protein deposition, Ld, Ld/Pd and L:P ratio, and kLys data for the restriction phase (weeks 1-3) and the recovery phase (weeks 4-9) can be found in Table 3.7; while data for the first (weeks 4-6) and second (weeks 7-9) half of the recovery phase can be found in Table 3.8. For the effects of a 3 week dietary Lys restriction overall for the entire experimental period (restriction + recovery phase), please refer to Table 3.9.

During the restriction phase, linear decreases ($P \leq 0.02$) in the Pd and linear increases ($P < 0.04$) in Ld of the carcass and viscera were observed with decreasing dietary Lys content (Table 3.7). Subsequently, as dietary Lys content decreased, the Ld/Pd ratio of the carcass and viscera increased linearly ($P < 0.01$; Table 3.7). This repartitioning of energy between protein and fat in both the carcass and the viscera resulted in a linear increase ($P < 0.01$) in the L:P ratio for the carcass and viscera with decreasing dietary Lys levels (Table 3.7). As a result of the changes in the Pd and Ld of the carcass and viscera, there was a linear decrease ($P < 0.01$) in WB Pd and a linear increase ($P < 0.01$) in WB Ld as dietary Lys content decreased (Table 3.7). Consequently, the WB Ld/Pd ratio increased linearly ($P < 0.01$) with decreasing dietary Lys levels (Table 3.7). This resulted in the WB L:P ratio being 29% and 46% greater ($P<0.01$) compared to the controls at the end of the restriction phase for the Lys20 and Lys40 pigs, respectively (Table 3.7). Due to a dietary Lys restriction altering the partitioning of energy between protein and fat, previously restricted pigs were fatter than control pigs at the end of the restriction phase. These findings are consistent with the body composition data described previously (Table 3.4).

No differences ($P > 0.11$) in Pd or Ld for the carcass, viscera, and ultimately the WB were observed during the recovery phase (Table 3.7). In agreement, there were no differences ($P > 0.14$) in Pd and Ld for both the first half (weeks 4-6) and the second half (weeks 7-9) of the recovery phase (Table 3.8). Furthermore, there were no differences ($P > 0.10$) in kLys during the recovery phase (Table 3.7). In pigs consuming the same amount of Lys, it could be expected that the kLys would be greater in pigs achieving a greater rate of Pd. These results are in disagreement with the ADG results discussed previously, which suggested that compensatory growth may have primarily occurred during the first half of the recovery phase (Table 3.3). However, the WB L:P ratio observed at the middle of the recovery (end of week 6) suggested that the restricted pigs still tended ($P = 0.07$) to remain fatter at this point (Table 3.8). This is in agreement with the body composition data at this point (Table 3.5). These results disagree with numerous studies conducted in the past, which suggest that an increase in Pd and decrease in Ld are expected when a previous nutritional restriction is removed (de Greef, 1993, Whang et al., 2003, Skiba, 2005; Fabian et al., 2004). The latter reflects the attempt of the pig to correct for a previous nutritionally derived difference in body composition from a “predetermined” target body composition (Whitermore and Kyriazakis, 2006). Martinez-Ramirez et al. (2008a) examined compensatory growth in barrows previously restricted in dietary Lys from 15 to 35 kg BW; these pigs were unable to compensate due to their low Pdmax, thereby limiting their ability to accelerate their growth beyond that of the controls. However, in the current study it does not appear that Pdmax limited the previously restricted pigs’ ability to compensate; as overall for the entire experimental period (restriction + recovery), there were no differences ($P > 0.54$) in the Pd or Ld of the carcass, viscera, and WB (Table 3.9). This suggests that restricted pigs were capable adjusting their growth, by redistributing the dietary energy between protein and fat. At the end of the recovery phase, there were no differences ($P > 0.99$) in the WB L:P ratio (Table 3.7). It is important to note that ultimately, previously restricted pigs were capable of achieving the same body composition in the same amount of time as the controls by using less Lys ($P < 0.01$; Table 3.2), more efficiently based on the kLys differences ($P < 0.05$) between the control and Lys20 pigs (Table 3.9).

Reynolds and O’ Doherty (2006) suggested that the duration of compensatory growth is determined by the amount of time that is required for pigs to achieve the “target” WB L/P ratio. Following this, changes in Pd and Ld will return to levels similar to that of the control pigs. This implies that constraints on the L/P ratio rather than the Ld/Pd ratio will determine the composition of growth. The latter highlights the influences the actual body composition (i.e. the actual L:P ratio) has on nutrient partitioning. Since there were no differences in Pd and Ld during the recovery phase in the current study, it is difficult to explain when full compensatory growth may have concluded. Unfortunately, it is plausible that small changes in Pd that were sufficient to compensate, may not have been detected by the serial slaughter method. Likewise, Martinez-Ramirez et al. (2008b) reported a numerical increase in Pd following a previous Lys restriction; however this increase was sufficient enough for entire male pigs to fully compensate for previous nutritional differences in body composition.

3.5 Conclusion

Following a 3-week dietary Lys restriction period, previously restricted pigs had more body fat, less protein, and weighed less than the unrestricted controls. However, when provided with a high protein diet, a compensatory growth response was induced and previously restricted pigs were capable of achieving the same body composition in the same amount of time compared to unrestricted controls. To the authors knowledge, few studies focusing on compensatory growth in newly weaned pigs have been completed. The latter may be related to increased postweaning stress and dramatic physiological changes commonly observed in newly weaned pigs. However, the current study highlights that early protein nutrition may not be as pertinent as previously believed. As a result, compensatory growth may be a viable way to reduce feed costs by reducing total dietary Lys content without jeopardizing overall growth performance and body composition. That being said, compensatory growth is a highly dynamic and complex phenomenon, and the mechanism(s) behind it are not fully understood. More research is required before a compensatory growth feeding strategy can be utilized in a commercial setting, although the results of the current study are promising.

Table 3.2
Effects of a short term Lys restriction postweaning on pig growth performance traits during the restriction (Weeks 1-3), recovery (Weeks 4-9), and combined restriction and recovery phases (Weeks 1-9) (where pigs were fed diets differing in Lys concentration during the restriction phase, and common diets thereafter).

	Dietary Treatment[1]					**Contrast[2]**	
Trait	Control	Lys-20%	Lys-40%	SEM	P-value	L	Q
Restriction[3]							
Initial BW (kg)	6.9	6.9	6.9	0.21	0.985	0.893	0.914
Final BW (kg)	15.6[a]	14.7[b]	13.6[c]	0.17	<0.001	<0.001	0.434
ADFI[4] (g)	457	464	457	15.0	0.940	0.977	0.725
ADLysI[5] (g)	7.2[a]	5.4[b]	4.6[c]	0.17	<0.001	<0.001	0.027
ADG[6] (g)	411[a]	373[b]	319[c]	8.2	<0.001	<0.001	0.443
G/F[7]	0.906[a]	0.805[b]	0.711[c]	0.0137	<0.001	<0.001	0.842
Recovery[3]							
Initial BW (kg)	15.6[a]	14.7[b]	13.6[c]	0.17	<0.001	<0.001	0.434
Final BW (kg)	50.8	50.2	50.0	0.46	0.446	0.225	0.681
ADFI[4] (g)	1451	1411	1418	18.9	0.296	0.229	0.320
ADLysI[5] (g)	18.6	18.1	18.2	0.22	0.195	0.158	0.257
ADG[6] (g)	863	870	892	11.0	0.137	0.057	0.577
G/F[7]	0.612[b]	0.640[ab]	0.654[a]	0.0112	0.023	0.007	0.573
Restriction + Recovery[3]							
Initial BW (kg)	6.9	6.9	6.9	0.21	0.985	0.893	0.914
Final BW (kg)	50.8	50.2	50.0	0.46	0.446	0.225	0.681
ADFI[4] (g)	1120	1095	1098	14.6	0.413	0.290	0.420
ADLysI[5] (g)	14.8[a]	13.9[b]	13.6[b]	0.18	<0.001	<0.001	0.092
ADG[6](g)	714	702	701	8.0	0.469	0.262	0.606
G/F[7]	0.711[a]	0.693[ab]	0.673[b]	0.0082	0.004	<0.001	0.874

[1]Restriction phase: Pigs fed at 110%, 80%, and 60% of the SID Lys:NE raito requirements (NRC, 2012) during the restriction phase (weeks 1-3); Recovery phase: Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]N = 6 pens per treatment for the restriction, recovery, and combined restriction + recovery period.
[4]Average Daily Feed Intake (DM basis).
[5]Average Daily Lysine Intake (DM basis).
[6]Average Daily Gain.
[7]Average Daily Gain/ Average Daily Feed Intake.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 3.3
Effects of a short term Lys restriction postweaning on pig growth performance traits during the first half of the recovery (Weeks 4-6) and the second half of the recovery phases (Weeks 7-9) (were pigs were fed common diets).

	Dietary Treatment[1]					**Contrast[2]**	
Trait	Control	Lys-20%	Lys-40%	SEM	P-value	L	Q
Recovery (Weeks 4-6)[3]							
Initial BW (kg)	15.6[a]	14.7[b]	13.6[c]	0.17	<0.001	<0.001	0.434
Final BW (kg)	30.8[a]	30.4[ab]	29.6[b]	0.33	0.026	0.009	0.542
ADFI[4] (g)	1080	1048	1050	15.9	0.286	0.178	0.406
ADLysI[5] (g)	15.9	15.5	15.5	0.23	0.286	0.177	0.409
ADG[6] (g)	722	750	759	13.0	0.112	0.044	0.567
G/F[7]	0.670[b]	0.718[a]	0.728[a]	0.0136	0.007	0.003	0.265
Recovery (Weeks 7-9)[3]							
Initial BW (kg)	30.8[a]	30.4[ab]	29.6[b]	0.33	0.026	0.009	0.542
Final BW (kg)	50.8	50.2	50.0	0.46	0.446	0.225	0.681
ADFI[4] (g)	1823	1774	1786	30.4	0.497	0.407	0.399
ADLysI[5] (g)	21.3	20.7	20.9	0.35	0.497	0.408	0.398
ADG[6] (g)	1007	983	1025	15.9	0.161	0.407	0.089
G/F[7]	0.558	0.559	0.579	0.0124	0.425	0.256	0.527

[1]Recovery phase: Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase. (weeks 4-6; weeks 7-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]N = 6 pens per treatment for the recovery (weeks 4-6) and recovery (weeks 7-9).
[4]Average Daily Feed Intake (DM basis).
[5]Average Daily Lysine Intake (DM basis).
[6]Average Daily Gain.
[7]Average Daily Gain/ Average Daily Feed Intake.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; P < 0.05).

Table 3.4
Effects of a short term Lys restriction postweaning on pig body characteristics at the end of the restriction phase (Week 3) (where pigs were fed diets differing in Lys concentration).

	Dietary Treatment[1]					Contrast[2]	
Physical and Chemical Composition Traits	Control (n = 12)	Lys-20% (n = 12)	Lys-40% (n = 12)	SEM	P-value	L	Q
Carcass Composition[3]							
Carcass weight (kg)	11.6[a]	11.0[ab]	10.3[b]	0.30	0.023	0.007	0.996
Protein (%)	16.47[a]	16.14[a]	15.36[b]	0.193	0.003	0.001	0.356
Fat (%)	8.54[c]	11.48[b]	13.43[a]	0.366	<0.001	<0.001	0.278
Ash (%)	3.29	3.66	3.65	0.107	0.042	0.029	0.174
Water (%)	71.06[a]	68.76[b]	66.93[c]	0.321	<0.001	<0.001	0.567
Viscera Composition[3]							
Viscera weight (kg)	2.54	2.39	2.39	0.077	0.305	0.186	0.432
Empty GIT (%)[4]	59.34[a]	61.24[ab]	62.97[b]	0.698	0.007	0.002	0.920
Remaining Viscera (%)[5]	40.66[a]	38.76[ab]	37.09[b]	0.026	0.008	0.002	0.888
Protein (%)	14.74[a]	14.32[ab]	14.05[b]	0.132	0.006	0.002	0.651
Fat (%)	4.07[b]	4.24[b]	4.77[a]	0.132	0.004	0.002	0.288
Ash (%)	1.19[a]	1.18[ab]	1.15[b]	0.010	0.035	0.018	0.265
Water (%)	80.07	80.15	80.07	0.179	0.945	0.999	0.740
Whole Body (WB) Composition[6]							
EBW (kg)	15.0[a]	14.3[ab]	13.5[b]	0.38	0.036	0.011	0.966
Carcass Weight (%)	77.3	77.0	76.3	0.37	0.198	0.084	0.659
Viscera Weight (%)	16.9	16.8	17.8	0.40	0.161	0.131	0.229
WB Protein (%)	16.4[a]	16.0[a]	15.4[b]	0.15	0.001	<0.001	0.557
WB Fat (%)	7.3[a]	9.6[b]	11.1[c]	0.29	<0.001	<0.001	0.324
WB Ash (%)	2.8	3.1	3.1	0.08	0.067	0.054	0.170
WB Water (%)	73.5[a]	71.4[b]	70.4[b]	0.35	<0.001	<0.001	0.226

[1]Pigs fed at 110%, 80%, and 60% of the SID Lys:NE ratio requirements (NRC, 2012) during the restriction phase (weeks 1-3).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Excluding carcass and total viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.
[4]Empty Gastrointestinal Tract (GIT).
[5]Includes: Heart, lungs, kidneys, liver, spleen, pancreas, bladder, and reproductive tract.
[6]Excluding empty body weight (EBW) mass (kg), expressed as a % of EBW where whole body (WB) is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 3.5
Effects of a short term Lys restriction postweaning on pig body characteristics at the end of the middle of the recovery phase (Week 6) (where pigs were fed common diets).

Physical and Chemical Composition Traits	Dietary Treatment[1] Control (n = 12)	Lys-20% (n = 12)	Lys-40% (n = 12)	SEM	P-value	Contrast[2] L	Q
Carcass Composition[3]							
Carcass weight (kg)	24.9	24.0	23.7	0.51	0.211	0.092	0.643
Protein (%)	17.67[a]	17.30[ab]	16.96[b]	0.162	0.021	0.006	0.935
Fat (%)	11.58	11.99	12.63	0.473	0.317	0.138	0.845
Ash (%)	3.32	3.49	3.50	0.100	0.398	0.234	0.524
Water (%)	67.02	67.07	66.62	0.520	0.769	0.589	0.696
Viscera Composition[3]							
Viscera weight (kg)	4.52	4.55	4.38	0.113	0.524	0.381	0.475
Empty GIT (%)[4]	57.85	58.31	57.87	0.583	0.820	0.974	0.535
Remaining Viscera (%)[5]	42.12	41.67	42.13	0.577	0.814	0.987	0.527
Protein (%)	13.27	13.23	13.43	0.172	0.687	0.514	0.576
Fat (%)	5.99	6.08	6.09	0.160	0.883	0.650	0.851
Ash (%)	1.10	1.12	1.12	0.018	0.507	0.309	0.583
Water (%)	79.61	79.60	79.36	0.197	0.596	0.371	0.642
Whole Body (WB) Composition[6]							
EBW (kg)	31.3	30.4	29.8	0.61	0.249	0.103	0.835
Carcass Weight (%)	79.7	79.0	79.3	0.33	0.320	0.356	0.232
Viscera Weight (%)	14.5	15.0	14.8	0.31	0.532	0.486	0.382
WB Protein (%)	17.2[a]	16.8[ab]	16.6[b]	0.13	0.022	0.007	0.658
WB Fat (%)	10.1	10.4	10.9	0.40	0.368	0.170	0.796
WB Ash (%)	2.9	3.0	3.0	0.08	0.424	0.238	0.586
WB Water (%)	69.8	69.8	69.4	0.40	0.749	0.497	0.749

[1]Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Excluding carcass and total viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.
[4]Empty Gastrointestinal Tract (GIT).
[5]Includes: Heart, lungs, kidneys, liver, spleen, pancreas, bladder, and reproductive tract.
[6]Excluding empty body weight (EBW) mass (kg), expressed as a % of EBW where whole body (WB) is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 3.6
Effects of a short term Lys restriction postweaning on pig body characteristics at the end of the recovery phase (Week 9) (where pigs were fed common diets).

Physical and Chemical Composition Traits	Dietary Treatment[1] Control (n = 12)	Lys-20% (n = 12)	Lys-40% (n = 12)	SEM	P-value	Contrast[2] L	Q
Carcass Composition[3]							
Carcass weight (kg)	40.5	40.3	39.6	0.81	0.737	0.456	0.846
Protein (%)	16.79	17.41	17.14	0.224	0.179	0.298	0.121
Fat (%)	16.80	17.40	17.04	0.831	0.880	0.845	0.646
Ash (%)	3.38	3.27	3.36	0.127	0.816	0.902	0.538
Water (%)	62.68	62.00	62.12	0.638	0.731	0.546	0.618
Viscera Composition[3]							
Viscera weight (kg)	6.36	6.40	6.15	0.136	0.388	0.279	0.399
Empty GIT (%)[4]	54.56	53.95	54.47	0.790	0.843	0.933	0.569
Remaining Viscera (%)[5]	45.44	46.04	45.53	0.784	0.847	0.936	0.574
Protein (%)	14.11	14.43	14.07	0.180	0.337	0.856	0.149
Fat (%)	8.39	8.23	8.29	0.404	0.960	0.867	0.822
Ash (%)	1.06	1.07	1.03	0.012	0.099	0.131	0.113
Water (%)	76.46	76.23	76.59	0.364	0.776	0.798	0.512
Whole Body (WB) Composition[6]							
EBW (kg)	49.8	49.7	48.7	0.96	0.640	0.406	0.670
Carcass Weight (%)	81.3	81.0	81.5	0.24	0.349	0.623	0.177
Viscera Weight (%)	12.8	12.9	12.7	0.21	0.793	0.588	0.690
WB Protein (%)	16.6	17.1	16.9	0.18	0.192	0.298	0.133
WB Fat (%)	14.7	15.1	15.0	0.71	0.922	0.837	0.733
WB Ash (%)	3.0	2.9	2.9	0.10	0.770	0.898	0.485
WB Water (%)	65.7	64.9	65.2	0.60	0.648	0.589	0.455

[1]Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Excluding Carcass and total viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.
[4]Empty Gastrointestinal Tract (GIT).
[5]Includes: Heart, lungs, kidneys, liver, spleen, pancreas, bladder, and reproductive tract.
[6]Excluding empty body weight (EBW) mass (kg), expressed as a % of EBW where whole body (WB) is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$)

Table 3.7
Effects of a short term Lys restriction postweaning on pig carcass, viscera, and whole body (WB) protein deposition (Pd), and lipid deposition (Ld) parameters during the restriction (Weeks 1-3) and the recovery phases (Weeks 4-9) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

	Dietary Treatment[1]					Contrast[2]	
Trait	Control (n = 12)	Lys-20% (n = 12)	Lys-40% (n = 12)	SEM	P-value	L	Q
Restriction							
kLys (%)[3]	64.8[b]	75.8[a]	74.6[ab]	2.87	0.028	0.027	0.100
$Pd_{carcass}$ (g/d)	51.4[a]	44.5[ab]	35.9[b]	2.64	0.003	<0.001	0.788
$Ld_{carcass}$ (g/d)	8.9[b]	22.0[a]	27.9[a]	3.10	0.002	<0.001	0.363
$Ld/Pd_{carcass}$[4]	0.16[c]	0.47[b]	0.76[a]	0.048	<0.001	<0.001	0.885
$L/P_{carcass}$[5]	0.52[c]	0.71[b]	0.87[a]	0.022	<0.001	<0.001	0.586
$Pd_{viscera}$ (g/d)	12.4[a]	11.0[ab]	10.6[b]	0.48	0.044	0.020	0.358
$Ld_{viscera}$ (g/d)	3.1	3.1	3.7	0.19	0.052	0.032	0.215
$Ld/Pd_{viscera}$[4]	0.25[b]	0.28[b]	0.35[a]	0.013	<0.001	<0.001	0.265
$L/P_{viscera}$[5]	0.27[b]	0.30[b]	0.34[a]	0.010	<0.001	<0.001	0.331
WB_{Pd} (g/d)	63.7[a]	55.5[ab]	46.5[b]	2.91	0.003	<0.001	0.926
WB_{Ld} (g/d)	12.0[b]	25.0[a]	31.6[a]	3.20	0.002	<0.001	0.419
$WB_{Ld/Pd}$[4]	0.18[c]	0.43[b]	0.66[a]	0.040	<0.001	<0.001	0.817
L/P_{WB}[6]	0.45[c]	0.60[b]	0.72[a]	0.02	<0.001	<0.001	0.517
Recovery							
kLys (%)[3]	51.4	56.8	55.7	1.78	0.101	0.103	0.149
$Pd_{carcass}$ (g/d)	116.4	124.5	124.2	3.98	0.292	0.187	0.398
$Ld_{carcass}$ (g/d)	139.6	136.6	128.9	9.79	0.732	0.450	0.847
$Ld/Pd_{carcass}$[4]	1.21	1.11	1.04	0.070	0.261	0.109	0.833
$L/P_{carcass}$[5]	1.01	1.00	1.00	0.056	0.992	0.902	0.984
$Pd_{viscera}$ (g/d)	12.5	13.8	12.6	0.48	0.117	0.925	0.042
$Ld_{viscera}$ (g/d)	10.4	10.1	9.5	0.66	0.612	0.335	0.877
$Ld/Pd_{viscera}$[4]	0.82	0.74	0.77	0.059	0.624	0.528	0.467
$L/P_{viscera}$[5]	0.60	0.57	0.60	0.033	0.836	0.989	0.555
WB_{Pd} (g/d)	128.9	138.3	136.7	4.25	0.271	0.211	0.303
WB_{Ld} (g/d)	150.0	146.7	138.4	10.3	0.719	0.437	0.847
$WB_{Ld/Pd}$[4]	1.17	1.07	1.01	0.066	0.275	0.119	0.767
L/P_{WB}[6]	0.89	0.89	0.89	0.048	0.997	0.951	0.958

[1] Restriction phase: Pigs fed at 110% (Ctl), 80% (Lys20), and 60% (Lys40) of the SID Lys:NE raito requirements (NRC, 2012), during the restriction phase (weeks 1-3); Recovery phase: Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2] Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3] Lysine utilization efficiency for whole body (WB) protein growth.
[4] Fat deposition/ Protein deposition for carcass, viscera, and WB, respectively.
[5] Fat (kg)/ Protein (kg) for carcass and viscera, respectively.
[6] WB Fat (kg) / WB protein (kg).
[abc] Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 3.8
Effects of a short term Lys restriction postweaning on pig carcass, viscera, and whole body (WB) protein deposition (Pd) and lipid deposition (Ld) parameters during the first half of the recovery (Weeks 4-6) and the second half of the recovery phases (Weeks 7-9) (where pigs were fed common grower diets).

