Universitat Autònoma de Barcelona

SEMI-PRECISION FEEDING OF NON-CASTRATED GROW-FINISHING PIGS

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de Barcelona

SEMI-PRECISION FEEDING OF NON-CASTRATED GROW-FINISHING PIGS

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Portada dissenyada per **Olga Solà Montrabeta**.

David Solà Oriol, investigador del Departament de Ciència Animal i dels Aliments de la Facultat de Veterinària de la Universitat Autònoma de Barcelona i **Jaume Coma Subirà**, director de nutrició i investigació del Grup Vall Companys,

CERTIFIQUEN:

Que la memòria titulada "**Semi-precision feeding of non-castrated grow-finishing pigs**", presentada per Pau Aymerich Montrabeta amb la finalitat d'optar al grau de Doctor en Veterinària, ha estat realitzada sota la seva direcció i, considerant-la acabada, autoritzen la seva presentació perquè sigui jutjada per la comissió corresponent.

I perquè consti als efectes oportuns, signen la present a Bellaterra, 16 de setembre de 2020.

Dr. David Solà Oriol

Dr. Jaume Coma Subirà

La present memòria de tesis ha estat realitzada amb el suport del Pla de Doctorats Industrials de la Secretaria d'Universitats i Recerca del Departament d'Empresa i Coneixement de la Generalitat de Catalunya (Ref: 2017 DI 046) juntament amb el conveni de col·laboració entre el Grup Vall Companys i la Universitat Autònoma de Barcelona.

Als meus pares,

Redactada en temps de la COVID-19

Agraïments

Qualsevol projecte, i més una tesis doctoral, requereix la implicació de moltes persones, que en diferent grau han ajudat a que avui pugueu disposar d'aquest exemplar, que resumeix la feina que he fet els últims tres anys. Ja fa gairebé sis anys, vaig conèixer al David i al Josep tot buscant un projecte de final de grau que em permetés endinsar-me al món de la recerca en producció animal. Ells, em van obrir les portes del SNIBA i allà vaig començar una trajectòria, que culmina per ara a nivell acadèmic amb aquesta tesi doctoral. Un cop finalitzat, em van animar a marxar a fora, en aquest cas a Wageningen University & Research, on vaig continuar el camí formatiu com a investigador (MSc), amb un enfoc diferent, però que crec que també he plasmat en parts d'aquesta tesi. Finalment, de pràctiques en empresa vaig decidir tornar a Catalunya, concretament a Vall Companys, on en acabar el Jaume em va proposar quedar-m'hi per a desenvolupar aquest projecte de doctorat industrial juntament amb la Universitat Autònoma de Barcelona.

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Resum

Actualment, els sistemes convencionals d'alimentació de porcí pretenen alimentar un porc representatiu de la mitjana de la població, o nivells lleugerament superiors, per assegurar que no s'està limitant el creixement de la població en global. La majoria d'aquests sistemes utilitzen l'alimentació en fases a l'engreix per imitar la disminució de concentració de nutrients requerida lligada a un increment de la capacitat d'ingestió dels porcs a major edat i pes viu. Tanmateix, en una població de porcs d'engreix hi ha altres factors que modifiquen la capacitat de deposició proteica i d'ingestió voluntària de pinso (variabilitat pes viu, sexe, genètica...), i, per tant, també poden modificar els requeriments nutricionals. Per exemple, la variabilitat en pes viu representa un problema en els sistemes de producció tot dins-tot fora, no només per el problema de porcs petits al moment de la càrrega, sinó també perquè comporta una ineficiència i imprecisió dels sistemes d'alimentació en fases. Conseqüentment, l'objectiu d'aquesta tesi doctoral fou descriure les respostes a variacions dels nivells nutricionals del pinso i confirmar si aquestes respostes diferien entre grups de porcs amb diferent capacitat de deposició de teixits i productivitat. Posteriorment, avaluar les implicacions econòmiques i ambientals de sistemes d'alimentació de semiprecisió basats en alimentar aquests grups de forma diferenciada.

Inicialment es va analitzar la influència sobre el creixement i la composició de la canal de factors com la genètica paterna, el sexe, el pes de canal i el dia de càrrega respecte els primers porcs carregats d'un engreix (Capítol 3). La línia paterna sintètica va mostrar un major creixement i capacitat d'ingestió de pinso que la línia Pietrain, que es va traduir en unes canals més grasses. El pes de canal i el nivell d'engreixament de les canals van mostrar una relació positiva, però les femelles eren sempre més grasses que els mascles enters a igualtat de pes de canal. A més, les canals dels últims porcs carregats eren més magres que les dels primers. Posteriorment, l'efecte d'incrementar el rati entre lisina digestible ileal estandarditzada i energia neta (Lis DIS:EN) es va comparar entre grups de porcs

classificats segons el seu pes viu a inici d'engreix (Capítol 4) o sexe (Capítols 5 i 6). Els porcs d'engreix (30-60 kg) classificats per pes viu inicial van mostrar una resposta diferenciada entre grups al incrementar el rati Lis DIS:EN. Els més petits van mostrar una major resposta lineal als increments de lisina al pinso que els més grossos. A més, dels 70 al 100 kg de pes viu, els mascles sencers van mostrar una major resposta lineal que les femelles al incrementar el rati Lis DIS:EN. En conseqüència, els mascles requeriren 0.5 g Lis DIS/Mcal EN més que les femelles per maximitzar el seu creixement.

Reduir la concentració d'energia neta al pinso 190-250 kcal/kg respecte a una dieta de 2450-2550 kcal/kg no va reduir el creixement quan la ingestió d'energia diària no es va veure afectada considerablement (Capítol 7). Tanmateix, es va observar un menor creixement i canals més magres quan els porcs no van poder incrementar suficientment el consum de pinso per superar la reducció d'energia de la dieta. En resum, aquesta dissertació doctoral mostra el potencial de l'alimentació de semi-precisió de porcs d'engreix no castrats basada en l'alimentació diferenciada dels porcs més petits en la fase inicial (30-60 kg) i dels mascles sencers en la fase de finalització (70-100 kg). A més, en el Capítol 8 es presenten i discuteixen els beneficis econòmics d'aquestes estratègies en contraposició als sistemes d'alimentació convencionals en diferents contexts de cost de matèries primeres. Finalment, també s'hi presenta el potencial d'aquests sistemes d'alimentació per a reduir l'excreció de nitrogen quan s'alimenta diferenciadament mascles i femelles en la fase de finalització. En conclusió, els sistemes d'alimentació de semiprecisió de porcs d'engreix per pes inicial o sexe són una estratègia factible per millorar la sostenibilitat dels sistemes de producció porcina en contexts específics.