	Dietary Treatment[1]					Contrast[2]	
Trait	Control (n = 12)	Lys-20% (n = 12)	Lys-40% (n = 12)	SEM	P-value	L	Q
Recovery (weeks 4-6)							
kLys (%)[3]	59.9	59.7	60.3	2.07	0.988	0.919	0.912
$Pd_{carcass}$ (g/d)	118.4	113.2	115.4	4.8	0.745	0.660	0.537
$Ld_{carcass}$ (g/d)	90.2	77.2	77.5	5.8	0.225	0.141	0.363
$Ld/Pd_{carcass}$[4]	0.77	0.67	0.65	0.053	0.305	0.150	0.605
$L/P_{carcass}$[5]	0.66	0.69	0.75	0.030	0.132	0.049	0.805
$Pd_{viscera}$ (g/d)	10.7	12.3	12.0	0.81	0.393	0.304	0.370
$Ld_{viscera}$ (g/d)	8.1	8.3	7.3	0.49	0.343	0.297	0.304
$Ld/Pd_{viscera}$[4]	0.76[a]	0.67[ab]	0.61[b]	0.035	0.032	0.010	0.754
$L/P_{viscera}$[5]	0.45	0.46	0.46	0.014	0.903	0.834	0.694
WB_{Pd} (g/d)	129.2	125.4	127.3	5.13	0.876	0.802	0.660
WB_{Ld} (g/d)	98.3	85.5	84.8	6.21	0.251	0.142	0.437
$WB_{Ld/Pd}$[4]	0.77	0.67	0.64	0.050	0.252	0.117	0.611
L/P_{WB}[6]	0.59	0.62	0.66	0.026	0.180	0.070	0.827
Recovery (weeks 7-9)							
kLys (%)[3]	44.9	54.4	51.8	2.93	0.088	0.113	0.111
$Pd_{carcass}$ (g/d)	114.1	135.7	132.7	7.96	0.146	0.116	0.226
$Ld_{carcass}$ (g/d)	188.9	196.4	181.8	19.58	0.871	0.798	0.652
$Ld/Pd_{carcass}$[4]	1.76	1.48	1.40	0.175	0.327	0.159	0.645
$L/P_{carcass}$[5]	1.01	1.00	1.00	0.056	0.992	0.902	0.984
$Pd_{viscera}$ (g/d)	14.2	15.3	13.1	0.95	0.298	0.441	0.177
$Ld_{viscera}$ (g/d)	12.8	11.9	11.7	1.32	0.842	0.588	0.841
$Ld/Pd_{viscera}$[4]	0.86	0.82	0.95	0.13	0.765	0.634	0.585
$L/P_{viscera}$[5]	0.60	0.57	0.60	0.033	0.836	0.989	0.555
WB_{Pd} (g/d)	128.3	151.0	145.9	8.50	0.171	0.162	0.199
WB_{Ld} (g/d)	201.7	208.3	193.5	20.64	0.880	0.782	0.678
$WB_{Ld/Pd}$[4]	1.64	1.40	1.35	0.151	0.392	0.206	0.628
L/P_{WB}[6]	0.89	0.89	0.89	0.048	0.997	0.951	0.958

[1]Recovery phase: Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-6; weeks 7-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Lysine utilization efficiency for whole body (WB) protein growth.
[4]Fat deposition/ Protein deposition for carcass, viscera, and WB, respectively.
[5]Fat (kg)/ Protein (kg) for carcass and viscera, respectively.
[6] WB Fat (kg) / WB protein (kg).
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 3.9
Effects of a short term Lys restriction postweaning on pig carcass, viscera, and whole body (WB) protein deposition (Pd) and lipid deposition (Ld) parameters for the entire experimental period (Weeks 1-9) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

	Dietary Treatment[1]					Contrast[2]	
Trait	Control (n = 12)	Lys-20% (n = 12)	Lys-40% (n = 12)	SEM	P-value	L	Q
kLys (%)[3]	53.6[b]	59.4[a]	57.9[ab]	1.55	0.043	0.065	0.071
$Pd_{carcass}$ (g/d)	94.7	97.9	94.7	2.65	0.626	0.988	0.341
$Ld_{carcass}$ (g/d)	96.0	98.3	95.1	6.53	0.940	0.925	0.739
$Ld/Pd_{carcass}$[4]	1.02	1.01	1.01	0.064	0.992	0.903	0.988
$L/P_{carcass}$[5]	1.01	1.00	1.00	0.056	0.992	0.902	0.984
$Pd_{viscera}$ (g/d)	12.5	12.9	12.0	0.32	0.141	0.247	0.102
$Ld_{viscera}$ (g/d)	8.0	7.7	7.6	0.44	0.810	0.523	0.970
$Ld/Pd_{viscera}$[4]	0.63	0.61	0.64	0.039	0.819	0.909	0.540
$L/P_{viscera}$[5]	0.60	0.57	0.60	0.033	0.836	0.989	0.555
WB_{Pd} (g/d)	107.2	110.7	106.6	2.83	0.544	0.883	0.281
WB_{Ld} (g/d)	104.0	106.0	102.7	6.88	0.942	0.897	0.754
$WB_{Ld/Pd}$[4]	0.97	0.96	0.96	0.060	0.994	0.944	0.938
L/P_{WB}[6]	0.89	0.89	0.89	0.048	0.997	0.951	0.958

[1]Restriction phase: Pigs fed at 110%, 80%, and 60% of the SID Lys:NE ratio requirements (NRC, 2012) during the restriction phase (weeks 1-3); Recovery phase: Pigs fed at 120% of SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Lysine utilization efficiency for whole body (WB) protein growth.
[4]Fat deposition/ Protein deposition for carcass, viscera, and WB, respectively.
[5]Fat (kg)/ Protein (kg) for carcass and viscera, respectively.
[6] WB Fat (kg) / WB protein (kg).
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

CHAPTER 4: THE EFFECTS OF A TEMPORARY LYSINE RESTRICTION IN NEWLY WEANED PIGS ON LONG TERM PERFORMANCE AND CARCASS AND MEAT QUALITY

4.1 Abstract

It is well established that compensatory growth can occur in pigs following a period of AA intake restriction. Unfortunately, work on the effects of compensatory growth early in life on subsequent carcass and meat quality at market weight is limited. For this reason, a serial slaughter study was conducted to determine the effects of a temporary Lys restriction immediately following weaning on subsequent growth and body composition. To measure carcass and meat quality, a full carcass dissection at market weight (124 ± 0.9 kg) was performed. Two hundred and forty pigs with an IBW of 7.2 ± 0.07 kg were randomly allocated to one of three dietary treatments, with 8 pens per treatment (4 barrow pens, 4 gilt pens) and 10 pigs per pen. For three weeks (restriction phase), pigs were fed starter diets that were 110% (Control), 80% (Lys20), or 60% (Lys40) of the estimated SID Lys:NE ratio requirements for nursery pigs according to the NRC (2012). After the restriction phase, all pigs were fed a common grower diet containing 120% of the NRC (2012) requirement for the ratio of SID Lys:NE content (14.6 g/kg) for 6 weeks (recovery phase). Thereafter, pigs were fed commercial grower, grower-finisher, and finisher diets until a final market weight of approximately 124 kg BW was attained. During the restriction phase, ADG ($P < 0.01$; 343, 324, 271 ± 10.0 g/d, respectively for CTL, Lys20, and Lys40) and G:F ($P < 0.01$; 0.741, 0.682, and 0.595 ± 0.0106, respectively) decreased linearly with decreasing dietary Lys levels. In addition, WB protein content ($P < 0.01$; 15.3, 15.2, 14.7 ± 0.11% , respectively) decreased

linearly, while fat content (P < 0.01 7.3,9.4, 10.9 ± 0.27%, respectively) increased linearly with decreasing dietary Lys levels. At the end of the restriction phase, BW (P < 0.01; 14.4, 13.9, and 12.9 ± 0.19 kg, respectively) decreased linearly with decreasing dietary Lys levels. Conversely, there were no significant differences in BW (P = 0.29; 51.5, 50.2, 50.3 ± 0.29 kg, respectively) across dietary treatments at the end of the recovery phase; although WB protein content (P = 0.07; 17.0, 16.6, 16.6 ± 0.12%, respectively) and WB fat content (P = 0.06; 13.7, 15.5, 15.1 ± 0.51%, respectively) tended to decrease and increase linearly, respectively. When combining the restriction and recovery phase data, ADG (P = 0.08; 706. 683, 682 ± 9.6 g/d, respectively) tended to decrease linearly, while G:F (P < 0.01; 0.612, 0.597, 0.541 ± 0.0105, respectively) decreased linearly with decreasing dietary Lys levels. For the entire study (restriction phase to slaughter at market weight), there tended to be a quadratic response for ADG (P = 0.07; 879, 852, 866 ± 9.2 g/d) while G:F (P = 0.04; 0.480, 0.472, 0.469 ± 0.0029) decreased linearly with decreasing dietary Lys levels. However, at final market weight there were no significant differences in WB protein content (P = 0.52; 15.8, 16.1, 15.8 ± 0.19%, respectively) and WB fat content (P = 0.40; 28.0, 26.8, 28.1 ± 0.76%, respectively) across dietary treatments. Although Lys20 pigs tended to have leaner prime carcass cuts relative to the control and Lys40 pigs, there were no significant differences (P > 0.10) in carcass and meat quality across dietary treatments. NPPC subjective marbling scores (P = 0.03; 1.62, 1.87, 2.17 ± 0.18, respectively) did increase linearly at market weight with decreasing dietary Lys levels in the restriction phase. In conclusion, full compensatory growth was achieved after a 3 week Lys restriction for newly weaned pigs, without negatively impacting carcass and meat quality when pigs were slaughtered at conventional market weights.

Key words: weaned pigs, SID Lys, compensatory growth, body composition, carcass quality, meat quality

4.2 Introduction

Providing the consumer with safe, nutritious, and affordable pork is a key component for ensuring pork production remains sustainable. In order to remain sustainable, innovative nutrition strategies are required for pig operations to remain profitable. Previous studies have effectively utilized the physiological phenomenon of compensatory growth to reduce diet costs without jeopardizing overall performance and body composition (Skiba, 2005; Martinez-Ramirez and de Lange, 2008; Skinner, 2012), However, only a few studies have examined nutrient restrictions in newly weaned pigs, and the effects of compensatory growth on carcass and meat quality (Wellock et al., 2009; Taylor et al., 2013, 2015). It is well understood that feeding pigs diets low in Lys will lead to an excessive amount of back fat relative to unrestricted pigs (Chiba et al., 1999). The latter may result in the producer being penalized by the packer for fat pigs and represents the inefficiency of a low Lys diet for Pd. Conversely in past studies, compensatory growth following a Lys restriction did not affect carcass and meat quality in pigs marketed at approximately 110 kg (Chiba, 1995; Kamalaker et al., 2009). In fact, previous studies have examined compensatory growth in grower pigs and found compensatory growth can improve pork tenderness when pigs are slaughtered at market weight (Therkildsen et al., 2002). This increase in tenderness with compensatory growth is the result of increased protein turnover during the compensatory growth phase (Andersen et al., 2005). In other studies where compensatory growth was achieved following a Lys restriction, greater amounts of marbling were found in pigs slaughtered at market weight than pigs fed diets that met Lys requirements. (D'Souza et al., 2003). Interestingly, consumer pressure on the pork industry to produce leaner pigs has resulted in pigs with less marbling which may reduce overall eating quality (Dunshea and D' Souza, 2003). Therefore incorporating compensatory growth in pork production may not only be an effective way to reduce diet costs but also improve carcass and meat quality, ultimately improving consumer satisfaction. The objectives of this study were to determine the effects of a temporary dietary Lys restriction early in life on subsequent growth and carcass and meat quality at market weight. We hypothesize that 1) pigs receiving the low Lys diets will have reduced growth performance and Pd, and increased fat gain during the restriction period and 2) following the restriction period, pigs will be provided with a high Lys diet and go on to achieve full compensatory growth with improved meat tenderness and marbling relative to the controls when all pigs are slaughtered at market weight.

4.3 Material and Methods

4.3.1 Animals and General Management

Prior to commencement of the study, the experimental protocol was approved by the University of Guelph animal care committee. Furthermore, all pigs were cared for according to the CCAC guidelines on the care and use of farm animals in research, teaching, and testing (CCAC, 2009).

Two hundred and forty pigs were sourced from the University of Guelph swine breeding herd, and housed at the University of Guelph Arkell Swine Research Station in Guelph, Ontario, Canada for the duration of the experiment. Pigs were acquired from 38 litters and had an IBW of 7.2 $\pm$ 0.07 kg. Due to a limited number of pigs available at the time of the experiment, three different breeds YLD; Yorkshire Dam, Duroc sires (YD); and Yorkshire Dam, Landrace sires (YL) of pigs were used to meet the required numbers. While the YLD pigs was the primary breed used for the experiment, care was taken to ensure all dietary treatments and pens were balanced for breed to the best of our abilities. For the first 5 weeks of the experiment, all pigs were housed in an environmentally controlled room (26ºC), which contained 24 plastic-coated pens split evenly in the middle by an alleyway (12 pens on one side, 12 pens on the other side). For logistical purposes, all pigs were relocated from their respective pens at the beginning of week 6 to two new rooms in the barn based on the initial side of the room they were previously located on. Each room was environmentally controlled (21 ºC) with 12 fully slatted pens. In both cases, pig space allowance and feeder space met the recommendations of the Canadian Code of Practice for the Care and Handling of Pigs (NFACC, 2014).

For the duration of the experiment, all pigs were fed *ad libitum* and had free access to water via a nipple drinker. Feed refusals were collected and weighed (Defender 3000 bench scale, OHAUS Corporation, Parsippany, NJ, USA) weekly for calculation of ADFI. At the same time, individual pig BW was recorded (Week 1-4: Defender 3000 bench scale, OHAUS Corporation, Parsippany, NJ, USA; Week 4-9: Model 450 floor scale, GSE, Livonia, MI, USA) for calculation of ADG.

4.3.2 Experimental Design

Directly at weaning, pigs were removed from the sow and randomly allocated to one of three dietary treatments (Control, Lys20, Lys40) that were based on diets being 10% above (Control), 20% below (Lys20), or 40% below (Lys40) the estimated NRC (2012) requirements for the SID Lys:NE ratio in nursery pigs. Each treatment consisted of 8 pens (4 barrow pens, 4 gilt pens) with 10 pigs per pen. Due to the variability in weights of pigs that were available for the experiment at weaning, pigs were spilt equally into 12 pens of light BW pigs and 12 pens of heavy BW pigs (average of 6.3 kg and 8.0 kg, respectively). For the first 5 weeks of the experiment, one half of the room housed light BW pigs while the other half of the room housed heavy BW pigs. Thereafter, pigs were split into two rooms based off of their respective weight category. In both cases, it was ensured that dietary treatment and gender were balanced for each room. Furthermore, littermates were delegated to separate pens to the best of our abilities.

Pigs were fed experimental diets based on the 3 dietary treatments for a total period of 3 weeks (restriction phase). Following this, all pigs were fed common grower diets for a 6 week period (recovery phase). For the remainder of the trial, all pigs received the identical commercial grower, grower-finisher, and finisher diets when average room BW reached 52, 74, and 93 kg, respectively.

At the end of week 3 (end of restriction phase), two pigs from pens 1-6 and pens 13-18, and three pigs from pens 7-12 and pens 19-24 were slaughtered and utilized for body composition analysis. Likewise at the end of week 9 (end of recovery phase), three pigs from pens 1-6 and pens 13-18, and two pigs from pens 7-12 and pens 19-24 were slaughtered and utilized for body composition analysis. Finally, at final market weight (approximately 124 kg), 3 pigs per pen were slaughtered and utilized for body composition analysis and carcass and meat quality. It should be noted that for logistical purposes, slaughtering of market hogs occurred every Monday for four consecutive weeks with 18 pigs slaughtered per week. The slaughter of market weight hogs began with the 6 heaviest pens followed by the 6 lightest pens in the heavy group of pigs. The same protocol was then followed in the light group of pigs. It should be noted that for each week, pigs slaughtered were balanced for dietary treatment and gender.

4.3.3 Experimental Diets

Experimental diet formulations for the starter period, sampling, analysis, and feeding duration were the same as described for the diets used in the previous experiment. Please refer to section 3.3.3 for an extensive explanation. The analyzed nutrient composition of the diets used in the current study are presented in Table 4.1. Since commercially prepared diets were used for grower, grower-finisher, and finisher diets, ingredient inclusion and nutrient levels will not be provided on the basis of confidentiality for the commercial feed mill supplying the diets.

4.3.4 Serial Slaughter Procedure

On the day before slaughter, all pigs were weighed and the average BW of the pen was calculated to select the pigs closest in BW to the average pen weight for physical and chemical body composition analysis. Aside from the final slaughter at market weight (where no feed was provided), all pigs had access to water and feed directly before slaughter. At slaughter, pigs were reweighed and live BW were recorded prior to electrical stunning for rendering the pigs insensible. Pigs were than exsanguinated via severing major blood vessels in the neck; blood was collected and weighed. Following this, visceral organs were removed and the entire GIT, kidneys, liver, and spleen (not included in week 3 slaughter) were weighed separately with weights recorded. The remaining viscera (heart, lungs, pancreas, bladder, and reproductive tract) were weighed together with weights recorded. Following the initial weighing, the GIT was separated into the stomach, small intestine, large intestine, and cecum (not included in week 3 slaughter), and each portion was washed and then reweighed individually for calculation of gut fill. After weighing, all visceral organs were pooled, placed into a plastic bag, and stored at -20ºC for a minimum of 2 weeks before grinding. The whole empty carcass was also weighed, placed into a plastic bag, and frozen at -20ºC for two weeks before grinding for pigs slaughtered at the end of week 6 and the end of week 9. In the case of the slaughter at final market weight, carcasses were split in half using a commercial splitting saw. The left side of the carcass was used for carcass and meat quality evaluation, while the right side was used for body composition analysis. For logistical purposes, the right side of the carcass was not immediately stored at -20ºC which was the procedure followed for earlier slaughters; the right carcass side remained with the left side of the carcass in a < 4ºC chill cooler until being moved to a -20ºC freezer the following day.

4.3.5 Sample Preparation and Chemical Body Composition Analysis

The methodology and equipment used for body composition analysis have been described elsewhere (see section 3.3.5). In the current study, carcass and viscera nitrogen content were determined using the Kjeldahl method (model Kjeltec™ 8200, Foss Analytical, Hilleroed Denmark) according to the AOAC (1997). It should be noted that for the final slaughter at market weight, both the hair and hooves were removed at the time of slaughter. In addition, only half the carcass was used for body composition analysis in pigs slaughtered at a conventional market weight.

4.3.6 Carcass and Meat Quality Evaluation

Individual pigs that had reached or exceeded the target slaughter weight of approximately 124 kg were transported the same day to the University of Guelph Meat Laboratory and slaughtered using standard commercial slaughter procedures. Carcasses were graded and weighed 30 to 40 minutes after electrical stunning and death by exsanguination. The left side of each carcass was probed using a Hennessey probe between the third and fourth last ribs, 7 cm off the mid-line for estimation of carcass lean content and fat carcass content. Carcasses were placed in a 1°C chill cooler approximately 45 minutes post mortem. Temperature and pH of the longissimus (LM) and semimembranosus (SM) muscles were taken at 1 h and 24 h post mortem on the left side of the carcass using an Accumet A71 pH meter (Fisher Scientific, Toronto, ON) with a Hanna Instruments spear tipped electrode attached. Carcass were moved from a 1°C chill cooler to a ≤ 4°C chill cooler after chilling for 24 hours.

After a 48 h chilling period, the entire left side of the carcass was weighed and cut into primal cuts (shoulder, belly, loin and ham). Each primal was weighed and further dissected into lean, fat and bone. Prior to dissection, loins were cut into two pieces at the grading site (between the third and fourth last ribs) to expose the rib interface. Carcass measurements were assessed by an experienced carcass evaluator and included fat depth (mm; ruler measurement of subcutaneous fat at the grading site), loin length (mm), loin depth (mm) and loin eye area (LEA; mm^2) (measured by tracing on acetate paper and quantified by an electronic planimeter,MOP; Carl Zeiss, Inc.).

Six 3.0 cm thick chops were cut from the LM and individually identified. The first chop was saved for determination of intramuscular fat content as described below. The second chop was used for subjective evaluation (colour, firmness, wetness and marbling), ultimate pH measurement, and determination of drip loss. Chops 3, 4, 5 and 6 were saved for the determination of Warner-Bratzler shear force and aged for 2 or 7 days with 2 chops aged for each time period. All chops except the one used to measure colour, pH and drip loss were vacuum packaged and then stored at -20^{o}C prior to analysis.

The second LM chop was placed on butcher paper and allowed to oxygenate for 30 min prior to evaluation. Subjective evaluation of the LM chop was conducted by meat lab personnel and comprised the following:

i. Muscle colour score based on the National Pork Producers Council (NPPC, 2000) six point scale (1 = pale pinkish gray to white, 2 = grayish pink, 3 = reddish pink, 4 = dark reddish pink, 5 = purplish red, 6 = dark purplish red) and the Canadian Pork Quality Standards (CPI, 2013) six point scale.

ii. Muscle firmness score on the National Pork Producers Council (NPPC, 2000) three point scale: (1 = soft – cut surfaces distort easily and are visibly soft, 2 = firm – cut surfaces tend to hold their shape, 3 = very firm – cut surfaces tend to be very smooth with no distortion of shape).

iii. Muscle wetness score based on the National Pork Producers Council (NPPC, 2000) three point scale: (1 = exudative – excessive fluid pooling on cut surfaces, 2 = moist – cut surfaces appear moist, with little or no free water, 3 = dry – cut surfaces exhibit no evidence of free water).

iv. Japanese colour score based on a six point scale using plastic Japanese Meat Grading Association colour standards (Nakai et al., 1975) (1 = extremely pale pink to gray, to 6 = dark purplish red).

v. Marbling score based on the National Pork Producers Council (NPPCs 2000) ten point scale (1 = devoid of marbling, to 10 = very abundant marbling) and the Canadian Pork Quality Standards (CPI, 2013) six point scale (0 = devoid of marbling, to 6 = very abundant).

Ultimate pH was determined from the average of three measurements from each chop 48 h post mortem using a smart foodcare spear tipped electrode (Hanna Instruments, USA) attached to a Accumet A71 pH meter (Fisher Scientific, Toronto, ON). Drip loss was then determined using the method described by Honikel (1998).

After thawing and removal of all remaining subcutaneous fat, LM chops saved for intramuscular fat determination were cubed for freeze drying. Freeze dried samples were ground in a commercial coffee grinder and mixed. Dry matter was determined from the difference in weight before and after freeze drying and corrected by oven drying at 100ºC.

4.3.6.1 Warner-Bratzler Shear Force

Frozen LM chops were prepared for WBSF determination by overnight thawing at < 4ºC. Post thawing, chops were trimmed of external fat, weighed, and cooked using a Garland Grill (ED-30B broiler, Garland Commercial Range Ltd., Mississauga, ON) to an internal end point temperature of 74°C. Cooking temperatures were continually monitored by a thermocouple inserted in the geometric center of each chop with initial and final temperatures recorded. Chops were turned after reaching an internal temperature of approximately 40ºC. Once the chop was cooked to the target temperature endpoint, the cooked weight was recorded for determination of cooking losses. Chops were then placed in individual bags, sealed, and immediately chilled in ice water. Chops were stored at ≤ 4°C for 24 h before coring. Prior to coring, chops were allowed to equilibrate to room temperature. Six 1.27 cm meat cores were removed parallel to the muscle fibers from each chop using a drill press-mounted corer. Cores were sheared using a Warner-Bratzler blade on a TA-XT Plus texture analyzer (Texture Technologies Corp., Scarsdale, NY) with crosshead speed set at 3.3 mm s^{-1}. Peak shear force was determined using a custom macro program in Stable Microsystems Exponent software, and the average of the 6 peak force values was taken as the shear force value for each loin chop.

4.3.7 Calculations and Statistical Analysis

Calculations for determination of carcass, viscera, and WB protein, fat, ash, and water content, as well as daily protein and fat growth were explained in section 3.3.6. In addition, determination of WB kLys for WB protein growth was also described in section 3.3.6. Since there was a need to account for unequal splitting of the carcass in pigs slaughtered at final market weight, carcass side weight was standardized based on Huber (2012) according to the following:

1. $\text{Deviation from an accurate half side wt} = \dfrac{\text{Cold Side Wt (kg)} + \text{Half Head Wt (kg)}}{\text{HCW (kg)}}$
2. $\text{Standardized side weight} = \text{Cold Side Wt (kg)} \times \dfrac{50}{100\text{-deviation from an accurate half side wt}}$.

All data were analyzed as a randomized complete block design using the PROC GLIMMIX function of SAS (v.9.4, SAS Institute Inc., Cary, NC), with pen as the experimental unit. In this model, dietary treatment and gender were considered as fixed effects with pen as a random effect. When pigs were moved to their new rooms at week 6, block (room) was considered a fixed effect. For growth performance data, IBW was used as a covariate, and week of the experiment was treated as a repeated measure. For body composition data, live slaughter weight (LSW) was used as a covariate for pigs slaughtered at final market weight. Hot carcass weight was also used as a covariate for all carcass and meat quality measures. Interactive effects between dietary treatment, block, week, and gender were also tested when applicable. If not significant, a reduced model was used. Differences among least square treatment means were assessed using the Tukey's Honest Significance Test. Furthermore, linear and quadratic contrasts were conducted to determine responses to changes in dietary SID Lys intake. Differences between least squared means were considered significant when $P < 0.05$, while a trend was noted when $0.05 \leq P \leq 0.10$.

Table 4.1.

Ingredient composition and nutrient levels of experimental diets fed from weeks 1-9 (% as-fed basis).

	Diet[1]							
	Control I	Lys20 I	Lys40 I	Control II	Lys20 II	Lys40 II	Grower I	Grower II
Ingredient (%)								
Corn	6.92	20.62	29.76	30.13	41.92	49.78	40.65	64.96
Soybean Meal	22.90	9.16	-	23.30	11.60	3.80	30.1	28.50
Barley	25.00	25.00	25.00	25.00	25.00	25.00	20.00	-
Oat Groats	10.00	10.00	10.00	-	-	-	-	-
Whey	20.00	20.00	20.00	8.00	8.00	8.00	-	-
Fish Meal	5.00	5.00	5.00	3.00	3.00	3.00	-	-
Blood Plasma	4.50	4.50	4.50	2.00	2.00	2.00	-	-
Blood Meal	-	-	-	2.00	2.00	2.00	2.00	-
Mono/Dicalcium Phosphate	0.37	0.56	0.68	0.83	0.99	1.10	1.09	1.34
Vitamin and Mineral Premix[2]	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.6
Limestone	0.83	0.86	0.88	0.80	0.82	0.84	1.10	1.25
Salt	0.10	0.12	0.13	0.40	0.42	0.43	0.73	0.21
Fat, animal/vegetable blend	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Lysine	0.28	0.18	0.12	0.35	0.22	0.14	0.47	0.39
Methionine	0.15	0.07	0.02	0.17	0.07	0.01	0.20	0.14
Threonine	0.05	0.02	-	0.12	0.05	-	0.16	0.11
Calcium Formate	0.40	0.40	0.40	0.40	0.40	0.40	0.20	-
Calcium Propionate	0.40	0.40	0.40	0.40	0.40	0.40	0.20	-
Calculated Nutrient Composition[3]								
NE (kcal/kg)	2486	2557	2605	2462	2510	2557	2438	2533
CP (%)	25.1	19.5	15.8	23.1	18.2	15.0	22.4	19.5

Total Lys (%)	1.78	1.33	1.03	1.66	1.24	0.96	1.62	1.31
SID Lys (%)	1.59	1.18	0.90	1.49	1.10	0.84	1.46	1.18
SID Thr (%)	0.92	0.70	0.56	0.88	0.65	0.50	0.85	0.70
SID Trp (%)	0.30	0.23	0.18	0.26	0.19	0.15	0.25	0.20
SID Met + Cys (%)	0.88	0.68	0.55	0.82	0.62	0.49	0.79	0.67
SID Lys/Ne	6.38	4.63	3.46	6.04	4.38	3.28	5.99	4.65
Ca (%)	0.90	0.90	0.90	0.84	0.84	0.84	0.79	0.77
P (%)	0.67	0.65	0.63	0.64	0.62	0.61	0.62	0.65
Analyzed Nutrient Composition (%)[4]								
DM	87.4	87.5	87.8	87.8	88.0	88.0	89.0	89.5
CP	23.0	18.0	15.1	22.4	19.0	15.2	23.3	20.3
Total Lys	1.75	1.33	1.05	1.66	1.27	1.02	1.76	1.39
Ca	0.98	0.86	0.94	1.01	0.90	0.90	0.80	0.87
P	0.63	0.58	0.64	0.69	0.62	0.65	0.64	0.67

[1] Control I, Lys20 I, and Lys40 I, fed for week 1; Control II, Lys20 II, and Lys40 II, fed from weeks 2-3; Grower I fed from weeks 4-6 and Grower II fed from weeks 7-9.

[2] Supplied per kg of diet: vitamin A, 12,000 IU as retinyl acetate; vitamin D3, 1,200 IU as cholecalciferol, vitamin E, 48 IU as D,L-α-tocopherol acetate; vitamin K, 3 mg as menadione; vitamin B12, 0.03 mg; d-pantothenic acid, 18 mg; riboflavin, 6 mg; choline, 600 mg; folic acid, 2.4 mg; niacin, 30 mg; thiamine, 18 mg; pyridoxine, 1.8 mg; biotin, 200 µg; Cu, 18 mg as $CuSO_4 \cdot 5H_2O$; Fe, 120 mg as $FeSO_4$; Mn, 24 mg as $MnSO_4$; Zn, 126 mg as ZnO; Se, 0.36 mg as $FeSeO_3$; I, 0.6 mg as KI (DSM Nutritional Products Canada Inc., Ayr, ON, Canada).

[3]Calculated using ingredient values on an as-fed basis according to the NRC (2012).

[4] Values represent the means of 1 batch for Control I, Lys20, and Lys40, respectively; 2 batches for Control II, Lys20 II, and Lys40 II, respectively; 5 Batches for Grower I; and 8 batches for Grower II.

4.4 Results and Discussion

4.4.1 General Observations and Health

According to the nutrient analysis of experimental diets, most nutrient composition values were within acceptable range of expected values (Table 4.1). The Lys content of the Grower I diet was slightly greater than anticipated, while the Ca content in most diets was greater than expected. Previously it was hypothesized that the increased Ca levels may be related to two ingredients Ca propionate and Ca formate used; however, Ca levels were substantially greater than formulated in the grower II diet where no acidifier was used. The latter may reflect an underestimation of the Ca levels in some of the ingredients used in the diets. Nonetheless, the discrepancies discussed did not appear to influence the relative response to dietary treatments in the pigs.

Based on subjective visual observations, no significant health issues were observed in all but two pigs for the entire duration of the experiment. These two pigs from the Lys20 treatment appeared to be poor doing and were removed from the trial on the advice of trained barn personnel.

As stated for the first trial, there still appeared to be inconsistences in the collection of blood between pigs. These errors may be related to inevitable blood clotting, and missed blood collection due to the movement of the pig during the slaughter procedure. For this reason, the blood volume used for whole body calculations (e.g. Pd) was assumed to be 6% of EBW (Upton, 2008).

Unfortunately, due to unforeseen mechanical issues with the floor scale used for measuring individual pig BW, two weeks of growth performance data were not recorded during the commercial grower phase. In addition, scale problems were observed during two consecutive weeks for the recovery phase (week 2 and 3 post restriction). The BW data were recorded; these weight data were used because it was not appropriate to remove these BWs from the data set. Therefore, these weights were utilized in calculation and analysis of growth performance data. However, there may be problems with this weight data that may have had an effect on the overall outcome of the growth performance data during the recovery phase.

In this study, barrows and gilts were raised in separate pens. The experimental data were statistically analyzed to examine gender, dietary treatment, and gender by dietary treatment effects. Since there is extensive information in the scientific literature examining gender differences in pig production, the following results and discussion exclusively covers dietary treatment effects. The exception is a limited presentation and discussion of the few gender by dietary treatment interactions found in the study. The ANOVA covering gender, dietary treatment, and gender by dietary treatment effects for all traits are presented in Appendix tables 1 through 16.

4.4.2 Growth Performance

The growth performance data for the restriction phase, recovery phase, and the combined restriction and recovery period can be found in Table 4.2; growth performance data for the commercial phases and the overall entire experimental period (weaning to market weight) can be found in Tables 4.4 and 4.5, respectively.

During the restriction phase, linear decreases ($P < 0.01$) in final BW, ADG, and G:F were observed with decreasing dietary Lys levels (Table 4.2). The decrease in performance may be attributed to the linear decrease ($P < 0.01$) in ADLysI as dietary Lys levels decreased despite no dietary treatment differences ($P = 0.87$) in ADFI (Table 4.2). These results are indicative of the effects of a Lys restriction on growth performance (Mosenthin and Rademacher, 2003) and are consistent with results of the first trial (Chapter 3), as previously discussed.

Differences in BW imposed by a previous Lys restriction in the restriction phase were no longer evident at the end of the recovery phase (end of week 9) ($P > 0.29$; Table 4.2). Previously restricted pigs were able to compensate in terms of BW for growth lost during the restriction phase. Although pigs previously restricted in Lys during the restriction phase appeared to compensate for nutritionally induced differences in BW during the recovery phase, no differences ($P > 0.54$) in G:F were observed during the recovery phase (Table 4.2). While there were quadratic tendencies ($P \leq 0.09$) in ADG and ADLysI in the recovery phase, these responses are difficult to explain given there were no differences ($P = 0.16$) in ADFI during the recovery phase (Table 4.2). The latter is most likely explained by a gender by dietary treatment interaction in ADFI and ADLysI in the recovery phase ($P < 0.02$; Table 4.3). Past studies have noted that for pigs to compensate for a previous loss in growth, they must be able to accelerate their growth beyond that of the unrestricted controls, when provided with a non-limiting diet. (Hornick et al., 2000; Skiba, 2005; Martinez-Ramirez and de Lange, 2008). The latter is often presented as an increase in ADG and G:F in the pigs previously restricted in Lys relative to the unrestricted controls. When considering growth performance data for both the restriction and recovery phases combined, there was a linear trend ($P = 0.08$) for ADG to decrease while G:F decreased linearly ($P < 0.01$) with decreasing dietary Lys levels (Table 4.2). In addition, there were no diet differences ($P = 0.53$) in ADFI, although

ADLysI decreased linearly ($P < 0.01$) with decreasing dietary Lys levels. This can be attributed to lower Lys intakes for restricted pigs during the restriction phase (Table 4.2). The response to G:F for both the restriction and recovery phases combined is consistent with results of the first trial (chapter 3). However, in the case of the latter trial, it is believed that pigs restricted in Lys for a 3 week period achieved full compensatory growth after a 6 week recovery period. Based on performance data alone for the present study, it is plausible that previously restricted pigs did not fully compensate after a 6 week recovery period due to conflicting factors between the ADG, G:F, and BW. Since ADG and G:F are derived from BW measures, it is plausible that some error(s) was accumulated over time, including the final BW recorded at the end of the recovery phase.

Once pigs completed the first 9 weeks of the growing period, there were no differences ($P > 0.16$) for most growth performance traits when pigs were fed commercially prepared diets for the commercial grower, grower-finisher, and finisher stages of production (Table 4.4). During the commercial grower phase, there was a trend ($P = 0.08$) for a quadratic response in ADG as dietary Lys levels decreased; this is most likely attributed to a quadratic response ($P = 0.03$) in ADFI with decreasing dietary Lys levels (Table 4.4). In addition, a quadratic tendency ($P = 0.09$) in ADG with decreasing dietary Lys levels was also observed during the commercial finisher phase, but with no dietary treatment differences in ADFI ($P = 0.23$; Table 4.4). Similarly, when considering the entire experimental period (weaning to market), there was a trend for a quadratic response ($P = 0.08$) in ADG, but with no differences in ADFI ($P = 0.26$; Table 4.5). The reasoning for this quadratic tendency is not well understood, given there were no significant differences in ADFI for the entire experimental period. It should be noted, that the quadratic tendency ($P < 0.10$) in ADG was found in the recovery phase (Table 4.2), the commercial grower and finisher phases (Table 4.4), and for the entire experimental period (Table 4.5), in which the lowest numerical ADG values were found for pigs fed the Lys20 diet in the restriction phase. Although, two Lys20 pigs had to be euthanized due to poor health, it is not believed that the latter was a result of a dietary treatment effect on health as one pig was euthanized during the restriction and another 9 weeks post restriction (grower phase); this response requires further investigation. However, there were spoilage problems in the feeder of the Lys20 diet, such that these pigs may have had increased exposure to mycotoxins which could have reduced ADG. While care was taken to reduce exposure to spoilage, 3 of the 8 Lys20 pens consistently spoiled their feed throughout the experiment.

Based on the results for the combined restriction and recovery phases (Table 4.2), it appears that both the Lys20 and Lys40 pigs were unable to fully compensate for lost growth, based on performance data alone due to conflicting factors in ADG, G:F, and BW. By the end of experiment (Table 4.5), there were no differences in ADG ($P = 0.73$) and BW ($P = 0.25$) as affected by dietary treatment fed in the restriction phase. However there was a quadratic trend ($P = 0.07$) for lower ADG from weaning to market for pigs fed the Lys20 diet (Table 4.5). In addition, both Lys20 and Lys40 pigs were unable to fully compensate for G:F by the end of the recovery ($P < 0.01$; Table 4.2); this resulted in Ctl pigs being more efficient at producing gain from feed from weaning to market ($P = 0.05$; Table 4.5). Although, these results suggested that previously restricted pigs may have achieved compensatory growth by the end of the experiment in terms of ADG and BW, due to the conflicting factors previously described, further investigation is required.

4.4.3 Physical and Chemical Body Composition

Body composition data for the end of the restriction, recovery, and final market weight can be found in tables 4.6, 4.8, and 4.10, respectively. Individual organ weight data for the end of the restriction phase, recovery phase, and market weight are presented in tables 4.7, 4.9, and 4.11, respectively. Body composition data for protein, fat, ash, and water are expressed as a % of the mass (kg) of the carcass, viscera, and WB, respectively.

Previous studies have shown that following a period of a dietary Lys restriction, there will be a decreases in the size of the carcass (Wellock et al., 2009). This is due to repartitioning of dietary energy between carcass protein and fat (de Greef, 1993). In the current study, immediately following the Lys restriction, there was a linear decrease ($P < 0.01$) in carcass weight (Table 4.6). There were also linear decreases ($P < 0.01$) in protein and water contents of the carcass with decreasing dietary Lys levels, while there were linear increases ($P < 0.01$) in fat and ash contents as dietary Lys decreased (Table 4.6). The amount of protein that can be synthesized for lean tissue deposition in theory, is dependent upon the amount of the first limiting amino acid available, given that no other nutrient is limiting (Lewis, 1991, NRC 2012). Lysine utilization efficiency for protein growth in the present study approached the maximum utilization efficiency according to the NRC (2012) during the restriction phase ($P < 0.01$; Table 4.12). Since there were no differences ($P = 0.87$; Table 4.2) in ADFI observed for the Lys restricted pigs, dietary Lys content was most likely the limiting factor for protein growth in the carcass for Lys20 and Lys40 pigs. As a result of a dietary Lys restriction, there was also a linear decrease ($P < 0.01$) in the size of the viscera at the end of the restriction phase as dietary Lys levels decreased (Table 4.6). Fat content in the total viscera increased linearly (P <

0.01) as dietary Lys decreased, while there were no effects ($P > 0.44$) of dietary Lys in the restriction phase on protein, ash, or water contents (Table 4.6). This is in contrast to the previous study (Chapter 3) where protein content in the viscera decreased linearly ($P < 0.01$) as dietary Lys decreased (Table 3.4). Although individual organ composition was not analyzed, there was a linear decrease ($P < 0.01$) in the size of the liver as dietary Lys decreased (Table 4.7). The latter may be the result of the liver's ability to adapt to protein intake (Kerr, 1995). Since the liver is the primary organ involved in the production of urea, pigs consuming low levels of protein may produce lower amounts of urea, conserving energy and nutrients for other physiological processes. Interestingly, the size of the empty gut increased linearly ($P < 0.01$) with decreasing dietary Lys levels (Table 4.7). This appeared to be the result of a linear increase ($P < 0.01$) in the size of the small intestine as dietary Lys levels decreased (Table 4.7). de Lange et al. (2003) reported an inverse relationship between diet digestibility and gut weight. It is plausible that this may also be the case in pigs fed low Lys diets. Although dietary Lys content had no effect ($P = 0.67$) on the remaining viscera (heart, lungs, pancreas, bladder, and reproductive tract), it is unclear whether or not individual organ(s) may have been influenced by dietary Lys content since they were evaluated as a group of organs for chemical composition (Table 4.7). However, the effects of a dietary Lys restriction on the viscera in previous studies has been variable; some studies reported no effects of a dietary Lys restriction on the partitioning of protein and fat in the viscera, while others have seen a reduction in the size and protein content of the viscera. This variability is difficult to explain given that some studies have been performed under similar conditions to the present study (Chiba, 1995; Whang et al., 2003; Skiba, 2005; Martinez-Ramirez et al., 2008; Taylor et al., 2015). In most cases, when an effect of a dietary Lys restriction on the viscera has been observed, this has been seen as a reduction in the size and protein content of the kidneys and(or) liver (Kerr, 1995). The size of organs in pigs can have an effect on energy expenditure (Nyachoti et al., 2000), and in theory the compensatory growth response. Nonetheless, as a result of a decrease in the protein content of the carcass, there was a linear decrease ($P < 0.01$) in WB protein and water contents as dietary Lys decreased (Table 4.6). Since energy that could have been utilized for protein growth was repartitioned towards Ld for both the carcass and viscera, there was a linear increase ($P < 0.01$) in the WB fat content with decreasing dietary Lys levels (Table 4.6). In addition, WB ash content increased linearly ($P < 0.01$) as dietary Lys levels decreased. These results are consistent with the growth performance data presented earlier (Table 4.2) and are consistent with the results of the previous trial discussed in Chapter 3 (Table 3.4).

At the end of the recovery phase (week 9), there were trends for protein content of the carcass to be lower ($P < 0.09$), and fat content to be greater ($P < 0.07$) as dietary Lys decreased (Table 4.8). In addition, a quadratic response ($P = 0.09$), in the ash content of the carcass was observed (Table 4.8). However, there were no longer any differences ($P \geq 0.20$) in the water content of the carcass across dietary treatments (Table 4.7). Similar to the end of the restriction phase (Table 4.6), there were no differences ($P > 0.29$) in the water or ash contents in the viscera at the end of the recovery phase (Table 4.8). There was a trend ($P = 0.07$) for a quadratic response for visceral fat content, with the greatest numerical value for fat content found for Lys 20 pigs (Table 4.8). There was also a trend ($P < 0.06$) for a quadratic response for the size of the liver, with the lowest numerical value for liver size found for Lys20 pigs (Table 4.9). These finding are difficult to explain given there were no differences (P = 0.16) in feed intake during the recovery period (Table 4.2), though may be the result of spoiled Lys20 feed as discussed previosuly. While there were no differences in the protein content of the viscera at the end of the restriction phase (Table 4.6), protein content of the viscera at the end of recovery phase tended to increase linearly (P = 0.07) with decreasing dietary Lys levels (Table 4.8). This most likely can be explained by the gender by dietary treatment interaction present for visceral protein content (P < 0.04; Table 4.3) where a numerical increase in this trait for gilts previously restricted in dietary Lys was observed; although this value was similar across dietary treatments for barrows. Although there were no differences (P = 0.42) in the weight of the kidneys at the end of the restriction phase (Table 4.7); the size of the kidneys responded quadratically (P <0.01), and decreased linearly (P = 0.01) as a % of total visceral weight with decreasing dietary Lys content at the end of the recovery phase (Table 4.9). The reason for the lower kidney weight in the previously restricted pigs relative to the controls is not entirely clear. Previous studies have shown that an increase in dietary protein will lead to an increase in the size of the kidneys most likely to help facilitate deamination of surplus protein (Kerr et al., 1995). However in the past, compensatory growth in pigs previously restricted in protein was accompanied by improved nitrogen utilization, with lower amounts of nitrogen excreted during the recovery phase (Fabian et al., 2004). It could be argued that similar kidney size relative to the controls may not be observed in the recovery phase (Table 4.9). Notably, in the current study, kLys for WB protein growth increased linearly (P = 0.01) with decreasing dietary Lys levels during the recovery phase (Table 4.12). Given that all pigs were on the same diet and consumed the same amount of Lys (P = 0.13; Table 4.2) this may imply that previously restricted pigs were more efficient at utilizing nitrogen which may explain the smaller kidney size in previously restricted pigs. However as discussed previously, the effects of dietary protein content on the viscera are inconsistent with many studies suggesting that protein restrictions have little to no effect on organ size or composition to begin with (Skiba et al., 2001; Whang et al., 2003; Martinez-Ramirez et al., 2008; Taylor et al., 2015). de Lange et al. (2003) noted that changes in visceral mass and whole body protein distribution between the viscera and lean tissue are often the result of changes in feed intake. The reasoning for the variable response of the viscera to changes in dietary Lys content is unclear and requires further investigation.