Resumen

En la actualidad, los sistemas convencionales de alimentación del ganado porcino tienen como objetivo alimentar un cerdo que sea representativo del promedio de la población, o niveles ligeramente superiores, para asegurar que no se está limitando el crecimiento de la población en global. La mayor parte de estos sistemas utilizan la alimentación en fases durante el engorde para imitar la disminución de la concentración de nutrientes requerida en el pienso cuando se incrementa la capacidad de ingestión de los cerdos a mayor edad y peso vivo. Sin embargo, en una población de cerdos de engorde hay otros factores que modifican la capacidad de deposición proteica y la ingestión voluntaria de pienso (variabilidad de peso vivo, sexo, genética…); y, por lo tanto, también pueden modular los requerimientos nutricionales. Por ejemplo, la variabilidad en peso vivo representa un problema en los sistemas de producción todo dentro-todo fuera, no solo por los cerdos pequeños al momento de la carga, sino porque también conlleva una ineficiencia e imprecisión de las estrategias de alimentación en fases. En consecuencia, el objetivo de esta tesis era describir las respuestas a variaciones de los niveles nutricionales de los piensos, y confirmar si estas respuestas diferían entre grupos de cerdos con distinta capacidad de deposición de tejidos y productividad. Subsecuentemente, evaluar las implicaciones económicas y ambientales de sistemas de alimentación de semi precisión basados en alimentar estos grupos de cerdos de forma diferenciada.

Inicialmente, se analizó la influencia de factores como la genética paterna, el sexo, el peso de canal y el día de carga en comparación con los primeros cerdos cargados de un engorde sobre el crecimiento y la composición de canal (Capítulo 3). La línea paterna sintética mostró un mayor crecimiento y capacidad de ingestión de pienso que la línea Pietrain, que resultó en canales más grasas. Se mostró una relación positiva entre el peso de canal y el nivel de engrasamiento de las canales, pero las hembras fueron más grasas que los machos enteros a igualdad de peso vivo. Además, las canales de los últimos cerdos cargados fueron más magras que las de los

primeros. Posteriormente, el efecto de incrementar la ratio entre lisina digestible ileal estandardizada y energía neta (Lis DIS:EN) se comparó entre grupos de cerdos clasificados según su peso a inicio de engorde (Capítulo 4) o sexo (Capítulos 5 y 6). Los cerdos de engorde (30-60 kg) clasificados por peso vivo mostraron una respuesta diferenciada según grupo al incrementar la ratio Lis DIS:EN, con los pequeños mostrando una mayor respuesta al incrementar el nivel de Lis DIS:EN que los cerdos grandes. Asimismo, de los 70 a los 100 kg de peso vivo, los machos enteros mostraron una respuesta lineal mayor que las hembras al incrementar la ratio Lis DIS:EN. Por consiguiente, los machos requirieron 0.5 g Lis DIS/Mcal EN más que las hembras para maximizar su crecimiento.

Reducir la concentración de energía neta en el pienso unas 190-250 kcal/kg respecto a una dieta de referencia de 2450-2550 kcal/kg no resultó en un peor crecimiento cuando la ingestión diaria de energía no se redujo considerablemente (Capítulo 7). No obstante, cuando los cerdos no pudieron incrementar suficientemente el consumo para superar la reducción de densidad energética del pienso, se observó un menor crecimiento y canales más magras. En definitiva, esta disertación doctoral muestra el potencial de la alimentación de semi precisión en cerdos de engorde no castrados fundamentada en la alimentación diferenciada de los cerdos más pequeños en la fase inicial (30-60 kg) y de machos enteros en la fase de finalización (70-100 kg). Igualmente, en el Capítulo 8 se presentan y discuten los beneficios económicos de estas estrategias en contraposición a los sistemas de alimentación convencionales en distintos contextos de coste de materias primas. Por último, también se presenta el potencial de estos sistemas para reducir la excreción de nitrógeno al alimentar de forma diferenciada a machos y hembras. En conclusión, los sistemas de alimentación de semi precisión de cerdos de engorde por peso inicial o sexo son una estrategia factible para mejorar la sostenibilidad de los sistemas de producción porcina en contextos específicos.

Summary

Conventional swine feeding systems usually aim to feed the average pig, or slightly higher nutrient levels to ensure that the overall population growth is not limited. To feed pigs in accordance with their requirements, most swine operations use phase feeding during the grow-finishing phase to match the diminishing dietary nutrient concentration for an increased feed intake at greater age and body weight. However, within a population of pigs there are factors that can modify protein deposition and feed intake potential (body weight variability, sex, sire line…), and consequently influence nutrient requirements. For instance, body weight variability constitutes a challenge in all-in all-out swine production systems not only for the issue of pigs with a low body weight at marketing, but also because it entails an inefficiency and inaccuracy of phase feeding strategies. Therefore, the purpose of this thesis was to describe the responses to varying nutrient levels and confirm whether these responses vary in pigs grouped for having different growth performance or tissue deposition rate. Afterwards, analyze the economic and environmental feasibility of semi-precision feeding systems consisting in feeding those groups differently.