Pigs previously restricted in Lys were unable to fully compensate for nutritionally induced differences in body composition following a 6 week recovery period. There was a trend for WB fat content to increase linearly ($P = 0.07$) with decreasing dietary Lys levels, while the converse was true ($P = 0.07$) for WB protein content (Table 4.8). This is in contrast to the previous study discussed in Chapter 3. The latter may be the result of inconsistencies in the Lys content of the experimental diets where the total Lys content of the Lys40 diet was on average 13% greater than anticipated (Table 3.1). That being said, it appears that dietary Lys was still limiting as kLys increased linearly ($P = 0.03$) with decreasing dietary Lys content (Table 3.7). In the current study, total Lys content was close to what was expected based on diet formulations (Table 4.1). Although previously restricted pigs were unable to fully compensate by the end of the recovery phase in the current study, there were no differences ($P > 0.10$) in chemical or physical body composition of the carcass, viscera, and ultimately the WB across dietary treatments when pigs were slaughtered at market weight (Tables 4.10 and 4.11). Previous nutritional history did not have a lasting effect on long term performance. This is in contrast to Campbell and Dunkin (1982) who suggested that early protein nutrition plays a pivotal role in supporting “optimal” life time performance. Although compensatory growth has been observed in pigs restricted later in life (Reynolds and O’Doherty, 2006; Martinez-Ramirez et al., 2008; Yang et al., 2008), few studies reported similar results to ours in newly weaned pigs. While previously restricted pigs had not fully compensated by the end of week 9 in the present study, it appears they were capable of compensating while consuming dietary Lys levels relatively similar to those recommended by the NRC (2012) (Table 4.10). It should be noted that for the combined restriction and recovery periods, kLys although greater in the restricted pigs, was much lower than the maximum Lys utilization efficiency for protein growth according to the NRC (2012) (Table 4.13). This may imply that dietary Lys was supplied in excess of what was required for the pig during the recovery phase. This is in contrast to Whang et al. (2003) and O’Connell et al. (2006) who suggested that an increase in dietary Lys during the recovery phase in growing pigs leads to improved performance. This does not go without saying that other factors such as Pdmax or dietary energy content could have led to a lower dietary Lys utilization efficiency. Mohn et al. (2000) suggested that when dietary Lys content determines protein growth, an increase in dietary Lys content will not lower kLys, until Lys supply exceeds the requirement for Pd. Nonetheless, in the present study, previously restricted pigs were still capable of fully compensating for previous nutritionally imposed differences in physical and chemical body composition.

4.4.4 Protein and Lipid Deposition Parameters

Protein deposition, Ld, Ld/Pd and L/P ratios, and kLys data can be found in Table 4.12 for the restriction and recovery phases. Data for the combined restriction and recovery period, commercial period (post recovery), and entire experimental period (weaning to market weight) are presented in Table 4.13.

During the restriction phase, there was a linear decrease ($P < 0.01$) in Pd and a linear increase ($P < 0.01$) in Ld for both the carcass and viscera as dietary Lys decreased (Table 4.12). Consequently, the Ld/Pd ratio for both the carcass and viscera increased linearly ($P < 0.01$) as the level of Lys in the diet decreased (Table 4.12). As a result, the L/P ratio of the carcass and viscera was greater ($P < 0.01$) in the restricted pigs relative to the Control pigs at the end of the restriction phase (Table 4.12). These changes in Pd and Ld for the carcass and viscera for the restricted pigs relative to the control pigs, represents the repartitioning of dietary energy between protein and fat. As such, a linear decrease ($P < 0.01$) in WB Pd and a linear increase ($P < 0.01$) in WB Ld with decreasing dietary Lys content were observed (Table 4.12). This resulted in a linear increase ($P < 0.01$) for the WB L/P ratio as dietary Lys decreased (Table 4.12). These results are consistent with the body composition data described previously, as well as the results for the previous experiment (Chapter 3) and other studies (de Greef, 1992).

For the recovery period (Table 4.12) as well as for the remainder of the trial (post recovery; Table 4.13), there were no differences ($P > 0.10$) in Pd or Ld for the carcass, viscera, and WB across dietary treatments. At the end of the recovery phase, there was a linear effect ($P < 0.05$) for the L/P ratio of the carcass and ultimately the WB, as dietary Lys decreased (Table 4.12). However, at the end of the experiment, there were no differences ($P \geq 0.39$) in the carcass, viscera, and WB L/P ratios across dietary treatments (Table 4.13). This is in agreement with the body composition data presented previously (Table 4.10), and suggests that full compensatory growth occurred in previously restricted pigs. The results for both the WB Pd and Ld, as well as the WB L/P ratio for the recovery are consistent with results from the previous trial (Chapter 3). However, these results are in contrast to many studies (Whang et al., 2002; Fabian et al., 2004; Martinez-Ramirez et al., 2008) that suggest that pigs previously restricted in dietary Lys may express elevated levels of Pd relative to the controls, and lower levels of Ld when provided with a non-restricted diet. The latter represents the pig's metabolic flexibility to adjust the deposition of protein and fat accordingly, when provided with a non-limiting diet, to obtain the "desired" body composition (Whittemore and Kyriazakis, 2006). Given that there were no differences ($P \geq 0.36$) in WB Pd and Ld during the recovery phase (Table 4.12), one may conclude that the restricted pigs in the current study would have been unable to compensate for nutrition induced differences in body composition. However, there were no differences ($P \geq 0.38$) in WB Pd and Ld for the entire experimental period (weaning to market; Table 4.13). This suggests that pigs were capable of compensating for a loss in Pd during the restriction phase at some point post-restriction. Skinner (2012) showed that although newly weaned pigs were capable of achieving compensatory growth, no differences in Pd and Ld were observed. The authors suggested that the period in which pigs were slaughtered for body composition analysis may have missed the compensatory growth period. The latter may have been the case in the current study. Nonetheless, newly weaned pigs restricted in dietary Lys were capable of achieving compensatory growth when provided with a non-limiting diet; the pigs were able to adjust the partitioning of energy between protein and fat to achieve an intrinsic body composition similar to that of the controls.

4.4.5 Carcass and Meat Quality at Market Weight

Basic carcass measure data are presented in Table 4.14. Carcass dissection data for the shoulder, loin, ham and belly are presented in tables 4.15 , 4.16., 4.17, respectively; while meat quality data are presented in Table 4.18.

Although compensatory growth has been observed in pigs following a Lys restriction, it is important to consider the effects this may have on carcass quality as producers are penalized when carcasses have undesirable characteristics (e.g. excess back fat and limited lean deposition). In the past, there have been limited studies examining the effects of a temporary Lys restriction early in life on carcass quality at market weight. In the current study, there were no differences ($P > 0.39$) in dressing percent, probe measures of lean and fat deposition immediately post mortem, loin length and width, back fat over the loin, and LEA as affected by dietary treatment (Table 4.14). There were also few significant differences in the carcass cut-out as a result of a temporary dietary Lys restriction early in life. While the shoulder was separated into the picnic and butt, and further dissected into lean, fat, bone, and skin components; only quadratic responses in the % of internal fat in the retail picnic ($P < 0.01$) and total fat content of the shoulder ($P = 0.03$) were observed with changes in dietary Lys content immediately postweaning. (Table 4.15). In both cases the lowest numerical values were found with Lys20 carcasses. Otherwise, total lean, skin, and bone content of the shoulder were not affected ($P > 0.27$) by a Lys restriction at weaning (Table 4.15).

While the total lean, fat, skin, and bone contents of the loin were not affected ($P > 0.12$) by a Lys restriction after weaning, there were various quadratic responses ($P < 0.07$) as dietary Lys content decreased (Table 4.16). The biological significance of these responses are questionable.

The total lean, skin, and bone contents of the ham were not affected ($P > 0.34$) by Lys restriction after weaning, while there was a dietary treatment effect ($P = 0.04$) for total fat content in the ham (Table 4.17). This response was quadratic ($P = 0.01$) with the lowest numerical value found for the Lys20 pigs. In addition, there were no differences ($P > 0.25$) for any of the belly traits across dietary treatments (Table 4.17).

Ultimately, carcass traits between the control and Lys40 pigs were relatively similar; while Lys20 pigs tended to have the lowest numerical amounts of dissected fat of the shoulder (Table 4.15), loin (Table 4.16) and ham (Table 4.17). It should be noted that ADG for the entire experimental period (weaning to market) tended ($P = 0.07$) to be quadratic in nature, with the ADG being numerically lowest in the Lys20 pigs as mentioned previously (Table 4.5). Furthermore, although not statistically different, ADFI was numerically lowest in the Lys20 pigs (Table 4.5). The latter may explain the lower dissected fat content in the Lys20 pigs, as previous studies have shown that pigs consuming less energy (less feed) often have lower carcass fat content (Bikker, 1994; Weis et al., 2004).

Based on carcass measures and cutout and primal separation, it is evident that previously restricted pigs were fully capable of compensating for any differences in lean and fat deposition during the growing phase. Although limited, previous studies examining the effects of a short term Lys restriction during the nursery phase are consistent with our findings (Taylor et al., 2015). Interestingly, Kouba et al. (1999) suggested that development of intermuscular fat appears to occur early in life at around 20 kg BW. In addition, Richmond and Berg (1971) suggested that the level of intermuscular fat in the carcass as a percentage decreases between 23 and 114 kg, while the percentage of subcutaneous fat increases. A Lys restriction early in life may therefore "alter" the development of intermuscular fat, leading to pigs with greater intermuscular fat at slaughter. However, in the current study this does not appear to be the case. Similar results to the present study have also been observed in pigs temporarily restricted in Lys during the grower phase (Chiba et al., 2002; Kamalaker et al., 2009). More commonly, an increase in the intramuscular fat content may be observed when pigs are restricted in dietary Lys (D'Souza et al., 2003). Increases in intramuscular fat content may actually be beneficial, and improve the overall eating experience.

Ultimately, the final product delivered to the consumer must uphold Canadian pork quality standards and ensure consumers are receiving a safe, nutritious, and flavorful product. In the current study, dietary treatment did not affect the conversion of muscle to meat with similar ($P > 0.82$) pH values in the loin at 1, 24, and 48 hours postmortem (Table 4.18). Water holding capacity was not affected ($P = 0.68$), with no dietary treatment differences in drip loss (Table 4.18). A previous Lys restriction early in life did not affect ($P > 0.20$) subjective evaluation of pork colour, firmness, and wetness with the exception of the National Pork Producers Council (NPPC, 2000) marbling score which increased linearly ($P = 0.03$) with decreasing dietary Lys levels (Table 4.18). This suggests that during the restriction period, "excess" fat deposition may have been distributed intramuscularly. Richmond and Berg (1971) proposed that during development, fat deposition appears to follow the path of least physical resistance. This implies that fat deposition more often may be found in loosely organized muscles as the animal matures. Furthermore, Kamalaker et al. (2009) hypothesized that the metabolism of branched chain AA in pigs fed a diet deficient in Lys may be responsible for the increase in marbling, although an explanation for this reasoning was not given. The increase in marbling score in the previously restricted pigs may lead to an improved eating experience for the consumer. Some studies have also suggested that compensatory growth may improve meat tenderness due elevated levels of protein synthesis, and ultimately protein degradation relative to the control pigs during the recovery phase (Andersen et al., 2004; Therkildsen et al., 2004; Skiba 2005). In the current study, there was no evidence of tenderness improvements as a result of a Lys restriction immediately postweaning, as there were no differences ($P > 0.58$) in shear force for loin chops aged for 3 or 7 days (Table 4.18).

4.5 Conclusion

The results of the current study indicated that a dietary Lys restriction early in life had no long term effects on growth performance, body composition, carcass quality, and meat quality. While Lys restriction early after weaning will increase Ld at the expense of Pd, these differences in body composition do not last long once the pig is fed a diet adequate in Lys. The desire to achieve a target L:P will govern the pigs growth, given that nothing (e.g. nutrients, environment) is limiting their ability to maximize their growth. In the current study, pigs restricted in Lys for a short period of time after weaning were able to recognize a deviation of their actual L:P ratio from the intrinsic target L:P ratio, and adjust their growth accordingly when the restriction was removed. Dietary Lys content during the restriction phase did have an effect on the size of some of the internal organs. The latter may have had an influence on the compensatory growth response, and therefore requires further investigation.

The current study was conducted in a high health herd in a research setting. Further research on compensatory growth in commercial facilities is required in order to improve the efficacy of utilizing compensatory growth as an alternative feeding strategy. In addition, few studies on compensatory growth in newly weaned pigs have been performed. Nonetheless, the results of the current study are promising.

Table 4.2

Effects of a short term Lys restriction postweaning on growth performance traits during the restriction (Weeks 1-3), recovery (Weeks 4-9), and combined restriction and recovery phases (Weeks 1-9) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

	Dietary Treatment[1]					Contrast[2]	
Trait	Control	Lys-20%	Lys-40%	SEM	P-value	L	Q
Restriction[3]							
Initial BW (kg)	7.1	7.2	7.2	0.07	0.798	0.605	0.668
Final BW (kg)	14.4[a]	13.9[a]	12.9[b]	0.19	<0.001	<0.001	0.100
ADFI[4] (g)	460	468	461	11.0	0.869	0.940	0.598
ADLysI[5] (g)	6.3[a]	4.8[b]	3.7[c]	0.14	<0.001	<0.001	0.181
ADG[6] (g)	343[a]	324[a]	271[b]	10.0	<0.001	<0.001	0.167
G/F[7]	0.741[a]	0.682[b]	0.595[c]	0.0106	<0.001	<0.001	0.280
Recovery[3]							
Initial BW (kg)	14.4[a]	13.9[a]	12.9[b]	0.19	<0.001	<0.001	0.100
Final BW (kg)	51.5	50.2	50.3	0.65	0.292	0.190	0.388
ADFI[4] (g)	1674	1664	1744	31.3	0.161	0.163	0.102
ADLysI[5] (g)	20.1	20.0	21.0	0.37	0.133	0.137	0.088
ADG[6] (g)	888	862	888	12.0	0.224	0.997	0.084
G/F[7]	0.545	0.545	0.555	0.0071	0.549	0.383	0.375
Restriction + Recovery[3]							
Initial BW (kg)	7.1	7.2	7.2	0.07	0.798	0.605	0.668
Final BW (kg)	51.5	50.2	50.3	0.65	0.292	0.190	0.388
ADFI[4] (g)	1283	1270	1298	17.0	0.529	0.573	0.314
ADLysI[5] (g)	16.0[a]	15.1[b]	14.5[b]	0.28	0.001	<0.001	0.649
ADG[6] (g)	706	683	682	9.6	0.133	0.076	0.343
G/F[7]	0.612[a]	0.597[b]	0.541[b]	0.0105	<0.001	<0.001	0.357

[1]Restriction phase: Pigs fed at 110%, 80%, and 60% of the SID Lys:NE ratio requirements (NRC, 2012) during the restriction phase (weeks 1-3); Recovery phase: Pigs fed at 120% of SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]N = 8 pens per treatment for the restriction, recovery, and combined restriction + recovery period.

[4]Average Daily Feed Intake (DM basis).

[5]Average Daily Lysine Intake (DM basis).

[6]Average Daily Gain.

[7]Average Daily Gain/ Average Daily Feed Intake.

[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.3
Gender by dietary treatment interactions for growth performance and body composition traits (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

		Dietary Treatment[1]				
Trait	Gender	Control	Lys-20%	Lys-40%	SEM	P-value[2]
Recovery[3]						
ADFI (g)	Barrow	1647	1725	1753	34.3	0.015
	Gilt	1702	1602	1734		
ADLysI (g)	Barrow	19.8	20.7	21.1	0.41	0.017
	Gilt	20.5	19.3	21.0		
Visceral Protein content (%)[4]	Barrow	14.04	14.06	13.98	0.127	0.033
	Gilt	13.72	13.74	14.27		

[1]Recovery phase: Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]P-value of diet by gender interactions.
[3] N=10 barrows and n=10 gilts per treatment.
[4]Total visceral mass protein content expressed as a % of total visceral weight (kg).

Table 4.4
Effects of a short term Lys restriction postweaning on pig growth performance traits during the commercial grower, grower-finisher, and finisher phase (where all pigs were fed common diets).

	Dietary Treatment[1]					Contrast[2]	
Trait	Control	Lys-20%	Lys40%	SEM	P-value	L	Q
Commercial Grower[3]							
Initial BW (kg)	51.5	50.2	50.3	0.65	0.292	0.190	0.388
Final BW (kg)	76.4	72.6	73.4	1.62	0.216	0.182	0.255
ADFI[4] (kg)	2.42	2.23	2.36	0.074	0.045	0.611	0.025
ADG[5] (g)	1041	963	1010	28.9	0.168	0.447	0.083
G/F[6]	0.379	0.388	0.406	0.0126	0.515	0.255	0.749
Commercial Grower-Finisher[3]							
Initial BW (kg)	76.4	72.6	73.4	1.62	0.216	0.182	0.255
Final BW (kg)	97.2	95.0	95.0	1.31	0.372	0.227	0.466
ADFI[4] (kg)	3.11	3.08	2.98	0.112	0.739	0.450	0.736
ADG[5] (g)	981	1002	988	32.9	0.883	0.878	0.635
G/F[6]	0.301	0.311	0.309	0.0121	0.768	0.709	0.621
Commercial Finisher[3]							
Initial BW (kg)	97.2	95.0	95.0	1.31	0.372	0.227	0.466
Final BW (kg)	127.5	124.0	125.8	1.62	0.254	0.406	0.150
ADFI[4] (kg)	3.74	3.53	3.57	0.131	0.227	0.358	0.243
ADG[5] (g)	1191	1161	1211	20.4	0.167	0.432	0.086
G/F[6]	0.286	0.296	0.302	0.0112	0.520	0.304	0.812

[1]Commercial Grower Phase: Pigs fed a commercial grower diet from 52-74 kg of BW; Commercial Grower-Finisher Phase: Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Commercial Finisher Phase: Pigs fed a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]N = 8 pens per treatment for all commercial phases.
[4]Average Daily Feed Intake (DM basis).
[5]Average Daily Gain.
[6]Average Daily Gain/ Average Daily Feed Intake.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.5
Effects of a short term Lys restriction postweaning on pig growth performance traits for the entire experimental period (weaning to market weight) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

	Dietary Treatment[1]					**Contrast[2]**	
Trait	Control	Lys-20%	Lys-40%	SEM	P-value	L	Q
Wean to Market[3]							
Initial BW (kg)	7.1	7.2	7.2	0.07	0.798	0.605	0.668
Final BW (kg)	127.5	124.0	125.8	1.62	0.254	0.406	0.150
ADFI[4] (kg)	2.04	1.97	2.00	0.035	0.264	0.419	0.187
ADG[5] (g)	879	852	866	9.2	0.733	0.345	0.074
G/F[6]	0.480[a]	0.472[b]	0.469[b]	0.0029	0.045	0.036	0.489

[1]Pigs fed at 110%, 80%, and 60% of the SID Lys:NE ratio requirements (NRC, 2012) during the restriction phase (weeks 1-3); Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9); Pigs fed a commercial grower diet from 52-74 kg of BW; Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Pigs fed a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]N = 8 pens per treatment for the restriction, recovery, and commercial phases.
[4]Average Daily Feed Intake (DM basis).
[5]Average Daily Gain.
[6]Average Daily Gain/ Average Daily Feed Intake.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.6
Effects of a short term Lys restriction postweaning on pig body characteristics at the end of the restriction phase (Week 3) (where pigs were fed diets differing in Lys concentration).

Physical and Chemical Composition Traits	Dietary Treatment[1] Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	Contrast[2] L	Q
Carcass Composition[3]							
Carcass Weight (kg)	11.2[a]	10.6[ab]	9.9[b]	0.23	0.002	<0.001	0.776
Protein (%)	15.24[a]	15.24[a]	14.59[b]	0.153	0.006	0.005	0.096
Fat (%)	8.84[c]	11.50[b]	13.28[a]	0.344	<0.001	<0.001	0.302
Ash (%)	3.02[c]	3.25[b]	3.46[a]	0.054	<0.001	<0.001	0.880
Water (%)	71.21[a]	68.70[b]	67.23[c]	0.374	<0.001	<0.001	0.260
Viscera Composition[3]							
Viscera Weight (kg)	2.5[a]	2.4[a]	2.2[b]	0.06	0.003	0.001	0.239
Protein (%)	12.83	12.69	12.71	0.081	0.440	0.301	0.452
Fat (%)	2.21[c]	2.72[b]	3.05[a]	0.092	<0.001	<0.001	0.410
Ash (%)	1.06	1.08	1.07	0.039	0.936	0.887	0.739
Water (%)	82.04	81.96	81.94	0.167	0.896	0.656	0.895
Whole Body (WB) Composition[4]							
EBW (kg)	14.2[a]	13.7[ab]	12.7[b]	0.30	0.003	0.001	0.574
Carcass Weight (%)	77.97	77.29	77.89	0.26	0.149	0.811	0.054
Viscera Weight (%)	17.26	17.54	17.00	0.20	0.152	0.352	0.087
WB Protein (%)	15.30[a]	15.23[a]	14.74[b]	0.11	0.001	0.001	0.118
WB Fat (%)	7.29[c]	9.39[b]	10.88[a]	0.266	<0.001	<0.001	0.356
WB Ash (%)	2.61[c]	2.78[b]	2.96[a]	0.04	<0.001	<0.001	0.914
WB Water (%)	74.79[a]	72.63[b]	71.44[c]	0.30	<0.001	<0.001	0.186

[1]Pigs fed at 110%, 80%, and 60% of the SID Lys:NE ratio requirements (NRC, 2012) during the restriction phase (weeks 1-3).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Excluding Carcass and viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.
[4]Excluding EBW mass (kg), expressed as a % of EBW where WB is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.7
Effects of a short term Lys restriction postweaning on pig organ weights as a % of total visceral weight at the end of the restriction phase (Week 3) (where pigs were fed diets differing in Lys concentration).