Initially, the influence of factors such as sire-line, sex, carcass weight and marketing day on growth performance and carcass composition was analyzed (Chapter 3). Synthetic sired pigs grew faster and had a higher feed intake compared to Pietrain sired pigs, which also resulted in fatter carcasses. Increasing carcass weight increased carcass fatness, but indistinctly, boars were leaner than gilts. Besides, increasing marketing day, as an indicator of body weight variability, reduced carcass fatness. Afterwards, the effect of increasing standardized ileal digestible lysine to net energy ratio (SID Lys:NE) was compared between pigs of different initial body weight (Chapter 4) and sex (Chapters 5 & 6). Growing pigs (30-60 kg) sorted by their initial body weight showed a different response to increasing dietary lysine. The lightest ones growth performance showed a greater linear improvement when increasing SID Lys:NE than the heavier ones. Moreover, from 70 to 100 kg

body weight, increasing SID Lys:NE improved linearly growth performance and carcass composition of boars in a greater manner than in gilts. Consequently, boars required around 0.5 g SID Lys/Mcal NE more than gilts to maximize their greater potential growth performance.

Reducing dietary net energy concentration 190-250 kcal/kg from a 2,450-2,550 reference diets did not impair growth performance when pigs could reach a sufficient energy intake (Chapter 7). However, if grow-finishing pigs could not overcome the reduced energy density by increasing sufficiently feed intake it resulted in impaired growth and reduced carcass fatness. Summarizing, the present PhD. dissertation provides evidence of the potential of semi-precision feeding to improve the growth performance of the lightest pigs in the growing phase (30-60 kg) whether improve boars performance in the finishing phase (70-100 kg) in a context of non-castration. In addition, in Chapter 8 the economic benefits of semi-precision feeding over conventional strategies in specific raw materials cost scenarios are shown and discussed. Finally, it shows the potential benefits to reduce nitrogen excretion by feeding gilts lower SID Lys:NE without much worsening their growth performance. In conclusion, semi-precision feeding by initial body weight or sex might be a feasible strategy to improve the sustainability of swine production in specific contexts.

Index of contents

Index of tables

Index of figures

Abbreviations

AA	amino acid
ADFI	average daily feed intake
ADG	average daily gain
ANOVA	analysis of variance
BFT	backfat thickness
BIC	Bayesian information criterion
BLQ	broken-line quadratic
BLL	broken-line linear
BW	body weight
BWCAT	body weight category
CI	confidence interval
CL	carcass leanness
CP	crude protein
CW	carcass weight
CY	carcass yield
FCR	feed conversion ratio
G:F	gain to feed
HCW	hot carcass weight
HFT	ham fat thickness
IGF-1	insulin like growth factor-1
IUGR	intrauterine growth retarded
Lp	large pig
LysE	lysine intake per kg gain
MD	marketing day
Mp	medium pig
NE	net energy
NEE	net energy intake per kg gain
PNN	pietrain sire line
QP	quadratic polynomial

SD	standard deviation
SID Lys:NE	standardized ileal digestible lysine
SID Lys:NE	standardized ileal digestible lysine to net energy ratio
SL	sire line
Sp	small pig
SYN	synthetic sire line

CHAPTER 1

General introduction

The expected world population increase in the next decades will entail a greater demand of animal products (Henchion et al., 2014). Nowadays, pork represents the largest meat production in the world (Food and Agriculture Organization of the United Nations, 2018). Therefore, to meet the global demand, a more efficient use of resources, as the ingredients used for swine feed, will be required to increase the sustainability of this production system. In the last decades, the continuous genetic selection has significantly improved swine feed efficiency (Knap and Wang, 2012). However, further improvements in resource use require a more precise assessment of the pig nutritional requirements, which is expected to minimize both excessive nutrient excretion and production costs (Pomar and Remus, 2019). Conventional swine operations commonly use phase feeding to better match the diminishing dietary nutrient density requirements when pigs get older (NRC, 2012). To further improve the current feeding systems, it is necessary to examine different factors that could influence nutrient requirements. Considering these additional factors might have productive, economic, and environmental consequences that will need careful evaluation.

1.1. Swine nutrient requirements and feeding systems

Energy and amino acids (AA) are the costliest constrains in feed formulation. According to Hauschild et al. (2010), AA requirements of growing pigs can be determined empirically for a population of pigs at a specific time or body weight (BW) period, or factorially for an individual depending on its maintenance and production requirements. In both models, lysine is commonly used as a reference for the amino acid (AA) content of the diet because it is the first limiting AA in most swine diets (van Milgen and Dourmad, 2015). In addition, lysine is commonly expressed in relation to the dietary energy density because the latter is one of the main regulators of feed intake (Li and Patience, 2017; Marçal et al., 2019). Therefore, formulating feeds using a ratio between lysine and energy is a method to better express the expected amino acid intake. Factorial requirement estimations have a biological basis which could make them suitable in varying conditions. However, as outlined by Hauschild et al. (2010), the output is highly dependent on the reference animal chosen. These models use potential protein deposition, usually estimated assuming it represents a 16 % of average daily gain (ADG), to determine the g of standardized ileal digestible lysine (SID Lys) required for growth. Therefore, these models could be used to compare the requirements of pigs that have a different protein deposition or feed intake (see section 1.2).

Once the total amount of SID Lys required is known, then the expected feed or energy intake can be used to calculate the dietary SID Lys concentration required (Remus et al., 2019b). Using net energy (NE) intake is a more accurate method because grow-finishing pigs tend to modify their average daily feed intake (ADFI) to maintain a constant NE intake (Li and Patience, 2017). Reducing dietary NE concentration can cause a lower NE intake (Hinson et al., 2011; Quiniou and Noblet, 2012), that impairs ADG (Nitikanchana et al., 2015) when pigs are in the energy dependent phase (Möhn et al., 2000). However, when pigs do reach the same NE intake, then NE concentration might not influence ADG (Cámara et al., 2016a) as long as a ratio between SID Lys and NE is used for formulating the diets (Marçal et al., 2019). In addition, the capacity of pigs to increase their ADFI when fed low NE diets depends on the age, finishing pigs have a greater capacity (Beaulieu et al., 2009), and on the ingredients used. For instance, fibrous ingredients might limit ADFI in a physical manner (Gondret et al., 2014; Li and Patience, 2017).

1.1.1. Conventional vs. precision feeding

In a survey of nine pig integration companies representing a 20% of the Spanish grow-finishing pig production, Agostini et al. (2013b) found that almost all them fed 3 or 4 different feeds along the grow-finishing phase. This strategy, known as phase feeding, is a common commercial feeding strategy that consists in delivering different feeds along the fattening pig life to better match their nutrient requirements. Pigs feed intake increases when they get older, and therefore, the density of some nutrients in the diets, especially amino acids and minerals, is reduced (Menegat et al., 2020b). **Figure 1.1** illustrates an example of a 3 feeds phase feeding strategy for grow-finishing gilts in relation to the SID Lys requirement modelled according to NRC (2012). The main benefits from phase feeding strategies are reducing nitrogen excretions (Han et al., 2001; Dourmad and Jondreville, 2007) and feed costs when the number of phases is correctly adjusted (Pomar et al., 2014). However, if too many feeds are used to better match the animal requirements, this can lead to logistic problems which will finally increase the production costs. Although it is already a practical strategy to minimize nutrient excretion and therefore the impacts of swine production to the environment, it requires a good estimation of the pigs' nutritional requirements.

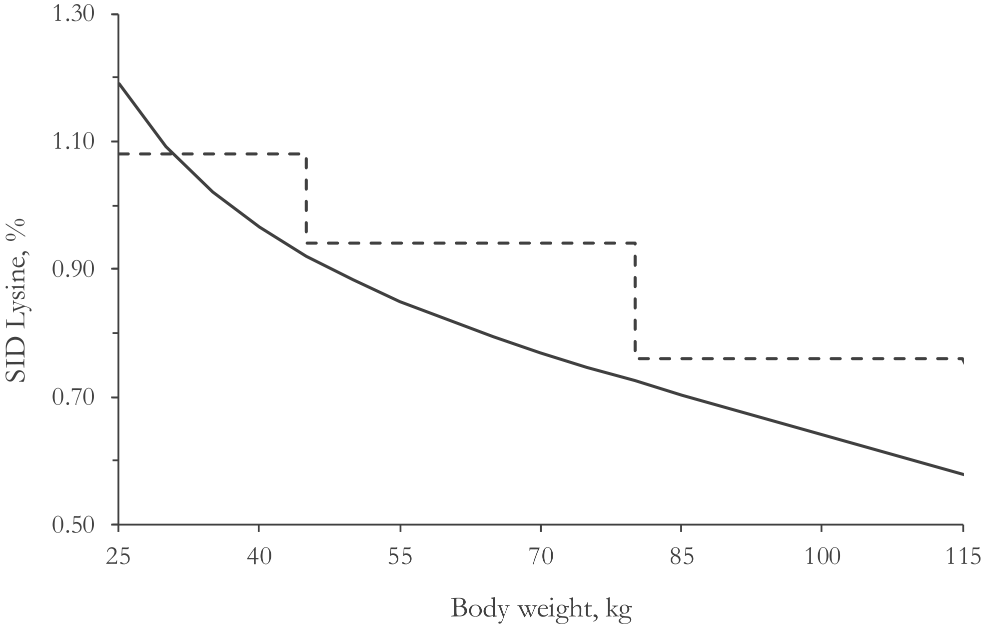

Figure 1.1. Example of a 3 phase feeding strategy (---) for grow-finishing gilts in comparison to the standardized ileal digestible (SID) lysine requirements (—) based on equations in NRC (2012). The energy density of the diet was 3,150 Mcal ME/kg and pigs were fed 1.08, 0.94 and 0.76 % SID between 25-45, 45-80 and 80-115 kg body weight, respectively.

One of the main concerns regarding phase feeding strategies is their inefficiency when BW variability is considered (Patience et al., 2004). Although the groundings of this strategy are feeding pigs in accordance to their potential growth, the best strategy for the average pig might not always be the best for the smallest ones (López-Vergé et al., 2018b). For instance, Brossard et al. (2009) showed that it is necessary to feed at least 110% of the mean population lysine requirements to maximize the whole population performance and reduce growth variability. Besides, not only BW variability, but other important factors affecting protein deposition potential such as sex (Moore et al., 2013) may be considered in phase feeding programs. However, in many contexts those factors are frequently ignored for the increased logistic difficulties that would suppose split-feeding by sex, or for the unknown benefits of doing it.

In recent years, numerous studies have been conducted to determine the benefits of precision feeding over conventional feeding strategies. In a review, Pomar and Remus (2019) defined precision feeding as those techniques used to feed groups of animals or individuals a specific feed composition and quantity at desired times, in order to improve the profitability, efficiency and sustainability of livestock systems. Therefore, precision feeding systems require automated individual or group data collection, at least for BW and feed intake (Banhazi et al., 2012). Afterwards, the data collected will be used as an input in models that allow estimating the pigs real-time individual nutrient requirements in order to maximize growth performance (Cloutier et al., 2015). However, to be worthwhile, these systems must be cost effective and not increase farmer's labor.

Generally, application of precision feeding systems has not represented an improved growth performance, but rather a reduction of the nitrogen and mineral excretions to the environment and feed cost reduction in some studies compared to the conventional feeding systems (Pomar et al., 2010). For instance, Pomar et al. (2014) showed that a daily multiphase strategy based on mixing 2 extreme feeds could reduce nitrogen excretion a 12% and marginally improve ADG compared to a 3-phase feeding strategy. The reduction was the result of a lower protein intake and not of an increased N retention, because feeds were more tailored to the pig daily requirements. On the contrary, Andretta et al. (2014) showed that a multiphase-individual feeding program restricted gain to feed, because of a lower daily lysine intake, but improved phosphorus retention compared to a commercial 3 phase feeding strategy. Therefore, a correct adjustment of the factorial model used to calculate nutrient requirements is necessary to not limit the pigs' growth potential.

Moreover, Remus et al. (2019a) found that basic concepts in swine nutrition as ideal protein cannot be used straightforward in individual precision feeding systems. Although it may need further evaluation, their results suggest that individually precision fed pigs require a greater SID Thr: SID Lys ratio than group phase-fed pigs. Another work from the same authors (Remus et al., 2020) showed that protein deposition curves differed between individual pigs. Consequently, the application of precision feeding techniques would require methods to estimate real time protein deposition potential of individuals, which cannot be easily done nowadays. Although precision feeding systems might have a promising future, a deeper knowledge on the individual responses might be required before these systems can be extensively applied. Furthermore, if the differences in nutrient requirements between groups of pigs known to have non-identical protein deposition can be empirically determined, split feeding by those groups could be a more feasible short-term strategy (Cromwell et al., 1993; López-Vergé et al., 2018b).