	Dietary Treatment[1]					**Contrast**[2]	
Visceral Weights	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	L	Q
Restriction[3]							
Stomach	5.35	5.51	5.59	0.140	0.479	0.236	0.827
Small Intestine	39.49[b]	40.11[b]	42.02[a]	0.439	<0.001	<0.001	0.236
Large Intestine	12.06	12.17	11.72	0.279	0.502	0.397	0.418
Empty GIT	56.89[b]	57.77[b]	59.33[a]	0.421	<0.001	<0.001	0.513
Kidneys	4.43	4.29	4.22	0.113	0.421	0.200	0.794
Liver	20.58[a]	19.57[a]	18.49[b]	0.303	<0.001	<0.001	0.914
Remaining Viscera[4]	18.11	18.37	17.95	0.337	0.673	0.746	0.411

[1]Pigs fed at 110%, 80%, and 60% of the SID Lys:NE ratio requirements (NRC, 2012) during the restriction phase (weeks 1-3).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Individual organ weights expressed as a % of total visceral weight.
[4]Includes: Heart, lungs, pancreas, bladder, and reproductive tract.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.8
Effects of a short term Lys restriction postweaning on pig body characteristics at the end of the recovery phase (Week 9) (where pigs were fed common grower diets).

Physical and Chemical Composition Traits	Dietary Treatment[1] Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	Contrast[2] L	Q
Carcass Composition[3]							
Carcass Weight (kg)	41.0	41.2	41.4	0.74	0.935	0.716	0.994
Protein (%)	17.03	16.59	16.64	0.147	0.083	0.068	0.190
Fat (%)	15.59	17.57	17.17	0.585	0.053	0.064	0.107
Ash (%)	3.31	3.13	3.28	0.075	0.220	0.809	0.087
Water (%)	63.09	61.83	62.11	0.510	0.200	0.185	0.224
Viscera Composition[3]							
Viscera Weight (kg)	5.5	5.6	5.4	0.12	0.632	0.597	0.427
Protein (%)	13.88	13.91	14.12	0.090	0.127	0.065	0.397
Fat (%)	6.52	7.27	6.64	0.299	0.179	0.783	0.068
Ash (%)	1.12	1.09	1.11	0.025	0.764	0.749	0.512
Water (%)	77.54	76.88	77.16	0.291	0.294	0.363	0.202
Whole Body (WB) Composition[4]							
EBW (kg)	49.1	49.5	49.5	0.87	0.945	0.758	0.898
Carcass Weight (%)	83.4	83.3	83.5	0.20	0.614	0.556	0.430
Viscera Weight (%)	11.3	11.4	11.0	0.18	0.375	0.297	0.351
WB Protein (%)	17.0	16.6	16.6	0.12	0.074	0.071	0.152
WB Fat (%)	13.7	15.5	15.1	0.51	0.055	0.071	0.102
WB Ash (%)	3.0	2.8	3.0	0.06	0.199	0.817	0.076
WB Water (%)	66.3	65.2	65.3	0.44	0.134	0.116	0.207

[1]Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Excluding Carcass and viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.
[4]Excluding EBW mass (kg), expressed as a % of EBW where WB is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.9
Effects of a short term Lys restriction postweaning on pig organ weights as a % of total visceral weight at the end of the recovery phase (Week 9) (where pigs were fed common grower diets).

Visceral Weights	Dietary Treatment[1] Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	Contrast[2] L	Q
Recovery[3]							
Stomach	6.09	5.77	5.94	0.156	0.377	0.518	0.217
Small Intestine	32.80	34.09	33.38	0.553	0.270	0.464	0.150
Large Intestine	13.79	13.06	13.44	0.355	0.359	0.491	0.211
Cecum	1.82	1.89	1.94	0.094	0.648	0.356	0.961
Empty GIT	54.41	54.79	54.53	0.520	0.866	0.870	0.612
Kidneys	4.90[a]	4.38[b]	4.58[b]	0.085	<0.001	0.014	0.002
Liver	18.92	17.87	18.45	0.331	0.100	0.329	0.053
Spleen	1.67	1.54	1.70	0.055	0.115	0.656	0.043
Remaining Viscera[4]	20.14	21.39	20.76	0.572	0.318	0.447	0.191

[1]Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Individual organ weights expressed as a % of total visceral weight.
[4]Includes: Heart, lungs, pancreas, bladder, and reproductive tract.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$)

Table 4.10
Effects of a short term Lys restriction postweaning on pig body characteristics at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Physical and Chemical Composition Traits	Dietary Treatment[1] Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	Contrast[2] L	Q
Carcass Composition[3]							
Carcass Weight (kg)	108.2	107.7	107.9	0.25	0.419	0.400	0.312
Protein (%)	15.45	15.69	15.35	0.209	0.501	0.728	0.263
Fat (%)	29.89	28.46	29.93	0.832	0.369	0.971	0.160
Ash (%)	3.37	3.33	3.40	0.115	0.913	0.827	0.715
Water (%)	49.92	50.94	49.87	0.587	0.357	0.950	0.154
Viscera Composition[3]							
Viscera Weight (kg)	10.6	10.5	10.5	0.143	0.672	0.500	0.564
Protein (%)	14.70	14.91	14.98	0.207	0.610	0.345	0.769
Fat (%)	23.52	23.26	23.82	0.730	0.867	0.777	0.652
Ash (%)	1.08	1.11	1.13	0.023	0.297	0.122	0.891
Water (%)	56.81	57.74	57.19	0.656	0.602	0.685	0.359
Whole Body (WB) Composition[4]							
EBW (kg)	124.4	123.6	123.9	0.25	0.128	0.190	0.120
Carcass Weight (%)	86.98	87.12	87.06	0.140	0.769	0.653	0.574
Viscera Weight (%)	8.55	8.47	8.48	0.115	0.868	0.677	0.745
WB Protein (%)	15.83	16.07	15.77	0.192	0.517	0.828	0.261
WB Fat (%)	28.03	26.79	28.10	0.758	0.395	0.948	0.176
WB Ash (%)	3.09	3.07	3.13	0.098	0.912	0.786	0.742
WB Water (%)	53.07	54.06	53.07	0.555	0.352	0.999	0.151

[1]Pigs fed a commercial grower diet from 52-74 kg of BW; Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Pigs fed a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Excluding Carcass and viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.
[4]Excluding EBW mass (kg), expressed as a % of EBW where WB is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.11
Effects of a short term Lys restriction postweaning on pig organ weights as a % of total visceral weight at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

	Dietary Treatment[1]					Contrast[2]	
Visceral Weights	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	L	Q
Market Weight[3]							
Stomach	6.11	6.40	6.37	0.228	0.610	0.419	0.566
Small Intestine	17.58	16.49	16.57	0.551	0.308	0.204	0.391
Large Intestine	13.74	13.32	13.79	0.622	0.841	0.957	0.559
Cecum	1.61	1.42	1.49	0.070	0.176	0.250	0.140
Empty GIT	48.93	47.56	48.06	0.908	0.559	0.501	0.402
Kidneys	3.91	3.99	3.84	0.112	0.624	0.640	0.396
Liver	15.83	15.87	16.03	0.241	0.833	0.569	0.848
Spleen	1.91	1.98	1.83	0.089	0.511	0.564	0.317
Remaining Viscera[4]	29.49	30.67	30.24	0.949	0.673	0.577	0.491

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Individual organ weights expressed as a % of total visceral weight.
[4]Includes: Heart, lungs, pancreas, bladder, and reproductive tract.
[abs] Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.12
Effects of a short term Lys restriction postweaning on pig carcass, viscera, and whole body (WB) protein deposition (Pd) and lipid deposition (Ld) parameters during the restriction (Weeks 1-3) and the recovery phases (Weeks 4-9) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

	Dietary Treatment[1]					Contrast[2]	
Trait	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	L	Q
Restriction							
kLys (%)[3]	58.55[b]	70.61[a]	72.80[a]	2.852	0.002	0.001	0.166
$Pd_{carcass}$ (g/d)	40.2[a]	36.2[a]	30.0[b]	2.03	0.001	<0.001	0.394
$Ld_{carcass}$ (g/d)	5.6[b]	16.8[a]	20.8[a]	1.95	<0.001	<0.001	0.135
$Ld/Pd_{carcass}$[4]	0.06[c]	0.43[b]	0.75[a]	0.063	<0.001	<0.001	0.779
$L/P_{carcass}$[5]	0.58[c]	0.76[b]	0.91[a]	0.023	<0.001	<0.001	0.746
$Pd_{viscera}$ (g/d)	10.1[a]	9.6[a]	7.8[b]	0.40	0.001	<0.001	0.219
$Ld_{viscera}$ (g/d)	0.9[b]	1.3[a]	1.3[a]	0.12	0.014	0.010	0.143
$Ld/Pd_{viscera}$[4]	0.08[b]	0.13[a]	0.17[a]	0.010	<0.001	<0.001	0.377
$L/P_{viscera}$[5]	0.17[c]	0.21[b]	0.24[a]	0.007	<0.001	<0.001	0.309
WB_{Pd} (g/d)	50.4[a]	45.8[a]	35.8[b]	2.39	<0.001	<0.001	0.356
WB_{Ld} (g/d)	6.4[b]	18.2[a]	22.2[a]	2.04	<0.001	<0.001	0.129
WB_{Ld}/WB_{Pd}[4]	0.07[c]	0.37[b]	0.62[a]	0.05	<0.001	<0.001	0.725
L/P_{WB}[6]	0.48[c]	0.62[b]	0.74[a]	0.02	<0.001	<0.001	0.678
Recovery							
kLys (%)[3]	48.17[b]	49.41[ab]	52.19[a]	1.005	0.023	0.008	0.534
$Pd_{carcass}$ (g/d)	125.9	124.1	129.3	2.77	0.418	0.390	0.317
$Ld_{carcass}$ (g/d)	129.5	143.1	138.0	7.69	0.459	0.444	0.326
$Ld/Pd_{carcass}$[4]	1.02	1.16	1.08	0.053	0.206	0.490	0.102
$L/P_{carcass}$[5]	0.92[b]	1.06[a]	1.04[ab]	0.041	0.036	0.040	0.102
$Pd_{viscera}$ (g/d)	10.9	11.5	12.1	0.39	0.14	0.048	0.904
$Ld_{viscera}$ (g/d)	7.5	8.3	7.1	0.48	0.248	0.643	0.609
$Ld/Pd_{viscera}$[4]	0.68[ab]	0.73[a]	0.60[b]	0.035	0.042	0.117	0.043
$L/P_{viscera}$[5]	0.47	0.52	0.47	0.021	0.131	0.957	0.045
WB_{Pd} (g/d)	136.8	135.6	141.3	2.98	0.363	0.289	0.342
WB_{Ld} (g/d)	137.0	151.4	145.1	8.01	0.452	0.479	0.299
WB_{Ld}/WB_{Pd}[4]	1.00	1.12	1.04	0.050	0.207	0.591	0.092
L/P_{WB}[6]	0.81[b]	0.93[a]	0.91[ab]	0.050	0.040	0.049	0.096

[1]Restriction phase: Pigs fed at 110%, 80%, and 60% of the SID Lys:NE ratio requirements (NRC, 2012) during the restriction phase (weeks 1-3); Recovery phase: Pigs fed at 120% of the SID Lys:NE raito requirements (NRC, 2012) during the recovery phase (weeks 4-9).
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Lysine Utilization Efficiency for WB protein growth.
[4]Fat deposition/ Protein deposition for carcass, viscera, and whole body (WB), respectively.
[5]Fat (kg)/ Protein (kg) for carcass and viscera, respectively.
[6] WB Fat (kg) / WB protein (kg).
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.13
Effects of a short term Lys restriction postweaning on pig carcass, viscera, and whole body (WB) protein deposition (Pd) and lipid deposition (Ld) parameters during the combined restriction and recovery (Weeks1-9), post recovery, and the entire experimental period (wean to market) (where pigs were fed differing Lys concentrations during the restriction and common diets thereafter).

	Dietary Treatment[1]					Contrast[2]	
Trait	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	L	Q
Restriction + Recovery[3]							
kLys (%)[4]	49.58[b]	51.72[ab]	53.91[a]	0.907	0.007	0.002	0.985
WB_{Pd} (g/d)	107.9	105.6	106.2	1.98	0.698	0.535	0.568
WB_{Ld} (g/d)	93.4	106.9	104.2	5.34	0.181	0.161	0.222
WB_{Ld}/WB_{Pd}[3]	0.86[b]	1.02[a]	0.99[ab]	0.044	0.039	0.048	0.097
Post Recovery							
$Pd_{carcass}$ (g/d)	114.4	117.9	113.2	2.63	0.429	0.737	0.211
$Ld_{carcass}$ (g/d)	305.3	276.8	300.0	11.84	0.206	0.747	0.082
$Ld/Pd_{carcass}$[3]	2.73	2.40	2.69	0.143	0.217	0.826	0.085
$Pd_{viscera}$ (g/d)	9.5	9.2	9.4	0.30	0.709	0.921	0.413
$Ld_{viscera}$ (g/d)	25.6	24.1	25.3	0.96	0.491	0.825	0.243
$Ld/Pd_{viscera}$[3]	2.76	2.69	2.77	0.154	0.921	0.958	0.689
WB_{Pd} (g/d)	123.9	127.0	122.6	2.75	0.506	0.739	0.265
WB_{Ld} (g/d)	330.9	300.9	325.2	12.39	0.202	0.745	0.080
WB_{Ld}/WB_{Pd}[3]	2.73	2.42	2.69	0.139	0.241	0.846	0.095
Wean to Market							
$Pd_{carcass}$ (g/d)	106.9	108.0	105.6	1.52	0.535	0.527	0.357
$Ld_{carcass}$ (g/d)	212.6	201.7	213.1	6.53	0.384	0.952	0.169
$Ld/Pd_{carcass}$[3]	2.01	1.89	2.03	0.080	0.391	0.823	0.178
$L/P_{carcass}$[5]	1.96	1.84	1.98	0.075	0.390	0.827	0.177
$Pd_{viscera}$ (g/d)	10.0	9.9	10.0	0.17	0.894	0.976	0.639
$Ld_{viscera}$ (g/d)	16.9	16.4	16.7	0.54	0.740	0.805	0.465
$Ld/Pd_{viscera}$[3]	1.70	1.67	1.70	0.067	0.921	0.941	0.692
$L/P_{viscera}$[5]	1.61	1.58	1.61	0.062	0.916	0.934	0.683
WB_{Pd} (g/d)	116.9	117.9	115.5	1.59	0.588	0.543	0.406
WB_{Ld} (g/d)	229.5	218.0	229.9	6.82	0.384	0.970	0.169
WB_{Ld}/WB_{Pd}[3]	1.98	1.87	2.00	0.077	0.414	0.833	0.192
L/P_{WB}[6]	1.79	1.69	1.80	0.066	0.410	0.848	0.188

[1]Pigs fed at 110%, 80%, and 60% of the SID Lys:NE raito requirements (NRC, 2012) during the restriction phase (weeks 1-3); Pigs fed at 120% of the SID Lys:NE ratio requirements (NRC, 2012) during the recovery phase (weeks 4-9); Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Fat deposition/ Protein deposition for carcass, viscera, and whole body, respectively.
[4]Lysine Utilization Efficiency for WB protein growth.
[5]Fat (kg)/ Protein (kg) for carcass and viscera, respectively.
[6]WB Fat (kg) / WB protein (kg).
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.14
Effects of a short term Lys restriction postweaning on basic carcass measures for market weight pigs (where pigs were fed commercial diets throughout the grower and finisher phases).

	Treatment[1]					**Contrast[2]**	
Carcass Quality	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	L	Q
Side Wt (kg)	46.9	46.7	46.2	0.62	0.702	0.422	0.814
Dressing %	87.3	87.0	87.1	0.20	0.399	0.381	0.302
Loin Measurements							
Probe Lean (mm)	59.1	59.3	58.1	0.98	0.671	0.481	0.584
Probe Fat (mm)	20.5	20.3	21.2	0.73	0.684	0.515	0.564
Loin Length (mm)	105.2	105.6	104.3	0.83	0.526	0.445	0.403
Loin Depth (mm)	70.7	71.5	70.6	0.96	0.743	0.956	0.444
Loin Eye Area (mm^2)	5375.9	5429.4	5321.1	86.07	0.675	0.655	0.446
Ruler Back Fat (mm)	19.3	18.8	19.2	0.89	0.901	0.899	0.663

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.15
Effects of a short term Lys restriction postweaning on carcass dissection of the shoulder for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Carcass Quality	Dietary Treatment[1]			SEM	P-value	Contrast[2]	
	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)			L	Q
Shoulder (%)[3]							
Primal	22.31	22.39	22.56	0.184	0.622	0.343	0.845
Rough Butt	10.51	10.66	10.56	0.117	0.659	0.793	0.384
Fat	1.27	1.15	1.30	0.073	0.286	0.765	0.122
Skin	0.59	0.60	0.64	0.017	0.171	0.075	0.558
Retail Butt	8.64	8.91	8.63	0.123	0.203	0.980	0.076
Lean	7.62	7.83	7.56	0.110	0.189	0.685	0.076
Internal Fat	0.53	0.56	0.57	0.022	0.472	0.227	0.882
Bone	0.49	0.52	0.49	0.018	0.367	0.810	0.165
Rough Picnic	11.78	11.71	11.93	0.114	0.376	0.349	0.298
Fat	0.48	0.42	0.57	0.047	0.092	0.190	0.077
Skin	0.81	0.83	0.82	0.021	0.854	0.695	0.690
Retail Picnic	10.52	10.51	10.63	0.132	0.789	0.584	0.678
Lean	7.94	8.02	7.96	0.109	0.858	0.906	0.591
Internal Fat	0.92^{ab}	0.84^{b}	0.99^{a}	0.030	0.003	0.098	0.002
External Fat	0.75	0.71	0.72	0.035	0.727	0.542	0.611
Bone	0.88	0.89	0.87	0.016	0.669	0.745	0.405
Total Lean	15.56	15.86	15.52	0.189	0.396	0.866	0.179
Total Fat	3.94^{ab}	3.67^{b}	4.15^{a}	0.136	0.051	0.307	0.026
Total Skin	1.40	1.43	1.46	0.028	0.377	0.165	0.960
Total Bone	1.37	1.41	1.36	0.024	0.273	0.692	0.119

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]All shoulder parameters expressed as a percentage of side weight (kg).
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.16
Effects of a short term Lys restriction postweaning on carcass dissection of the loin for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

	Dietary Treatment[1]					Contrast[2]	
Carcass Quality	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	L	Q
Loin (%)[3]							
Primal	26.85	26.74	26.78	0.200	0.915	0.782	0.753
Fat	3.58	3.16	3.75	0.177	0.067	0.495	0.026
Skin	1.46	1.50	1.50	0.026	0.371	0.247	0.425
Trimmed Loin	21.86	22.05	21.61	0.200	0.310	0.384	0.207
Tenderloin	1.78	1.84	1.77	0.033	0.255	0.958	0.100
Lean	1.49[ab]	1.53[a]	1.43[b]	0.028	0.056	0.157	0.048
Fat	0.27[b]	0.33[a]	0.32[ab]	0.014	0.018	0.027	0.068
Bone	4.98	5.06	4.85	0.082	0.217	0.287	0.163
Backrubs	1.44	1.42	1.47	0.030	0.568	0.544	0.383
Boneless Loin	15.07	15.11	14.94	0.140	0.672	0.516	0.542
Lean Trim	2.25	2.26	2.21	0.066	0.865	0.726	0.685
Fat Trim	2.73	2.59	2.82	0.078	0.131	0.375	0.069
Chub	2.40	2.50	2.38	0.060	0.300	0.765	0.129
Lean	1.95	2.15	1.98	0.073	0.125	0.762	0.045
Fat	0.45	0.49	0.39	0.121	0.836	0.722	0.632
Boneless Backs	7.71	7.78	7.50	0.126	0.274	0.246	0.261
Total Lean	13.40	13.72	13.12	0.203	0.123	0.345	0.068
Total Fat	7.02	6.58	7.28	0.276	0.203	0.513	0.096
Total Skin	1.46	1.50	1.50	0.026	0.371	0.247	0.425
Total Bone	4.98	5.06	4.85	0.082	0.217	0.287	0.163

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]All loin parameters expressed as a percentage of side weight (kg).
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.17
Effects of a short term Lys restriction postweaning on carcass dissection of the ham and belly for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Carcass Quality	Dietary Treatment[1]			SEM	P-value	Contrast[2]	
	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)			L	Q
Ham (%)[3]							
Primal	25.52	25.52	25.34	0.197	0.774	0.531	0.731
Fat	1.80	1.58	1.85	0.103	0.145	0.758	0.053
Skin	1.91	1.93	1.90	0.035	0.724	0.859	0.435
Bone	2.19	2.15	2.18	0.058	0.900	0.967	0.649
Boneless Ham	19.54	19.71	19.36	0.205	0.468	0.540	0.285
Internal Fat	0.62	0.60	0.63	0.022	0.683	0.944	0.387
Retail Ham	18.74	19.12	18.76	0.219	0.395	0.945	0.176
Lean	17.49	17.93	17.39	0.273	0.341	0.809	0.150
External Fat	1.35	1.19	1.35	0.051	0.049	0.993	0.015
Total Lean	17.49	17.93	17.39	0.273	0.341	0.809	0.150
Total Fat	3.78	3.37	3.83	0.136	0.041	0.806	0.012
Total Skin	1.91	1.93	1.90	0.035	0.724	0.859	0.435
Total Bone	2.19	2.15	2.18	0.058	0.900	0.967	0.649
Belly (%)[3]							
Primal	18.54	18.57	18.34	0.300	0.838	0.640	0.717
Skin	2.07	2.18	2.04	0.064	0.258	0.798	0.105
SideRibs	4.17	4.07	4.00	0.071	0.246	0.097	0.901
Retail Belly	12.30	12.32	12.30	0.228	0.998	0.987	0.955
Trimmed Belly	9.72	9.70	9.73	0.209	0.994	0.978	0.917
Total Lean	12.30	12.32	12.30	0.228	0.998	0.987	0.955
Total Fat	-	-	-	-	-	-	-
Total Skin	2.07	2.18	2.04	0.064	0.258	0.798	0.105
Total Bone	4.17	4.07	4.00	0.071	0.246	0.097	0.901