1.2. Factors that modify protein deposition and feed intake

Variation is an inherent property of any biological system, and thus, it cannot be completely withdrawn (van Milgen et al., 2012b). Body weight (BW) variability is one of the main concerns in swine production because it has a direct impact on carcass uniformity at the slaughterhouse and packing industries (Alfonso et al., 2010). Nevertheless, other factors such as sex and sire-line might also be considered for their impact on growth performance (Augspurger et al., 2002; Cámara et al., 2014), protein deposition (Carabús et al., 2017), and carcass composition (Gispert et al., 2007; Trefan et al., 2013), although there is no evidence that they affect carcass uniformity (Alfonso et al., 2010). These differences in growth performance and tissue deposition related to the beforementioned factors might entail a different response to dietary SID Lys or NE density (van Milgen et al., 2008).

1.2.1. Sire line

The genotype, which in swine commercial production systems is mainly modified by the sire line, is one of the most important factors of variation between farms. Nowadays, it can be easily modified by producers to best fit their needs: growth, conformation, fatness, leanness, efficiency… Whereas selection indices on carcass composition are usually breeding objectives for the sire lines, dam lines are basically selected for litter performance (Whittemore, 2006). Therefore, although dam line also influences body and carcass composition (Latorre et al., 2008), when the aim is to modify carcass composition and growth, sire line is considered a better alternative (Edwards et al., 2003; Cilla et al., 2006; Schinckel et al., 2012). For instance, Cisneros et al. (1996) reported that a three-bred cross [(Yorkshire × Duroc) × Hampshire] had a lower ADFI and ADG than a commercial hybrid, but with a greater backfat thickness at a similar slaughter BW. The literature reports in general that Pietrain sire lines, the most widely used in the Spanish swine market (Agostini et al., 2013a), are leaner than Duroc (Edwards et al., 2003; Alonso et al., 2009) as a result of a lower ADFI and ADG (Morales et al., 2013). Nevertheless, Latorre et al. (2003) did not found differences in ADFI between Danish Duroc and Pietrain × Large White genotypes.

The differences in growth performance and body composition between sire lines could entail different nutritional requirements as a result of different protein deposition potential (Chiba et al., 2002), ADFI (Liu et al., 2015), digestibility (Morel et al., 2006), or maintenance requirements (Campbell and Taverner, 1988). For instance, Noblet et al. (1999) related the differences in energy maintenance requirements between groups of sire line and sex to their visceral mass. The latter, contributing three times more than muscle mass to maintenance energy requirements per kg of tissue. In a modelling approach, Morel et al. (2008) compared the optimum lysine to energy ratio for fat, normal and lean genotypes. They found important differences between the 3 genotypes, with the lean ones requiring 10-20% more dietary lysine, depending on the modelling assumptions. No differences in the response to energy density between two Pietrain sire lines were observed, although one had a greater growth potential (Cámara et al., 2016a).

Pigs of two genotypes, a commercial crossbred and a fatty purebred, were tested two diets differing in their amino acid and protein content. Whereas the commercial crossbred ADG was impaired when fed the restricted protein diet, the purebred was not because dietary lysine was not limiting its protein deposition. This led to greater intramuscular fat in the commercial crossbred fed a reduced protein diet while no significant effect was found for the fatty autochthonous purebred (Madeira et al., 2013). The results also showed that lowering dietary protein only reduced plasma protein in the commercial crossbred (Madeira et al., 2016). Similarly, Palma-Granados et al. (2017) reported a greater effect in feed efficiency when commercial crossbred pigs were lysine restricted than in Iberian pigs. Chiba et al. (2002) suggested that the sires selected for high lean growth may be more easily lysine restricted. A recent study from Schiavon et al. (2019) did not report a different response to lysine restriction between two sire lines crossed to the same maternal line. The authors suggested that there was no different response due to a similar protein deposition in both sire lines.

Further characterization of each sire line is required to understand the mechanisms underlying the differences in growth performance. Augspurger et al. (2002) showed that the differences in ADFI between sire lines resulted from different feeding patterns. The hybrid line, that had the greatest ADFI ate faster, and although the number of visits per day was similar, their feed intake per visit was greater than the Pietrain line. Schinckel et al. (2012) observed that in addition to the differences in growth performance between sire lines, the differences in ADG between sexes were also different between sire lines. Therefore, a good characterization of the differences in feed intake patterns and lean deposition potential for each sire line and sex is required to optimize their feeding program. Moreover, the improvements in productive performance within each genotype in the last decades could represent greater differences than the ones between genotypes. For instance, Knap and Wang (2012) showed that feed conversion ratio (FCR) was reduced from 3.3 to 2.6, from 1975 to 2010. Consequently, the responses to different nutrients should be constantly evaluated with the improving genotypes.

1.2.2. Body weight variability

Since the adoption of all-in all-out production systems, BW and growth variability have become a concerning issue for its detrimental effect on barn use (Patience et al., 2004) and carcass uniformity (Hennessy, 2005). The greatest part of this variability is related to birth weight (Fix et al., 2010; López-Vergé et al., 2018a) but also to lactation length (Main et al., 2005; López-Vergé et al., 2019), BW at weaning (Douglas et al., 2013) and consequently BW at the end of the grow-finishing phase (Hastad et al., 2020). Recently, Camp Montoro et al. (2020) showed that weaning weight is a good estimator of how long takes pigs to reach a target marketing BW, but that some pigs born small can catch up the heavier ones. However, the capacity to catch up might require being fed a diet which allows them to express their full growth potential. Nevertheless, as shown in **Figure 1.2**, at the start of the grow-