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]All ham and belly parameters expressed as a percentage of side weight (kg).
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Table 4.18
Effects of a short term Lys restriction postweaning on subjective and objective meat quality characteristics for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Loin Chop Measurements	Dietary Treatment[1] Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	Contrast[2] L	Q
1 h pH[3]	6.44	6.44	6.48	0.050	0.827	0.601	0.748
24 h pH[3]	5.69	5.69	5.69	0.028	0.981	0.971	0.848
48 h pH[3]	5.51	5.51	5.50	0.026	0.964	0.823	0.881
NPPC Colour (1-6)[4]	3.00	3.16	3.09	0.103	0.515	0.514	0.345
Japanese Colour (1-6)[5]	2.96	3.13	3.06	0.105	0.533	0.495	0.377
CPQS Colour (1-6)[6]	3.04	3.08	3.17	0.135	0.803	0.517	0.901
NPCC Firmness (1-3)[7]	1.91	1.96	2.01	0.062	0.550	0.277	0.955
NPCC Wetness (1-3)[8]	1.75	1.67	1.92	0.100	0.200	0.236	0.175
NPPC Marbling (1-10)[9]	1.62	1.87	2.17	0.176	0.098	0.032	0.912
CPQS Marbling (1-6)[10]	3.13	3.09	3.41	0.256	0.624	0.439	0.558
Drip loss (%)	8.81	9.35	8.77	0.516	0.677	0.958	0.380
Shear Force 3 d aged (kg)	4.71	4.61	4.50	0.205	0.771	0.473	0.993
Shear Force 7 d aged (kg)	4.15	4.27	4.00	0.184	0.581	0.560	0.389

[1]Pigs fed a commercial grower diet from 52-74 kg of BW; Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Pigs fed a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]With average temperature after 1 hour of: 37.4, 37.6, and 37.5$\pm$ 0.41 °C for Ctl, Lys20, and Lys40, respectively; and after 24 hours of: 3.0, 3.1, 3.1$\pm$ 0.08 °C, respectively.
[4]Where 1 = pale pinkish gray to white, 2 = grayish pink, 3 = reddish pink, 4 = dark reddish pink, 5 = purplish red, 6 = dark purplish red.
[5]Where 1 = extremely pale pink to gray, to 6 = dark purplish red
[6]Where 1 = pale pinkish gray to white, 2 = grayish pink, 3 = reddish pink, 4 = dark reddish pink, 5 = purplish red, 6 = dark purplish red.
[7]Where 1 = soft – cut surfaces distort easily and are visibly soft, 2 = firm – cut surfaces tend to hold their shape, 3 = very firm – cut surfaces tend to be very smooth with no distortion of shape.
[8]Where 1 = exudative – excessive fluid pooling on cut surfaces, 2 = moist – cut surfaces appear moist, with little or no free water, 3 = dry – cut surfaces exhibit no evidence of free water.
[9]Where 1 = devoid of marbling, to 10 = very abundant marbling.
[10]Where 1= devoid of marbling, to 6 = very abundant marbling.
[abc]Different letters in the same row represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

5.0 General Discussion, Further Research, and Conclusion

With rising costs of high quality protein sources and crystalline amino acids, alternative feeding strategies may be required in order for pig producers to remain profitable. Historically, these ingredients have been used in order to alleviate postweaning growth depression often observed directly following weaning (Campbell et al., 2013). As the newly weaned pig is undergoing many physiological and environmental changes, nutritionists in the past have stressed the importance of providing a balanced and nutritious diet. However, the findings from numerous growing phase studies have suggested that while feeding low protein diets does reduce performance, long term performance is not affected when compensatory growth is induced through re-feeding (Ferguson and Theeruth, 2002; Reynolds and O'Doherty, 2006; Martinez-Ramirez et al., 2008b; Yang et al., 2008). In contrast, it is often believed that the time required for a pig to complete the grower phase ultimately determines its long term performance to market weight (Tokach et al., 1992; Dunshea et al., 2003). For these reasons, few studies have examined the effects of compensatory growth in newly weaned pigs. However, the cost of protein and(or) AA supplementation is often the greatest during the nursery phase relative to other phases of production, and utilizing alternative feeding strategies during this period may be warranted.

Ultimately, the common objective for both studies discussed in this thesis was to determine the effects of a temporary Lys restriction at weaning on subsequent growth performance and body composition in newly weaned pigs. In both chapters 3 and 4, Lys restricted pigs experienced a depression in growth (tables 3.2 and 4.2, respectively) relative to the controls, resulting in greater carcass fat content (tables 3.4 and 4.6, respectively) at the end of the Lys restriction. Many of the studies conducted in the past have reported similar findings when Lys was restricted in the grower phase (Chiba, 1994; Chiba et al., 1999; O'Connell et al., 2006; Whang et al., 2003; Martinez-Ramirez et al., 2008ab; Taylor et al., 2013; Taylor et al., 2015). For both studies, the Lys utilization efficiency (tables 3.7 and 4.12, respectively) for Lys restricted pigs was similar to the maximum Lys utilization efficiency for protein growth reported by the NRC (2012). The latter suggests that Lys was indeed limiting in the present studies, and that the amount of protein deposited was relative to the amount of available Lys in the diet. During the restriction phase, Pd was lowest for Lys restricted pigs while Ld was greatest (tables 3.7 and 4.12, respectively). However, the trials described in this thesis have shown that newly weaned pigs are capable of achieving compensatory growth when provided with a diet that is no longer limiting in Lys. Foremost, the findings in Chapter 4 found that a Lys restriction early in life did not have any lasting effects on long term growth performance up to market weight. These results are consistent with the few studies which have restricted dietary Lys in newly weaned pigs directly at weaning (Taylor et al., 2015).

The current study restricted Lys for pigs immediately after weaning in both trials during a period of significant physiological, environmental, and social challenges (Campbell et al., 2013). At weaning, the digestive tract of the newly weaned pig is still developing in respect to digestive enzymes and acid secretion and this often results in low levels of protease and amylase in the porcine digestive tract relative to lactase (Lalles et al., 2004). For this reason, high quality protein sources such as whey and blood plasma are often fed to newly weaned pigs. Yet, compensatory growth was not always achieved in past studies with grower pigs, which provided pigs time to "acclimatize" to their new environment before a restriction was imposed (de Greef, 1992; Chiba et al., 2002; Suarez-Belloch et al., 2015).

Researchers such as Martinez-Ramirez et al. (2008a) expected that pigs that have had time to “adapt” prior to a specific nutrient restriction, such as the 15 kg pigs utilized by Martinez-Ramirez et al. (2008a), would be able to compensate following a Lys restriction similar to the present studies. However compensatory growth was not achieved in Martinez-Ramirez et al. (2008a). The concept of compensatory growth is not as simple as described and often can be influenced by many factors. Martinez-Ramirez et al. (2008a) suggested that the barrows used in their experiment were unable to compensate due to their low genetic potential for protein growth. However in our second study (chapter 4), there were no dietary treatment by gender interactions for the majority of the body composition data (Appendix Tables 4 to 11). This suggests that both gilts and barrows were fully able to compensate, and genetic potential did not limit the ability of the barrows to compensate in our study. Martinez-Ramirez et al. (2008a) described in detail that compensatory growth can only occur when pigs are in the energy dependent phase of Pd; in other words compensatory growth can only occur before the PdMax is reached. Martinez-Ramirez et al. (2008a) suggested that the unrestricted pigs appeared to have already achieved a protein growth similar to that of the estimated PdMax, limiting the restricted pigs’ ability to accelerate their growth beyond that of the unrestricted pigs. Although newly weaned pigs in the current study may have undergone a substantial amount of physiological and environmental stress at the time of weaning, it appears that the unrestricted pigs remained in the energy dependent phase of Pd longer as the restricted pigs were capable of achieving compensatory growth. However, in both chapters 3 and 4, Pd did not increase during the recovery phase (tables 3.7 and 4.12, respectively), although no differences in Pd were observed overall for the entire experimental periods (Table 3.9 and 4.13, respectively). In the current study, previously restricted pigs were capable of compensating for Pd lost during the recovery phase; however the serial slaughter technique was ineffective for measuring small changes in Pd that may have occurred. In both trials in this thesis, kLys for protein growth during the recovery phase (tables 3.7 and 4.12, respectively) was greater in the pigs previously restricted immediately after weaning. Given that the calculated Lys intakes during this period were the same across treatments in both trials (tables 3.2 and 4.2, respectively), this suggests that the restricted pigs were indeed utilizing Lys more efficiently relative to the controls.

Indeed as noted by Whittemore and Kyriazakis (2006), it is evident that a pigs metabolism is responsive to a deviation from a desired L:P ratio. Given that protein growth is both highly desirable and highly efficient, the ability to maximize protein growth is the ultimate goal when nutrition and environment are not limiting (Whittemore and Kyriazakis, 2006). Based on the results of the trials presented in the current thesis, pigs were capable of identifying a deviation from the “preferred” body composition and adjust their growth accordingly until a L:P ratio similar to the controls was reached. Previous studies have shown that a period of superior growth in previously restricted pigs relative to controls occurs until the “preferred” body composition has been achieved, given that no other factors are limiting (Martinez-Ramirez et al., 2008b). Following compensatory growth, the growth of previously restricted pigs will return to normal, similar to that of the controls. Since there were no significant differences in L:P ratio at the end of both trials (tables 3.9 and 4.13, respectively), this appears to be the case in the current study. The latter also highlights the constraints on energy partitioning between protein and fat (Schinckel and de Lange, 1996).

Based on the current findings, newly weaned pigs can be fed diets limiting in Lys for a 3 week period early in life without affecting long term performance by utilizing compensatory growth. However, the effects of the initial accumulation of excess fat induced by the low Lys diet in the restriction phase must be considered for carcass and meat quality considerations when pigs are shipped at market weight for slaughter for pork to enter the human food chain. For this reason, the second trial (Chapter 4) followed the growth of pigs until a final market weight of approximately 124 kg was reached. With the exception of a linear increase in subjective marbling score (Table 4.18) with decreasing dietary Lys content, there was no other significant differences in carcass or meat quality as affected by a short term Lys restriction immediately postweaning. These findings are interesting considering that it is believed that fat deposition occurs first primarily in areas of least physical resistance (i.e. on the outside of the muscle [subcutaneous fat] vs. within the tightly packed muscle fibers of a given muscle [intramuscular fat] (Richmond and Berg, 1971). This may further highlight the ability of the pig to sense its current fat status and adjust fat distribution accordingly. While Lys restriction immediately after weaning may also increase marbling score, this was only a preliminary finding that was not confirmed by objective determination of intramuscular fat content via chemical fat determination, nor was a trained taste panel conducted to assess dietary treatment differences on juiciness and flavour. Nonetheless, restricting dietary Lys early in life had little to no effects on carcass and meat quality at market weight.

Ultimately, the goal for utilizing compensatory growth is to reduce feed costs. In some pigs restricted in dietary Lys, feed intake will increase in an attempt to compensate for a low Lys intake, due to the low Lys content of the diet (Fabian et al., 2002). Unfortunately, feed costs in research studies are generally not reported; although it could be speculated that feed costs may be similar or even greater than costs for unrestricted pigs if feed intake increases for previously restricted pigs. However in both trials, there were no significant differences in feed intake across dietary treatments (tables 3.2 and 4.5, respectively). The effects of compensatory growth on feed costs for the combined restriction and recovery period in the first trial (Chapter 3), were determined using the following feed ingredient costs ($/tonne): corn, $200; soybean meal, $505; barley, $185; oat groats, $700; dried whey, $950; fish meal, $2100; blood plasma, $1000; spray dried blood, $1000; monocalcium phosphate, $800; micro vitamin premix, $2000; limestone, $80; salt, $195; fat, $820; lysine, $2000; methionine, $4600; threonine, $2600; tryptophan, $13,000; acidifier, $2000. Feed costs per pig for the entire experimental period (restriction + recovery) were $28.87, $27.64, and $27.59 for control, Lys20, and Lys40, respectively. This resulted in a total cost savings per pig of $1.23 and a $1.28 relative to Ctl pigs for Lys20 and Lys40 pigs, respectively. However, the latter considered the fact that the Ctl pigs were also a fed a diet 20% above dietary Lys requirements for growing pigs according to the NRC (2012), when in reality this would not be the case. For this reason, diet costs were estimated for Ctl pigs based on feeding 10% above Lys requirements during the recovery phase; cost savings per pig were $0.27 and $0.46 for Lys20 and Lys40 pigs, respectively. Similarly in the second trial (Chapter 4) cost savings were $1.00 and a $1.60 under study conditions, and $0.22 and $0.82

based on feeding a diet 10% above Lys requirements to the Ctl pigs, and 20% above Lys requirements to the Lys20 and Lys40 pigs during the recovery phase.

Further research is still required despite the current data demonstrating that compensatory growth can be used as an alternative feeding strategy to lower feed costs, without jeopardizing long term performance and meat quality. Notably, the recovery period in these trials fed pigs diets which contained 20% above the SID Lys requirements for growing pigs according to the NRC (2012). The rationale behind this was that given that the restricted pigs may be able to achieve superior growth beyond that of the controls, their requirements for dietary Lys may be greater. In both trials, kLys (Tables 3.8 and 4.12) for protein growth during the recovery phase was greater in the previously restricted pigs relative to the controls, but was much lower than the maximum utilization efficiency (NRC, 2012) across dietary treatments. Mohn et al. (2000) explained that when dietary Lys determines protein growth, the Lys utilization efficiency does not decrease as Lys content increases. This may imply that the pigs in the current trials were oversupplied with dietary Lys, reducing their overall efficiency for Lys utilization. This does not go without saying that dietary energy, or the PdMax could have also limited the pigs' ability for protein growth reducing efficiency of dietary Lys utilization. Whang et al. (2003) reported that following a protein restriction, previously restricted pigs have higher requirements for dietary protein than unrestricted pigs. Depending on how high the protein level is increased, this may be counterproductive for reducing overall feed costs. More research is required to determine an "optimal" level (on both physiological and economical bases) of dietary Lys to feed during the recovery phase. In the past, most studies on compensatory growth used a recovery diet which was 20% above the NRC

(2012) requirements for Lys in growing pigs. However, if this value could be reduced without limiting the pigs ability to achieve compensatory growth, further cost savings could be achieved. Furthermore, oversupplying dietary Lys may increase the demands on the liver and kidneys to remove the excess protein, reducing available energy for compensatory gains.

Unlike most studies in the past, the second trial in the current study (Chapter 4) found that liver size was significantly smaller in the restricted pigs at the end of the restriction phase compared to controls, while the converse was true for the size of the small intestine (Table 4.7). However, when previously restricted pigs were provided with a diet that was no longer limiting, these pigs were fully able to compensate in terms of visceral weight and composition by the end of the recovery phase (Table 4.8). These results are consistent with those the first trial (Chapter 3), although in the first trial it was unclear which organ(s) may have undergone compensatory growth (Table 3.6). However, at the end of the recovery phase, the kidneys were significantly smaller in the restricted pigs relative to the Ctl pigs (Table 4.9). This is in contrast to the end of the restriction phase, where kidney size was similar across dietary treatments. It is plausible that this decrease in the size of the kidneys may have been due to improved kLys of the restricted pigs (Table 4.12). Few studies in the past have reported differences in organ weight and composition following a dietary Lys restriction (Skiba, 2005). It is not fully understood why changes in organ size and composition as a result of a dietary Lys restriction are inconsistent between studies. However, the findings of the trials presented in the thesis as well as some others may have major implications on the compensatory growth response. Nyachoti et al. (2000) noted that although the viscera accounts for only 15% of body weight, it often represents a major proportion of total energy expenditures (maintenance). This is especially true for highly metabolically active organs such as the liver and kidneys. The latter may imply that pigs who have been restricted in dietary Lys, may have greater dietary energy available to them for growth, initially aiding them for compensatory growth. For this reason, further research is required to understand the effects of dietary Lys restriction on organ size and composition, and how this may affect the compensatory growth response.

To date more than 75 years of research has been conducted on compensatory growth in pigs. However, use of compensatory growth has yet to be implemented in commercial operations. Since pigs fed high-protein diets are known to have superior growth, this may explain why the pork industry has been hesitant to implement compensatory growth feeding strategies. However with rising costs of feedstuffs, compensatory growth may be one of the feeding strategies that may need to be adopted for pig producers to stay profitable. This is especially true during the nursery phase when protein sources are relatively expensive and protein and(or) AA requirements are the greatest. In addition with consumer trends moving towards antibiotic-free raised animals, lower protein diets may be beneficial for reducing the need for treatment of enteric diseases. Unfortunately, research in compensatory growth following a period of protein restriction in nursery pigs is limited and often inconsistent. Consistent, well planned experiments will be required before this strategy can be put into practice. Nonetheless with the high genetic potential of pigs today, pigs are more likely to be in the energy dependent phase of protein deposition up to heavier body weights. Therefore, the opportunity to capitalize on compensatory growth has increased and remains promising.

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Appendix Table 1.

Effects of gender and dietary treatment on growth performance traits for pigs during the restriction phase (Weeks 1-3), recovery phase (Weeks 4-9), and combined restriction and recovery phase (weeks 1-9) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

Trait	Gender				Dietary Treatment[1]						Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control	Lys-20%	Lys-40%	SEM	P-value	*P*-value Diet x Gender	L	Q
Restriction[3]												
Initial BW (kg)	7.2	7.1	0.06	0.330	7.1	7.2	7.2	0.07	0.798	0.772	0.605	0.668
Final BW (kg)	13.7	13.8	0.16	0.625	14.4[a]	13.9[a]	12.9[b]	0.19	<0.001	0.872	<0.001	0.100
ADFI[4] (g)	458	468	9.8	0.507	460	468	461	11.0	0.869	0.840	0.940	0.598
ADLysI[5] (g)	4.9	4.9	0.11	0.691	6.3[a]	4.8[b]	3.7[c]	0.14	<0.001	0.871	<0.001	0.181
ADG[6] (g)	310	315	7.60	0.636	343[a]	324[a]	271[b]	10.0	<0.001	0.834	<0.001	0.167
G/F[7]	0.681	0.664	0.0088	0.189	0.741[a]	0.682[b]	0.595[c]	0.0106	<0.001	0.328	<0.001	0.280
Recovery[3]												
Initial BW (kg)	13.7	13.8	0.16	0.625	14.4[a]	13.9[a]	12.9[b]	0.19	<0.001	0.872	<0.001	0.100
Final BW (kg)	51.2	50.0	0.53	0.132	51.5	50.2	50.3	0.65	0.292	0.731	0.190	0.388
ADFI[4] (g)	1708	1680	17.3	0.244	1674	1664	1744	31.3	0.161	0.015	0.163	0.102
ADLysI[5] (g)	20.5	20.2	0.20	0.305	20.1	20.0	21.0	0.37	0.133	0.017	0.137	0.088
ADG[6] (g)	894[a]	865[b]	9.50	0.030	888	862	888	12.0	0.224	0.244	0.997	0.084
G/F[7]	0.554[a]	0.543[b]	0.0038	0.034	0.545	0.545	0.555	0.0071	0.549	0.315	0.383	0.375
Restriction + Recovery[3]												
Initial BW (kg)	7.2	7.1	0.06	0.330	7.1	7.2	7.2	0.07	0.798	0.772	0.605	0.668
Final BW (kg)	51.2	50.0	0.53	0.132	51.5	50.2	50.3	0.65	0.292	0.731	0.190	0.388
ADFI[4] (g)	1291	1276	13.3	0.427	1283	1270	1298	17.0	0.529	0.063	0.573	0.314
ADLysI[5] (g)	15.3	15.2	0.15	0.459	16.0[a]	15.1[b]	14.5[b]	0.28	0.001	0.382	<0.001	0.649
ADG[6] (g)	698	682	7.8	0.169	706	683	682	9.6	0.133	0.426	0.076	0.343
G/F[7]	0.594	0.585	0.0040	0.127	0.612[a]	0.597[b]	0.541[b]	0.0105	<0.001	0.617	<0.001	0.357

[1]Restriction phase: Pigs fed at 110%, 80%, and 60% of SID Lys requirements (NRC, 2012) during therestriction phase (weeks 1-3); Recovery phase: Pigs fed at 120% of SID Lys requirements (NRC, 2012) during the recovery phase (weeks 4-9).

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]N = 8 pens per treatment for the restriction, recovery, and combined restriction + recovery period.

[4]Average Daily Feed Intake (DM basis).

[5]Average Daily Lysine Intake (DM basis).

[6]Average Daily Gain.

[7]Average Daily Gain/ Average Daily Feed Intake.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; P < 0.05).

Appendix Table 2.

Effects of gender and dietary treatment on growth performance traits for pigs during the commercial grower, grower-finisher, and finisher phase (where all pigs were fed common diets).

Trait	Gender				Dietary Treatment[1]						Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control	Lys-20%	Lys-40%	SEM	P-value	*P*-value Diet x Gender	L	Q
Commercial Grower[3]												
Initial BW (kg)	51.2	50.0	0.53	0.132	51.5	50.2	50.3	0.65	0.292	0.731	0.190	0.388
Final BW (kg)	75.5	72.7	1.31	0.138	76.4	72.6	73.4	1.62	0.216	0.843	0.182	0.255
ADFI[4] (kg)	2.45^{a}	2.22^{b}	0.041	0.001	2.42	2.23	2.36	0.074	0.045	0.153	0.611	0.025
ADG[5] (g)	1062^{a}	948^{b}	23.7	0.001	1041	963	1010	28.9	0.168	0.223	0.447	0.083
G/F[6]	0.393	0.390	0.0081	0.778	0.379	0.388	0.406	0.0126	0.515	0.697	0.255	0.749
Commercial Grower-Finisher[3]												
Initial BW (kg)	75.5	72.7	1.31	0.138	76.4	72.6	73.4	1.62	0.216	0.843	0.182	0.255
Final BW (kg)	98.8^{a}	92.6^{b}	1.04	<0.001	97.2	95.0	95.0	1.31	0.372	0.702	0.227	0.466
ADFI[4] (kg)	3.25^{a}	2.87^{b}	0.062	<0.001	3.11	3.08	2.98	0.112	0.739	0.285	0.450	0.736
ADG[5] (g)	1049^{a}	932^{b}	27.0	0.001	981	1002	988	32.9	0.883	0.865	0.878	0.635
G/F[6]	0.299	0.315	0.0067	0.121	0.301	0.311	0.309	0.0121	0.768	0.109	0.709	0.621
Commercial Finisher[3]												
Initial BW (kg)	98.8^{a}	92.6^{b}	1.04	<0.001	97.2	95.0	95.0	1.31	0.372	0.702	0.227	0.466
Final BW (kg)	129.6^{a}	121.9^{b}	1.21	<0.001	127.5	124.0	125.8	1.62	0.254	0.569	0.406	0.150
ADFI[4] (kg)	3.74^{a}	3.37^{b}	0.063	<0.001	3.74	3.53	3.57	0.131	0.227	0.811	0.358	0.243
ADG[5] (g)	1219^{a}	1156^{b}	17.0	0.003	1191	1161	1211	20.4	0.167	0.500	0.432	0.086
G/F[6]	0.287^{b}	0.302^{a}	0.0050	0.033	0.286	0.296	0.302	0.0112	0.520	0.921	0.304	0.812

[1]Commercial Grower Phase: Pigs fed a commercial grower diet from 52-74 kg of BW; Commercial Grower-Finisher Phase: Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Commercial Finisher Phase: Pigs fed a commercial finisher diet from 93- 124 kg BW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]N = 8 pens per treatment for all commercial phases.

[4]Average Daily Feed Intake (DM basis).

[5]Average Daily Gain.

[6]Average Daily Gain/ Average Daily Feed Intake.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 3.

Effects of gender and dietary treatment on growth performance traits for pigs during the entire experimental period (weaning to market weight) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

Trait	Gender				Dietary Treatment[1]					P-value	Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control	Lys-20%	Lys-40%	SEM	P-value	Diet x Gender	L	Q
Wean to Market[3]												
Initial BW (kg)	7.2	7.1	0.06	0.330	7.1	7.2	7.2	0.07	0.798	0.772	0.605	0.668
Final BW (kg)	129.6[a]	121.9[b]	1.21	<0.001	127.5	124.0	125.8	1.62	0.254	0.569	0.406	0.150
ADFI[4] (kg)	2.08[a]	1.93[b]	0.025	<0.001	2.04	1.97	2.00	0.035	0.264	0.243	0.419	0.187
ADG[5] (g)	885[a]	847[b]	7.4	<0.001	879	852	866	9.2	0.733	0.563	0.345	0.074
G/F[6]	0.474	0.473	0.0018	0.676	0.480[a]	0.472[b]	0.469[b]	0.0029	0.045	0.183	0.036	0.489

[1]Pigs fed at 110%, 80%, and 60% of SID Lys requirements (NRC, 2012) during the restriction phase (weeks 1-3); Pigs fed at 120% of SID Lys requirements (NRC, 2012) during the recovery phase (weeks 4-9); Pigs fed a commercial grower diet from 52-74 kg of BW; Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Pigs fed a commercial finisher diet from 93- 124 kg BW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]N = 8 pens per treatment for the restriction, recovery, and commercial phases.

[4]Average Daily Feed Intake (DM basis).

[5]Average Daily Gain.

[6]Average Daily Gain/ Average Daily Feed Intake.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 4.

Effects of gender and dietary treatment on pig body characteristics at the end of the restriction phase (Week 3) (where pigs were fed diets differing in Lys concentration).

	Gender				Dietary Treatment[1]						Contrast[2]	
Physical and Chemical Composition Traits	Barrow	Gilt	SEM	P-value	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	*P*-value Diet x Gender	L	Q
Carcass Composition[3]												
Carcass Weight (kg)	10.6	10.5	0.19	0.668	11.2[a]	10.6[ab]	9.9[b]	0.23	0.002	0.631	<0.001	0.776
Protein (%)	14.77[b]	15.27[a]	0.125	0.008	15.24[a]	15.24[a]	14.59[b]	0.153	0.006	0.775	0.005	0.096
Fat (%)	11.06	11.36	0.281	0.453	8.84[c]	11.50[b]	13.28[a]	0.344	<0.001	0.416	<0.001	0.302
Ash (%)	3.20	3.27	0.043	0.289	3.02[c]	3.25[b]	3.46[a]	0.054	<0.001	0.231	<0.001	0.880
Water (%)	69.41	68.68	0.306	0.101	71.21[a]	68.70[b]	67.23[c]	0.374	<0.001	0.823	<0.001	0.260
Viscera Composition[3]												
Viscera Weight (kg)	2.4	2.3	0.051	0.289	2.5[a]	2.4[a]	2.2[b]	0.06	0.003	0.918	0.001	0.239
Protein (%)	12.76	12.73	0.066	0.749	12.83	12.69	12.71	0.081	0.440	0.969	0.301	0.452
Fat (%)	2.67	2.64	0.075	0.784	2.21[c]	2.72[b]	3.05[a]	0.092	<0.001	0.973	<0.001	0.410
Ash (%)	1.08	1.06	0.031	0.750	1.06	1.08	1.07	0.039	0.936	0.823	0.887	0.739
Water (%)	82.18[a]	81.78[b]	0.136	0.048	82.04	81.96	81.94	0.167	0.896	0.509	0.656	0.895
Whole Body (WB) Composition[4]												
EBW (kg)	13.7	13.5	0.25	0.572	14.2[a]	13.7[ab]	12.7[b]	0.30	0.003	0.731	0.001	0.574
Carcass Weight (%)	77.53	77.91	0.211	0.206	77.97	77.29	77.89	0.258	0.149	0.331	0.811	0.054
Viscera Weight (%)	17.46	17.07	0.157	0.088	17.26	17.54	17.00	0.192	0.152	0.733	0.352	0.087
WB Protein (%)	14.90	15.29	0.087	0.003	15.30[a]	15.23[a]	14.74[b]	0.107	0.001	0.744	0.001	0.118
WB Fat (%)	9.05	9.33	0.217	0.378	7.29[c]	9.39[b]	10.88[a]	0.266	<0.001	0.470	<0.001	0.356
WB Ash (%)	2.75[b]	2.81[a]	0.032	0.203	2.61[c]	2.78[b]	2.96[a]	0.039	<0.001	0.148	<0.001	0.914
WB Water (%)	73.32	72.59	0.245	0.042	74.79[a]	72.63[b]	71.44[c]	0.300	<0.001	0.567	<0.001	0.186

[1]Pigs fed at 110%, 80%, and 60% of SID Lys requirements (NRC, 2012) during the restriction phase (weeks 1-3).

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]Excluding Carcass and viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.

[4]Excluding EBW mass (kg), expressed as a % of EBW where WB is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 5.

Effects of gender and dietary treatment on pig organ weights as a % of total visceral weight at the end of the restriction phase (Week 3) (where pigs were fed diets differing in Lys concentration).

	Gender				Dietary Treatment[1]						Contrast[2]	
Visceral Weights	Barrow	Gilt	SEM	P-value	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	*P*-value Diet x Gender	L	Q
Restriction[3]												
Stomach	5.47	5.49	0.114	0.905	5.35	5.51	5.59	0.140	0.479	0.136	0.236	0.827
Small Intestine	41.01	40.07	0.358	0.070	39.49[b]	40.11[b]	42.02[a]	0.439	<0.001	0.179	<0.001	0.236
Large Intestine	11.84	12.12	0.228	0.395	12.06	12.17	11.72	0.279	0.502	0.965	0.397	0.418
Empty GIT	58.33	57.67	0.344	0.183	56.89[b]	57.77[b]	59.33[a]	0.421	<0.001	0.381	<0.001	0.513
Kidneys	4.18	4.45	0.092	0.050	4.43	4.29	4.22	0.113	0.421	0.687	0.200	0.794
Liver	19.37	19.72	0.248	0.323	20.58[a]	19.57[a]	18.49[b]	0.303	<0.001	0.187	<0.001	0.914
Remaining Viscera[4]	18.12	18.17	0.275	0.903	18.11	18.37	17.95	0.337	0.673	0.829	0.746	0.411

[1]Pigs fed at 110%, 80%, and 60% of SID Lys requirements (NRC, 2012) during the restriction phase (weeks 1-3).

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]Individual organ weights expressed as a % of total visceral weight.

[4]Includes: Heart, lungs, pancreas, bladder, and reproductive tract.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 6.

Effects of gender and dietary treatment on pig body characteristics at the end of the recovery phase (Week 9) (where pigs were fed common grower diets).

	Gender				Dietary Treatment[1]						Contrast[2]	
Physical and Chemical Composition Traits	Barrow	Gilt	SEM	P-value	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	*P*-value Diet x Gender	L	Q
Carcass Composition[3]												
Carcass Weight (kg)	41.6	40.7	0.61	0.294	41.0	41.2	41.4	0.74	0.935	0.108	0.716	0.994
Protein (%)	16.64	16.87	0.120	0.189	17.03	16.59	16.64	0.147	0.083	0.799	0.068	0.190
Fat (%)	16.92	16.63	0.478	0.675	15.59	17.57	17.17	0.585	0.053	0.285	0.064	0.107
Ash (%)	3.27	3.22	0.062	0.551	3.31	3.13	3.28	0.075	0.220	0.388	0.809	0.087
Water (%)	62.24	62.45	0.417	0.723	63.09	61.83	62.11	0.510	0.200	0.483	0.185	0.224
Viscera Composition[3]												
Viscera Weight (kg)	5.6	5.4	0.10	0.227	5.5	5.6	5.4	0.12	0.632	0.517	0.597	0.427
Protein (%)	14.03	13.91	0.074	0.266	13.88	13.91	14.12	0.090	0.127	0.033	0.065	0.397
Fat (%)	6.82	6.80	0.244	0.947	6.52	7.27	6.64	0.299	0.179	0.858	0.783	0.068
Ash (%)	1.13	1.08	0.021	0.129	1.12	1.09	1.11	0.025	0.764	0.331	0.749	0.512
Water (%)	77.18	77.21	0.238	0.933	77.54	76.88	77.16	0.291	0.294	0.709	0.363	0.202
Whole Body (WB) Composition[4]												
EBW (kg)	49.9	48.8	0.71	0.287	49.1	49.5	49.5	0.87	0.945	0.108	0.758	0.898
Carcass Weight (%)	83.37	83.40	0.161	0.899	83.37	83.26	83.54	0.197	0.614	0.457	0.556	0.430
Viscera Weight (%)	11.26	11.19	0.143	0.713	11.29	11.36	11.02	0.175	0.375	0.779	0.297	0.351
WB Protein (%)	16.64	16.80	0.100	0.248	16.95	16.57	16.63	0.123	0.074	0.747	0.071	0.152
WB Fat (%)	14.89	14.65	0.419	0.685	13.74	15.47	15.09	0.513	0.055	0.338	0.071	0.102
WB Ash (%)	2.93	2.88	0.052	0.524	2.96	2.81	2.94	0.064	0.199	0.409	0.817	0.076
WB Water (%)	65.55	65.67	0.359	0.810	66.34	65.15	65.34	0.440	0.134	0.339	0.116	0.207

[1]Pigs fed at 120% of SID Lys requirements (NRC, 2012) during the recovery phase (weeks 4-9).

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]Excluding Carcass and viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.

[4]Excluding EBW mass (kg), expressed as a % of EBW where WB is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 7.

Effects of gender and dietary treatment on pig organ weights as a % of total visceral weight at the end of the recovery phase (Week 9) (where pigs were fed common grower diets).

	Gender				Dietary Treatment[1]						Contrast[2]	
Visceral Weights	Barrow	Gilt	SEM	P-value	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	*P*-value Diet x Gender	L	Q
Recovery[3]												
Stomach	6.00	5.86	0.128	0.443	6.09	5.77	5.94	0.156	0.377	0.230	0.518	0.217
Small Intestine	33.49	33.35	0.451	0.832	32.80	34.09	33.38	0.553	0.270	0.931	0.464	0.150
Large Intestine	13.67	13.19	0.290	0.249	13.79	13.06	13.44	0.355	0.359	0.137	0.491	0.211
Cecum	1.86	1.90	0.077	0.703	1.82	1.89	1.94	0.094	0.648	0.242	0.356	0.961
Empty GIT	54.84	54.31	0.425	0.378	54.41	54.79	54.53	0.520	0.866	0.601	0.870	0.612
Kidneys	4.65	4.59	0.070	0.562	4.90[a]	4.38[b]	4.58[b]	0.085	<0.001	0.072	0.014	0.002
Liver	18.55	18.27	0.270	0.467	18.92	17.87	18.45	0.331	0.100	0.332	0.329	0.053
Spleen	1.62	1.65	0.045	0.607	1.67	1.54	1.70	0.055	0.115	0.231	0.656	0.043
Remaining Viscera[4]	20.32	21.20	0.467	0.190	20.14	21.39	20.76	0.572	0.318	0.429	0.447	0.191

[1]Pigs fed at 120% of SID Lys requirements (NRC, 2012) during the recovery phase (weeks 4-9).

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]Individual organ weights expressed as a % of total visceral weight

[4]Includes: Heart, lungs, pancreas, bladder, and reproductive tract

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; P < 0.05).

Appendix Table 8

Effects of gender and dietary treatment on pig body characteristics at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Physical and Chemical Composition Traits	Gender				Dietary Treatment[1]						Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	*P*-value Diet x Gender	L	Q
Carcass Composition[3]												
Carcass Weight (kg)	108.2	107.7	0.21	0.095	108.2	107.7	107.9	0.25	0.419	0.427	0.400	0.312
Protein (%)	15.08^{b}	15.92^{a}	0.179	0.003	15.45	15.69	15.35	0.209	0.501	0.245	0.728	0.263
Fat (%)	30.82^{a}	28.04^{b}	0.715	0.012	29.89	28.46	29.93	0.832	0.369	0.413	0.971	0.160
Ash (%)	3.26	3.47	0.098	0.155	3.37	3.33	3.40	0.115	0.913	0.483	0.827	0.715
Water (%)	49.15^{b}	51.33^{a}	0.509	0.006	49.92	50.94	49.87	0.587	0.357	0.358	0.950	0.154
Viscera Composition[3]												
Viscera Weight (kg)	10.5	10.6	0.124	0.348	10.6	10.5	10.5	0.143	0.672	0.243	0.500	0.564
Protein (%)	14.65	15.07	0.178	0.121	14.70	14.91	14.98	0.207	0.610	0.231	0.345	0.769
Fat (%)	24.75^{a}	22.31^{b}	0.618	0.010	23.52	23.26	23.82	0.730	0.867	0.695	0.777	0.652
Ash (%)	1.12	1.09	0.020	0.302	1.08	1.11	1.13	0.023	0.297	0.499	0.122	0.891
Water (%)	56.19	58.31	0.557	0.013	56.81	57.74	57.19	0.656	0.602	0.770	0.685	0.359
Whole Body (WB) Composition[4]												
EBW (kg)	123.9	124.1	0.220	0.650	124.4	123.6	123.9	0.25	0.128	0.110	0.190	0.120
Carcass Weight (%)	87.33^{a}	86.78^{b}	0.122	0.004	86.98	87.12	87.06	0.140	0.769	0.574	0.653	0.574
Viscera Weight (%)	8.43	8.57	0.100	0.370	8.55	8.47	8.48	0.115	0.868	0.406	0.677	0.745
WB Protein (%)	15.54^{b}	16.24^{a}	0.164	0.006	15.83	16.07	15.77	0.192	0.517	0.208	0.828	0.261
WB Fat (%)	29.02^{a}	26.26^{b}	0.651	0.006	28.03	26.79	28.10	0.758	0.395	0.420	0.948	0.176
WB Ash (%)	3.02	3.18	0.084	0.196	3.09	3.07	3.13	0.098	0.912	0.493	0.786	0.742
WB Water (%)	52.46^{b}	54.34^{a}	0.479	0.011	53.07	54.06	53.07	0.555	0.352	0.388	0.999	0.151

[1]Pigs fed a commercial grower diet from 52-74 kg of BW; Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Pigs fed a commercial finisher diet from 93- 124 kg BW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]Excluding Carcass and viscera mass (kg), parameters expressed as a % of carcass and viscera weight, respectively.

[4]Excluding EBW mass (kg), expressed as a % of EBW where WB is the sum of the carcass, viscera, and blood composition for protein, fat, ash, and water, respectively.

[a,b]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 9.

Effects of gender and dietary treatment on pig organ weights as a % of total visceral weight at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

	Gender				Dietary Treatment[1]						Contrast[2]	
Visceral Weights	Barrow	Gilt	SEM	P-value	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	*P*-value Diet x Gender	L	Q
Market Weight[3]												
Stomach	6.40	6.19	0.192	0.472	6.11	6.40	6.37	0.228	0.610	0.894	0.419	0.566
Small Intestine	17.21	16.55	0.462	0.328	17.58	16.49	16.57	0.551	0.308	0.975	0.204	0.391
Large Intestine	14.09	13.14	0.525	0.218	13.74	13.32	13.79	0.622	0.841	0.271	0.957	0.559
Cecum	1.54	1.47	0.059	0.408	1.61	1.42	1.49	0.070	0.176	0.529	0.250	0.140
Empty GIT	49.57[a]	46.80[b]	0.759	0.015	48.93	47.56	48.06	0.908	0.559	0.794	0.501	0.402
Kidneys	3.79	4.04	0.097	0.092	3.91	3.99	3.84	0.112	0.624	0.276	0.640	0.396
Liver	15.62	16.21	0.210	0.064	15.83	15.87	16.03	0.241	0.833	0.395	0.569	0.848
Spleen	1.88	1.93	0.075	0.673	1.91	1.98	1.83	0.089	0.511	0.805	0.564	0.317
Remaining Viscera[4]	29.23	31.04	0.793	0.120	29.49	30.67	30.24	0.949	0.673	0.769	0.577	0.491

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]Individual organ weights expressed as a % of total visceral weight .s

[4]Includes: Heart, lungs, pancreas, bladder, and reproductive tract.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 10.

Effects of gender and dietary treatment on pig carcass, viscera, and whole body (WB) protein deposition (Pd) and lipid deposition (Ld) parameters during the restriction (Weeks 1-3) and the recovery phases (Weeks 4-9) (where pigs were fed diets differing in Lys concentration during the restriction phase and common diets thereafter).

Trait	Gender				Dietary Treatment[1]					*P*-value	Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control (n=20)	Lys-20% (n=20)	Lys-40% (n=20)	SEM	P-value	Diet x Gender	L	Q
Restriction												
kLys (%)[3]	66.63	68.02	2.33	0.675	58.55^{b}	70.61^{a}	72.80^{a}	2.852	0.002	0.819	0.001	0.166
$Pd_{carcass}$ (g/d)	34.0	35.6	1.65	0.499	40.2^{a}	36.2^{a}	30.0^{b}	2.03	0.001	0.871	<0.001	0.394
$Ld_{carcass}$ (g/d)	14.0	14.8	1.60	0.725	5.6^{b}	16.8^{a}	20.8^{a}	1.95	<0.001	0.824	<0.001	0.135
$Ld/Pd_{carcass}$[4]	0.40	0.43	0.051	0.776	0.06^{c}	0.43^{b}	0.75^{a}	0.063	<0.001	0.597	<0.001	0.779
$L/P_{carcass}$[5]	0.75	0.75	0.019	0.832	0.58^{c}	0.76^{b}	0.91^{a}	0.023	<0.001	0.463	<0.001	0.746
$Pd_{viscera}$ (g/d)	9.3	9.0	0.33	0.444	10.1^{a}	9.6^{a}	7.8^{b}	0.40	0.001	0.872	<0.001	0.219
$Ld_{viscera}$ (g/d)	1.2	1.1	0.10	0.636	0.9^{b}	1.3^{a}	1.3^{a}	0.12	0.014	0.965	0.010	0.143
$Ld/Pd_{viscera}$[4]	0.13	0.13	0.008	0.887	0.08^{b}	0.13^{a}	0.17^{a}	0.010	<0.001	0.990	<0.001	0.377
$L/P_{viscera}$[5]	0.21	0.21	0.005	0.867	0.17^{c}	0.21^{b}	0.24^{a}	0.007	<0.001	0.964	<0.001	0.309
WB_{Pd} (g/d)	43.4	44.6	1.95	0.655	50.4^{a}	45.8^{a}	35.8^{b}	2.39	<0.001	0.868	<0.001	0.356
WB_{Ld} (g/d)	15.2	15.9	1.66	0.757	6.4^{b}	18.2^{a}	22.2^{a}	2.04	<0.001	0.844	<0.001	0.129
WB_{Ld}/WB_{Pd}[4]	0.34	0.36	0.040	0.764	0.07^{c}	0.37^{b}	0.62^{a}	0.05	<0.001	0.654	<0.001	0.725
L/P_{WB}[6]	0.61	0.61	0.015	0.923	0.48^{c}	0.62^{b}	0.74^{a}	0.02	<0.001	0.480	<0.001	0.678
Recovery												
kLys (%)[3]	50.08	49.77	0.821	0.788	48.17^{b}	49.41^{ab}	52.19^{a}	1.005	0.023	0.716	0.008	0.534
$Pd_{carcass}$ (g/d)	127.4	125.4	2.26	0.548	125.9	124.1	129.3	2.77	0.418	0.239	0.390	0.317
$Ld_{carcass}$ (g/d)	140.5	133.3	6.28	0.423	129.5	143.1	138.0	7.69	0.459	0.110	0.444	0.326
$Ld/Pd_{carcass}$[4]	1.11	1.07	0.043	0.510	1.02	1.16	1.08	0.053	0.206	0.397	0.490	0.102
$L/P_{carcass}$[5]	1.02	0.99	0.033	0.490	0.92^{b}	1.06^{a}	1.04^{ab}	0.041	0.036	0.348	0.040	0.102
$Pd_{viscera}$ (g/d)	11.9	11.1	0.32	0.117	10.9	11.5	12.1	0.39	0.14	0.431	0.048	0.904
$Ld_{viscera}$ (g/d)	7.8	7.5	0.39	0.609	7.5	8.3	7.1	0.48	0.248	0.791	0.643	0.609
$Ld/Pd_{viscera}$[4]	0.66	0.68	0.029	0.608	0.68^{ab}	0.73^{a}	0.60^{b}	0.035	0.042	0.479	0.117	0.043
$L/P_{viscera}$[5]	0.49	0.49	0.017	0.931	0.47	0.52	0.47	0.021	0.131	0.626	0.957	0.045
WB_{Pd} (g/d)	139.3	136.6	2.43	0.438	136.8	135.6	141.3	2.98	0.363	0.232	0.289	0.342
WB_{Ld} (g/d)	148.2	140.7	6.53	0.422	137.0	151.4	145.1	8.01	0.452	0.129	0.479	0.299
WB_{Ld}/WB_{Pd}[4]	1.07	1.04	0.041	0.565	1.00	1.12	1.04	0.050	0.207	0.449	0.591	0.092
L/P_{WB}[6]	0.90	0.86	0.029	0.543	0.81^{b}	0.93^{a}	0.91^{ab}	0.050	0.040	0.382	0.049	0.096

[1]Restriction phase: Pigs fed at 110%, 80%, and 60% of SID Lys requirements (NRC, 2012) during the restriction phase; Recovery phase: Pigs fed at 120% of SID Lys requirements (NRC, 2012) during the recovery phase.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Lysine Utilization Efficiency for WB protein growth.
[4]Fat deposition/ Protein deposition for carcass, viscera, and whole body (WB), respectively.
[5]Fat (kg)/ Protein (kg) for carcass and viscera, respectively.
[6] WB Fat (kg) / WB protein (kg).
[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 11.