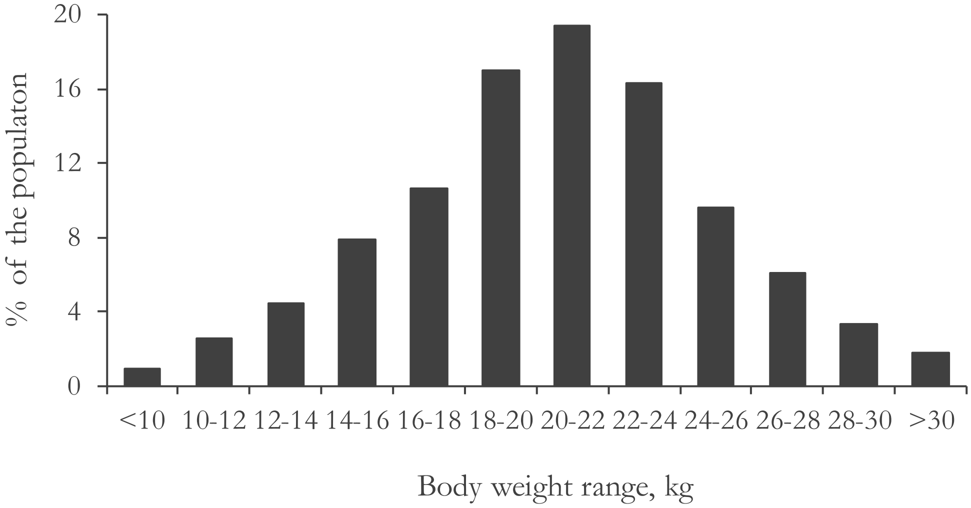

Figure 1.2. Histogram of the body weight (BW) variability in a population of 1,053 [Pietrain x (Landrace x Large White)] pigs (boars and gilts) at the beginning of the grow-finishing period. Average BW was 20.6 ± 4.5 kg (mean ± standard deviation). Unpublished data from Vall Companys (2015).

finishing period there is already a great BW variability, which has severe implications on the variability at the marketing time.

Although no consistent positive effects of sorting pigs by initial BW at both nursery and grow-finishing operations have been reported in the literature, it continues to be a common practice in commercial conditions (O'Quinn et al., 2001; Cámara et al., 2016b). Brumm et al. (2002) discussed that sorting might only be effective when lightweight pigs are offered a diet more tailored to their nutrient requirements. Small pigs or pigs that have a lower growth usually have a lower ADFI (Camp Montoro et al., 2020), even when it is expressed relative to the metabolic BW (Jones et al., 2012; van Erp et al., 2018). Therefore, when a phase-feeding strategy aiming to feed the average pig is applied, the smallest ones eat less amount of the initial feeds, which are more nutrient dense. While those pigs could be restrictedly fed, their heavier counterparts would be overfed, making current phase-feeding strategies inefficient when considering the variability in BW that exists in a pig population (Patience et al., 2004). This hypothesis was confirmed when lightweight pigs were allowed to eat the exact same amount of the initial feeds as the heavier ones (López-Vergé et al., 2018b). Furthermore, **Figure 1.3** illustrates that sorting by BW at the beginning of the grow-finishing phase only impacts average daily gain (ADG) during the first two months, but not afterwards. Therefore, from 66 kg BW or 125 days of age, the BW differences between the two extreme percentiles hardly increased.

The most relevant differences between feeds used in phase-feeding strategies are the concentration of AA and minerals (Menegat et al., 2020b). However, there is no clear answer whether energy should vary when growing pigs get older (NRC, 2012). Brossard et al. (2009) outlined that not all pigs in one herd have the same AA requirements. In a modelling approach using InraPorc (van Milgen et al., 2008) they showed that when the target was to feed the overall population, some pigs growth could be lysine restricted and the differences in ADG between individuals would increase. **Figure 1.4** shows that although ADG was just reduced by 4% in pigs fed

90% of the mean population lysine requirement compared to the ones fed a 100%, already a 37% of the pigs were underfed. Therefore, feeding lysine restricted diets might not impact overall population growth significantly, but can increase the percentage of pigs which need more time to reach the same marketing BW.

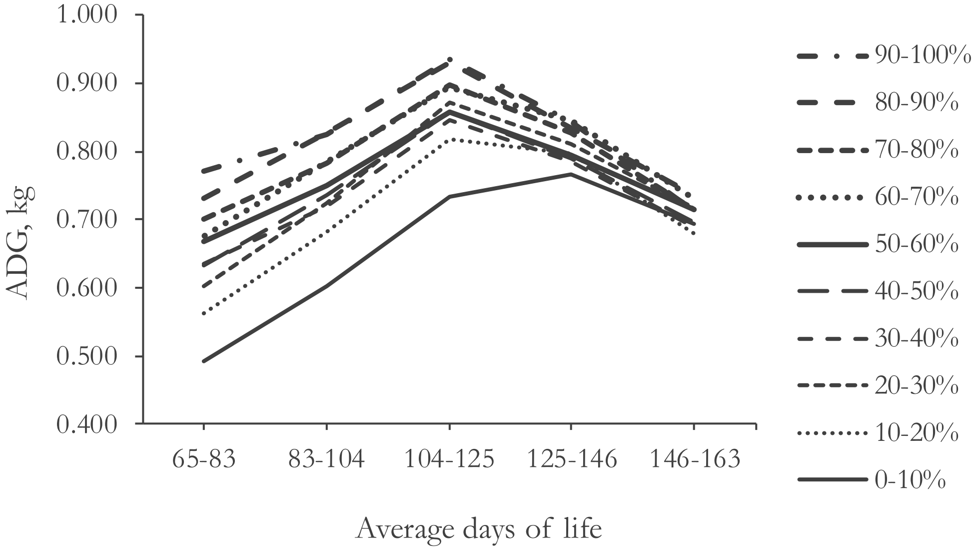

Figure 1.3. Average daily gain (ADG) evolution during the grow-finishing phase of 1,053 [Pietrain x (Landrace x Large White)] pigs (boars and gilts) classified in body weight percentiles at the beginning of the grow-finishing period. Unpublished data from Vall Companys (2015).