Effects of gender and dietary treatment on pig carcass, viscera, and whole body (WB) protein deposition (Pd) and lipid deposition (Ld) parameters during the combined restriction and recovery (Weeks1-9), post recovery, and the entire experimental period (wean to market) (where pigs were fed differing Lys concentrations during the restriction and common diets thereafter).

Trait	Gender				Dietary Treatment[1]					*P*-value	Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control	Lys-20%	Lys-40%	SEM	P-value	Diet x Gender	L	Q
Restriction + Recovery[3]												
WB_{Pd} (g/d)	107.5	105.7	1.62	0.438	107.9	105.6	106.2	1.98	0.698	0.232	0.535	0.568
WB_{Ld} (g/d)	10.4.0	99.0	4.36	0.422	93.4	106.9	104.2	5.34	0.181	0.129	0.161	0.222
WB_{Ld}/WB_{Pd}[3]	0.97	0.94	0.036	0.544	0.86[b]	1.02[a]	0.99[ab]	0.044	0.039	0.400	0.048	0.097
kLys (%)[4]	51.88	51.59	0.740	0.785	49.58[b]	51.72[ab]	53.91[a]	0.907	0.007	0.653	0.002	0.985
Post Recovery												
$Pd_{carcass}$ (g/d)	110.7[b]	119.6[a]	2.25	0.011	114.4	117.9	113.2	2.63	0.429	0.268	0.737	0.211
$Ld_{carcass}$ (g/d)	312.0[a]	276.0[b]	10.06	0.019	305.3	276.8	300.0	11.84	0.206	0.435	0.747	0.082
$Ld/Pd_{carcass}$[3]	2.88[a]	2.33[b]	0.123	0.004	2.73	2.40	2.69	0.143	0.217	0.389	0.826	0.085
$Pd_{viscera}$ (g/d)	9.0	9.7	0.26	0.080	9.5	9.2	9.4	0.30	0.709	0.849	0.921	0.413
$Ld_{viscera}$ (g/d)	26.4[a]	23.6[b]	0.82	0.027	25.6	24.1	25.3	0.96	0.491	0.457	0.825	0.243
$Ld/Pd_{viscera}$[3]	3.04[a]	2.45[b]	0.132	0.004	2.76	2.69	2.77	0.154	0.921	0.646	0.958	0.689
WB_{Pd} (g/d)	119.8[b]	129.3[a]	2.35	0.009	123.9	127.0	122.6	2.75	0.506	0.293	0.739	0.265
WB_{Ld} (g/d)	338.4[a]	299.6[b]	10.54	0.016	330.9	300.9	325.2	12.39	0.202	0.412	0.745	0.080
WB_{Ld}/WB_{Pd}[3]	2.88[a]	2.34[b]	0.120	0.004	2.73	2.42	2.69	0.139	0.241	0.391	0.846	0.095
Wean to Market												
$Pd_{carcass}$ (g/d)	104.2[b]	109.4[a]	1.30	0.010	106.9	108.0	105.6	1.52	0.535	0.271	0.527	0.357
$Ld_{carcass}$ (g/d)	219.8[a]	198.5[b]	5.58	0.013	212.6	201.7	213.1	6.53	0.384	0.437	0.952	0.169
$Ld/Pd_{carcass}$[3]	2.13[a]	1.82[b]	0.069	0.005	2.01	1.89	2.03	0.080	0.391	0.381	0.823	0.178
$L/P_{carcass}$[5]	2.07[a]	1.78[b]	0.065	0.005	1.96	1.84	1.98	0.075	0.390	0.378	0.827	0.177
$Pd_{viscera}$ (g/d)	9.7	10.1	0.15	0.072	10.0	9.9	10.0	0.17	0.894	0.845	0.976	0.639
$Ld_{viscera}$ (g/d)	17.46[a]	15.89[b]	0.46	0.024	16.9	16.4	16.7	0.54	0.740	0.391	0.805	0.465
$Ld/Pd_{viscera}$[3]	1.81[a]	1.57[b]	0.058	0.006	1.70	1.67	1.70	0.067	0.921	0.534	0.941	0.692
$L/P_{viscera}$[5]	1.71[a]	1.49[b]	0.053	0.006	1.61	1.58	1.61	0.062	0.916	0.523	0.934	0.683
WB_{Pd} (g/d)	114.0[b]	120.0[a]	1.36	0.008	116.9	117.9	115.5	1.59	0.588	0.301	0.543	0.406
WB_{Ld} (g/d)	237.2[a]	214.4[b]	5.82	0.011	229.5	218.0	229.9	6.82	0.384	0.405	0.970	0.169
WB_{Ld}/WB_{Pd}[3]	2.10[a]	1.80[b]	0.066	0.004	1.98	1.87	2.00	0.077	0.414	0.376	0.833	0.192
L/P_{WB}[6]	1.89[a]	1.63[b]	0.056	0.004	1.79	1.69	1.80	0.066	0.410	0.373	0.848	0.188

[1]Pigs fed at 110%, 80%, and 60% of SID Lys requirements (NRC, 2012) during the restriction phase (weeks 1-3); Pigs fed at 120% of SID Lys requirements (NRC, 2012) during the recovery phase (weeks 4-9); Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]Fat deposition/ Protein deposition for carcass, viscera, and whole body, respectively.
[4]Lysine Utilization Efficiency for WB protein growth.
[5]Fat (kg)/ Protein (kg) for carcass and viscera, respectively.
[6]WB Fat (kg) / WB protein (kg).
[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 12.

Effects of gender and dietary treatment on basic carcass measures for market weight pigs (where pigs were fed commercial diets throughout the grower and finisher phases).

Carcass Quality	Gender				Dietary Treatment[1]						Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	*P*-value Diet x Gender	L	Q
Side Weight (kg)	48.1[a]	45.1[b]	0.50	<0.001	46.9	46.7	46.2	0.62	0.702	0.551	0.422	0.814
Dressing %	87.4	87.0	0.17	0.094	87.3	87.0	87.1	0.20	0.399	0.442	0.381	0.302
Loin Measurements												
Probe Lean (mm)	57.8	59.8	0.84	0.108	59.1	59.3	58.1	0.98	0.671	0.521	0.481	0.584
Probe Fat (mm)	21.7[a]	19.6[b]	0.63	0.035	20.5	20.3	21.2	0.73	0.684	0.421	0.515	0.564
Loin Length (mm)	103.2[b]	106.8[a]	0.72	0.002	105.2	105.6	104.3	0.83	0.526	0.277	0.445	0.403
Loin Width (mm)	69.4[b]	72.4[a]	0.83	0.016	70.7	71.5	70.6	0.96	0.743	0.290	0.956	0.444
Loin Eye Area (mm^2)	5186.7	5564.2	74.67	0.002	5375.9	5429.4	5321.1	86.07	0.675	0.172	0.655	0.446
Ruler BackFat (mm)	20.4[a]	17.7[b]	0.77	0.022	19.3	18.8	19.2	0.89	0.901	0.671	0.899	0.663

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kgBW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[a,b]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 13.
Effects of gender and dietary treatment on carcass dissection of the shoulder for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Carcass Quality	Gender				Dietary Treatment[1]					*P*-value	Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	Diet x Gender	L	Q
Shoulder (%)[3]												
Primal	22.49	22.35	0.150	0.516	22.31	22.39	22.56	0.184	0.622	0.427	0.343	0.845
Rough Butt	10.71	10.44	0.101	0.077	10.51	10.66	10.56	0.117	0.659	0.336	0.793	0.384
Fat	1.36^{a}	1.12^{b}	0.064	0.010	1.27	1.15	1.30	0.073	0.286	0.556	0.765	0.122
Skin	0.60	0.63	0.015	0.252	0.59	0.60	0.64	0.017	0.171	0.232	0.075	0.558
Retail Butt	8.75	8.70	0.107	0.732	8.64	8.91	8.63	0.123	0.203	0.322	0.980	0.076
Lean	7.66	7.69	0.095	0.850	7.62	7.83	7.56	0.110	0.189	0.559	0.685	0.076
Internal Fat	0.59^{a}	0.52^{b}	0.019	0.020	0.53	0.56	0.57	0.022	0.472	0.239	0.227	0.882
Bone	0.50	0.50	0.015	0.741	0.49	0.52	0.49	0.018	0.367	0.452	0.810	0.165
Rough Picnic	11.86	11.78	0.099	0.757	11.78	11.71	11.93	0.114	0.376	0.185	0.349	0.298
Fat	0.62^{a}	0.36^{b}	0.040	$<$0.001	0.48	0.42	0.57	0.047	0.092	0.971	0.190	0.077
Skin	0.79^{b}	0.85^{a}	0.018	0.035	0.81	0.83	0.82	0.021	0.854	0.401	0.695	0.690
Retail Picnic	10.50	10.60	0.113	0.578	10.52	10.51	10.63	0.132	0.789	0.285	0.584	0.678
Lean	7.83^{b}	8.12^{a}	0.094	0.040	7.94	8.02	7.96	0.109	0.858	0.239	0.906	0.591
Internal Fat	0.95	0.88	0.026	0.063	0.92^{ab}	0.84^{b}	0.99^{a}	0.030	0.003	0.954	0.098	0.002
External Fat	0.76	0.69	0.029	0.115	0.75	0.71	0.72	0.035	0.727	0.904	0.542	0.611
Bone	0.88	0.88	0.014	0.674	0.88	0.89	0.87	0.016	0.669	0.204	0.745	0.405
Total Lean	15.48	15.81	0.164	0.192	15.56	15.86	15.52	0.189	0.396	0.370	0.866	0.179
Total Fat	4.29^{a}	3.56^{b}	0.118	$<$0.001	3.94^{ab}	3.67^{b}	4.15^{a}	0.136	0.051	0.787	0.307	0.026
Total Skin	1.38^{b}	1.47^{a}	0.024	0.026	1.40	1.43	1.46	0.028	0.377	0.485	0.165	0.960
Total Bone	1.38	1.38	0.021	0.986	1.37	1.41	1.36	0.024	0.273	0.829	0.692	0.119

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124kg BW.
[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.
[3]All shoulder parameters expressed as a percentage of side weight (kg).
[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 14.

Effects of gender and dietary treatment on carcass dissection of the loin for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

	Gender				Dietary Treatment[1]						Contrast[2]	
Carcass Quality	Barrow	Gilt	SEM	P-value	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	*P*-value Diet x Gender	L	Q
Loin (%)[3]												
Primal	26.78	26.80	0.174	0.935	26.85	26.74	26.78	0.200	0.915	0.276	0.782	0.753
Fat	3.87^{a}	3.13^{b}	0.154	0.003	3.58	3.16	3.75	0.177	0.067	0.621	0.495	0.026
Skin	1.46	1.50	0.023	0.240	1.46	1.50	1.50	0.026	0.371	0.191	0.247	0.425
Trimmed Loin	21.48^{b}	22.20^{a}	0.171	0.007	21.86	22.05	21.61	0.200	0.310	0.657	0.384	0.207
Tenderloin	1.73^{b}	1.86^{a}	0.031	0.006	1.78	1.84	1.77	0.033	0.255	0.148	0.958	0.100
Lean	1.42^{b}	1.55^{a}	0.024	0.001	1.49^{ab}	1.53^{a}	1.43^{b}	0.028	0.056	0.339	0.157	0.048
Fat	0.31	0.30	0.012	0.676	0.27^{b}	0.33^{a}	0.32^{ab}	0.014	0.018	0.696	0.027	0.068
Bone	4.89	5.03	0.070	0.156	4.98	5.06	4.85	0.082	0.217	0.823	0.287	0.163
Backribs	1.44	1.44	0.026	0.929	1.44	1.42	1.47	0.030	0.568	0.110	0.544	0.383
Boneless Loin	14.85^{b}	15.23^{a}	0.122	0.041	15.07	15.11	14.94	0.140	0.672	0.859	0.516	0.542
Lean Trim	2.16	2.32	0.056	0.073	2.25	2.26	2.21	0.066	0.865	0.862	0.726	0.685
Fat Trim	2.90^{a}	2.53^{b}	0.068	0.001	2.73	2.59	2.82	0.078	0.131	0.490	0.375	0.069
Chub	2.37	2.48	0.052	0.162	2.40	2.50	2.38	0.060	0.300	0.694	0.765	0.129
Lean	1.99	2.06	0.062	0.493	1.95	2.15	1.98	0.073	0.125	0.266	0.762	0.045
Fat	0.43	0.45	0.104	0.979	0.45	0.49	0.39	0.121	0.836	0.293	0.722	0.632
Boneless Backs	7.37^{b}	7.96^{a}	0.108	0.001	7.71	7.78	7.50	0.126	0.274	0.341	0.246	0.261
Total Lean	12.96^{b}	13.87^{a}	0.176	0.001	13.40	13.72	13.12	0.203	0.123	0.779	0.345	0.068
Total Fat	7.51^{a}	6.41^{b}	0.240	0.003	7.02	6.58	7.28	0.276	0.203	0.241	0.513	0.096
Total Skin	1.46	1.50	0.023	0.240	1.46	1.50	1.50	0.026	0.371	0.191	0.247	0.425
Total Bone	4.89	5.03	0.070	0.156	4.98	5.06	4.85	0.082	0.217	0.823	0.287	0.163

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg sBW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]All loin parameters expressed as a percentage of side weight (kg).

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 15.

Effects of gender and dietary treatment on carcass dissection of the ham and belly for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Carcass Quality	Gender				Dietary Treatment[1]						Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	*P*-value Diet x Gender	L	Q
Ham (%)[3]												
Primal	25.36	25.56	0.172	0.431	25.52	25.52	25.34	0.197	0.774	0.339	0.531	0.731
Fat	1.90^{a}	1.59^{b}	0.089	0.025	1.80	1.58	1.85	0.103	0.145	0.474	0.758	0.053
Skin	1.85^{b}	1.98^{a}	0.030	0.006	1.91	1.93	1.90	0.035	0.724	0.124	0.859	0.435
Bone	2.16	2.19	0.050	0.650	2.19	2.15	2.18	0.058	0.900	0.529	0.967	0.649
Boneless Ham	19.35	19.73	0.178	0.161	19.54	19.71	19.36	0.205	0.468	0.524	0.540	0.285
Internal Fat	0.65^{a}	0.59^{b}	0.019	0.034	0.62	0.60	0.63	0.022	0.683	0.290	0.944	0.387
Retail Ham	18.69	19.06	0.190	0.202	18.74	19.12	18.76	0.219	0.395	0.383	0.945	0.176
Lean	17.33	17.87	0.234	0.129	17.49	17.93	17.39	0.273	0.341	0.550	0.809	0.150
External Fat	1.36	1.24	0.045	0.061	1.35	1.19	1.35	0.051	0.049	0.353	0.993	0.015
Total Lean	17.33	17.87	0.234	0.129	17.49	17.93	17.39	0.273	0.341	0.550	0.809	0.150
Total Fat	3.91^{a}	3.41^{b}	0.118	0.007	3.78	3.37	3.83	0.136	0.041	0.412	0.806	0.012
Total Skin	1.85^{b}	1.98^{a}	0.030	0.006	1.91	1.93	1.90	0.035	0.724	0.124	0.859	0.435
Total Bone	2.16	2.19	0.050	0.650	2.19	2.15	2.18	0.058	0.900	0.529	0.967	0.649
Belly (%)[3]												
Primal	18.46	18.51	0.252	0.899	18.54	18.57	18.34	0.300	0.838	0.997	0.640	0.717
Skin	2.03	2.17	0.056	0.091	2.07	2.18	2.04	0.064	0.258	0.998	0.798	0.105
SideRibs	4.07	4.10	0.062	0.748	4.17	4.07	4.00	0.071	0.246	0.997	0.097	0.901
Retail Belly	12.37	12.24	0.195	0.658	12.30	12.32	12.30	0.228	0.998	0.997	0.987	0.955
Trimmed Belly	9.81	9.63	0.178	0.477	9.72	9.70	9.73	0.209	0.994	0.835	0.978	0.917
Total Lean	12.37	12.24	0.195	0.658	12.30	12.32	12.30	0.228	0.998	0.997	0.987	0.955
Total Fat	-	-	-	-	-	-	-	-	-		-	-
Total Skin	2.03	2.17	0.056	0.091	2.07	2.18	2.04	0.064	0.258	0.998	0.798	0.105
Total Bone	4.07	4.10	0.062	0.748	4.17	4.07	4.00	0.071	0.246	0.997	0.097	0.901

[1]Pigs fed a commercial grower diet from 52-74 kg of BW, a commercial grower-finisher diet from 74-93 kg BW, and a commercial finisher diet from 93- 124 kg BW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]All ham and belly parameters expressed as a percentage of side weight (kg).

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).

Appendix Table 16.

Effects of gender and dietary treatment on subjective and objective meat quality characteristics for pigs at market weight (where pigs were fed commercial diets throughout the grower and finisher phases).

Loin Chop Measurements	Gender				Dietary Treatment[1]					*P*-value	Contrast[2]	
	Barrow	Gilt	SEM	P-value	Control (n=24)	Lys-20% (n=24)	Lys-40% (n=24)	SEM	P-value	Diet x Gender	L	Q
1 h pH[3]	6.39[b]	6.52[a]	0.043	0.044	6.44	6.44	6.48	0.050	0.827	0.341	0.601	0.748
24 h pH[3]	5.67	5.71	0.023	0.290	5.69	5.69	5.69	0.028	0.981	0.750	0.971	0.848
48 h pH[3]	5.49	5.52	0.022	0.342	5.51	5.51	5.50	0.026	0.964	0.602	0.823	0.881
NPPC Colour (1-6)[4]	3.03	3.14	0.090	0.399	3.00	3.16	3.09	0.103	0.515	0.771	0.514	0.345
Japanese Colour (1-6)[5]	3.07	3.02	0.092	0.729	2.96	3.13	3.06	0.105	0.533	0.702	0.495	0.377
CPQS Colour (1-6)[6]	3.03	3.17	0.117	0.438	3.04	3.08	3.17	0.135	0.803	0.378	0.517	0.901
NPCC Firmness (1-3)[7]	1.92	1.99	0.055	0.378	1.91	1.96	2.01	0.062	0.550	0.047	0.277	0.955
NPCC Wetness (1-3)[8]	1.69	1.87	0.086	0.174	1.75	1.67	1.92	0.100	0.200	0.488	0.236	0.175
NPPC Marbling (1-10)[9]	1.95	1.82	0.153	0.578	1.62	1.87	2.17	0.176	0.098	0.466	0.032	0.912
CPQS Marbling (1-6)[10]	3.34	3.08	0.210	0.422	3.13	3.09	3.41	0.256	0.624	0.816	0.439	0.558
Drip loss (%)	9.36	8.59	0.445	0.251	8.81	9.35	8.77	0.516	0.677	0.213	0.958	0.380
Shear Force 3 d aged (kg)	4.69	4.53	0.177	0.532	4.71	4.61	4.50	0.205	0.771	0.167	0.473	0.993
Shear Force 7 d aged (kg)	4.28	4.02	0.129	0.293	4.15	4.27	4.00	0.184	0.581	0.091	0.560	0.389

[1]Pigs fed a commercial grower-finisher diet from 74-93 kg BW; Pigs fed a commercial finisher diet from 93- 124 kg BW.

[2]Probability of linear (L) and quadratic (Q) effects of diet, respectively.

[3]With average temperature after 1 hour of: 37.4, 37.6, and 37.5± 0.41 °C for Ctl, Lys20, and Lys40, respectively; and after 24 hours of: 3.0, 3.1, 3.1± 0.08 °C, respectively.

[4]Where 1 = pale pinkish gray to white, 2 = grayish pink, 3 = reddish pink, 4 = dark reddish pink, 5 = purplish red, 6 = dark purplish red.

[5]Where 1 = extremely pale pink to gray, to 6 = dark purplish red

[6]Where 1 = pale pinkish gray to white, 2 = grayish pink, 3 = reddish pink, 4 = dark reddish pink, 5 = purplish red, 6 = dark purplish red.

[7]Where 1 = soft – cut surfaces distort easily and are visibly soft, 2 = firm – cut surfaces tend to hold their shape, 3 = very firm – cut surfaces tend to be very smooth with no distortion of shape.

[8]Where 1 = exudative – excessive fluid pooling on cut surfaces, 2 = moist – cut surfaces appear moist, with little or no free water, 3 = dry – cut surfaces exhibit no evidence of free water.

[9]Where 1 = devoid of marbling, to 10 = very abundant marbling.

[10]Where 1= devoid of marbling, to 6 = very abundant marbling.

[abc]Different letters in the same row, within the same category (i.e. gender, dietary treatment), represent statistically significant differences between treatments (main effect of treatment; $P < 0.05$).