Many studies have focused on intrauterine growth retarded (IUGR) piglets instead of focusing in all lightweight pigs because those pigs are associated to specific morphological and physiological traits. In a review, Rehfeldt and Kuhn (2006) analyzed the effects of IUGR on growth and carcass quality. They found that these pigs have a lower number of muscle fibers, compared to their heavier counterparts and that to catch up, small pigs needed a minimum number of skeletal fibers. In addition, IUGR pigs had a greater percentage of internal fat than the heavier ones. By contrast, Jones et al. (2012) found a greater relative lipid body composition in heavy than in light weaned pigs at around 5 weeks post-weaning. Gondret et al. (2005) did neither report differences in adipose tissue content but confirmed a lower number of skeletal muscles and a reduced plasma insulin like growth factor-1 (IGF-1) in light birth weight pigs. Finally, Qi et al. (2019) related post-natal growth retardation with a reduced mRNA levels of growth hormone receptors and IGF-1, and suggested that these pigs are energy deficient as shown by a reduced serum glucose.

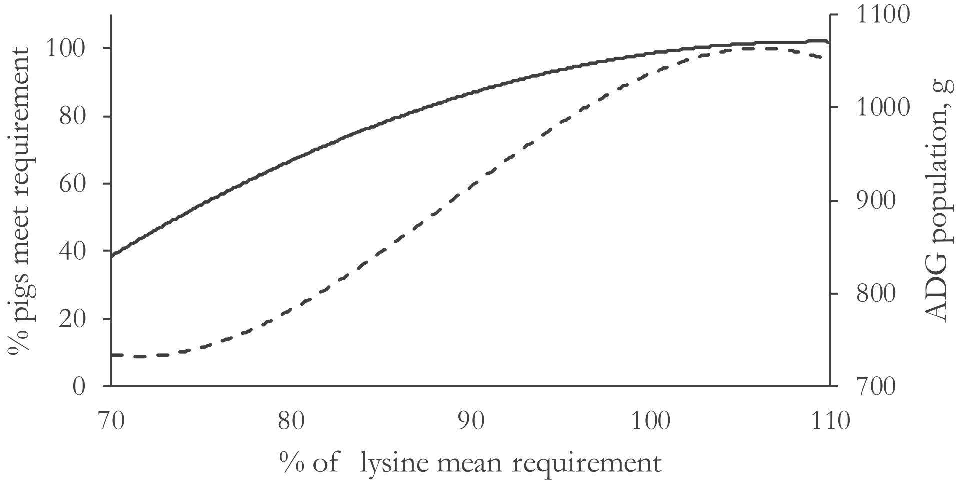

Figure 1.4. Individual growth simulation of a 3 phase feeding strategy using performance data of 192 grow-finishing barrows and gilts between 31.2 and 113.0 kg BW, fed *ad libitum*. The feeds SID Lys content was 0.90, 0.84 and 0.74% and was fed from 0-20, 20-43 and 43-78 days. The straight line (—) represents the average daily gain of the overall population of pigs whereas the dashed line (---) represents the percentage of individual pigs that met their lysine requirement. Adapted from Brossard et al. (2009).

In a preliminary study, we analyzed the effects of growth category on carcass composition of grow-finishing pigs (Aymerich et al., 2018). In this observational study, each truck going to the slaughterhouse was used as the experimental unit, and the ADG was estimated based on the farm initial average BW, the truck marketing BW and the average growing days of the group of pigs marketed. With this data, each truck was classified in one of three categories, each one representing a 33% of the overall dataset. The results (**Figure 1.5**) showed that fast growing pigs had a reduced carcass leanness and therefore increased fat deposition regardless of the BW at which pigs were marketed. Thus, we concluded that first marketed pigs are fatter than last marketed pigs. These results were in agreement with Correa et al. (2006), who also found fatter carcasses in fast than in slow growing pigs.

Some studies have already worked on nutritional interventions for lightweight pigs in the grow-finishing phase, although no consistent results have been found so far. Most of them have focused on increasing dietary nutrient density to offset their reduced ADFI. Hastad et al. (2020) found that increasing dietary energy by increasing fat addition was a worthwhile strategy to improve growth of lightweight pigs. However, the effect was not for a different effect on feed efficiency but from a smaller reduction in ADFI in light than in heavy pigs. As stated previously, ensuring that lightweight pigs eat the same amount of the initial feeds, more amino acid dense, has proven useful to improve the ADG of lightweight pigs (López-Vergé et al., 2018b). Similarly, Liu et al. (2018) observed that low birth weight pigs benefited from a high nutrient density diet (amino acids and energy), mainly in the 25-50 kg BW phase.

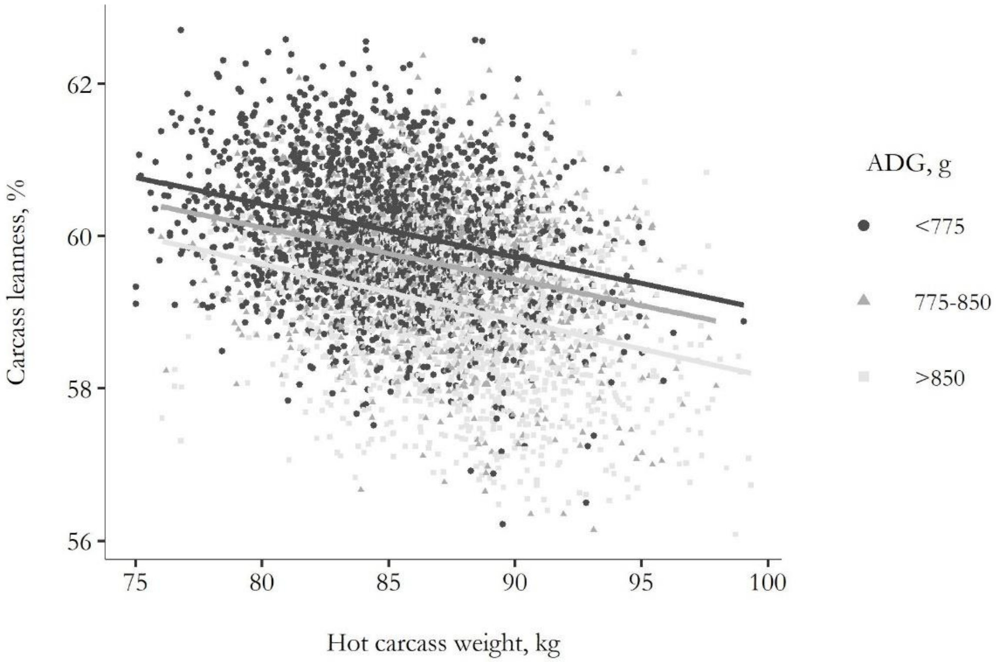

Figure 1.5. Effect of average daily gain (ADG) category (<775, 775-850 or >850 g/d) on carcass leanness when adjusted by hot carcass weight. Each point represents a truck from a single company going to the slaughterhouse in a dataset from two years (2016-2017), including data from 882,697 pigs. The ADG was estimated assuming the farm batch initial body weight (BW), the marketing BW of each truck, and the number of grow-finishing days. Data from Aymerich et al. (2018).

1.2.3. Sex related variation

Sex differentiation will remain an inherent trait in any swine population until techniques like sex-sorting are further developed and become economically feasible (Rath et al., 2015). In most countries, boars are castrated in order to avoid boar taint, especially when pigs are marketed at heavy BW (Fredriksen et al., 2009). Producing boars is economically and environmentally better because of their improved feed efficiency compared to gilts (Rikard-Bell et al., 2013b). Furthermore, barrows have even a worst feed efficiency than gilts because of their greater ADFI and fat deposition (Smit et al., 2017). According to Campbell et al. (1989), the differences in protein deposition between boars and gilts are related to a lower growth hormone production in gilts, because its production is inhibited by estrogens. Thus, when exogenous porcine growth hormone is administered to finishing pigs, the differences between boars and gilts in lean and fat tissue deposition are significantly reduced (Oliver et al., 2003).

The differences in growth performance between boars and gilts are known to start around 40-70 kg BW (Van Lunen and Cole, 1996; Moore et al., 2013; Cámara et al., 2016a), when gilts protein deposition potential begins to be lower than boars (Campbell et al., 1989; Giles et al., 2009). In contrast, there is no agreement whether barrows have a similar (Dunshea et al., 1993) or lower protein deposition than gilts (Carabús et al., 2017). According to Schinckel et al. (2008), barrows have a greater protein deposition potential when they are younger, while gilts greater when they are older. Nevertheless, barrows always have a lower protein deposition relatively to their ADG. Protein deposition of boars, gilts or barrows will depend on their AA intake, as long as pigs are in the amino acid dependent phase (Möhn et al., 2000). **Figure 1.6** shows the differences in protein deposition between boars and gilts after modelling production data with InraPorc software. The curves clearly indicate that before 40 kg BW the differences are hardly significant. However, from 70 kg BW onwards they start to be relevant, and this has a direct effect on the lysine requirements (**Figure 1.7**).

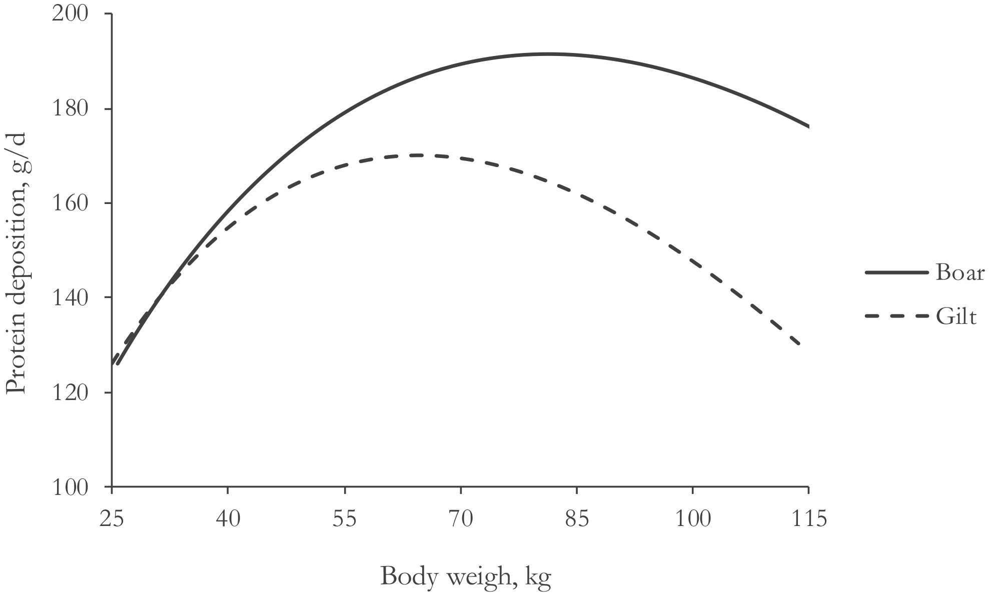

Figure 1.6. Potential protein deposition of boars and gilts between 25 and 115 kg body weight when only energy intake is initially limiting. Results from Quiniou et al. (2010) were modelled using InraPorc software.

Although dietary lysine intake influences protein deposition and growth of pigs of different sexes, an issue that lacks clarity is whether the response will differ in their shape. Krick et al. (1993) showed that the slope of the response to increasing digestible lysine intake on lysine accretion was different between pigs supplemented or not with porcine growth hormone. Thus, the efficiency of using the increasing lysine intake for deposition was greater in pigs treated with porcine somatotropin compared to the untreated ones. However, the level at which they maximized lysine accretion did not differ between the two groups (**Figure 1.8**). In a review, Dunshea et al. (2013) compared the nutrient requirements of immunocastrated, surgically castrated and entire males. They found that immunocastrated males required diets with the same nutrient density as boars until the second immunization. Afterwards, their nutrient requirements better matched the ones of barrows. They also reported that boars had greater dietary lysine requirements than gilts already at 25 kg BW, although the differences were greater at heavier weights.

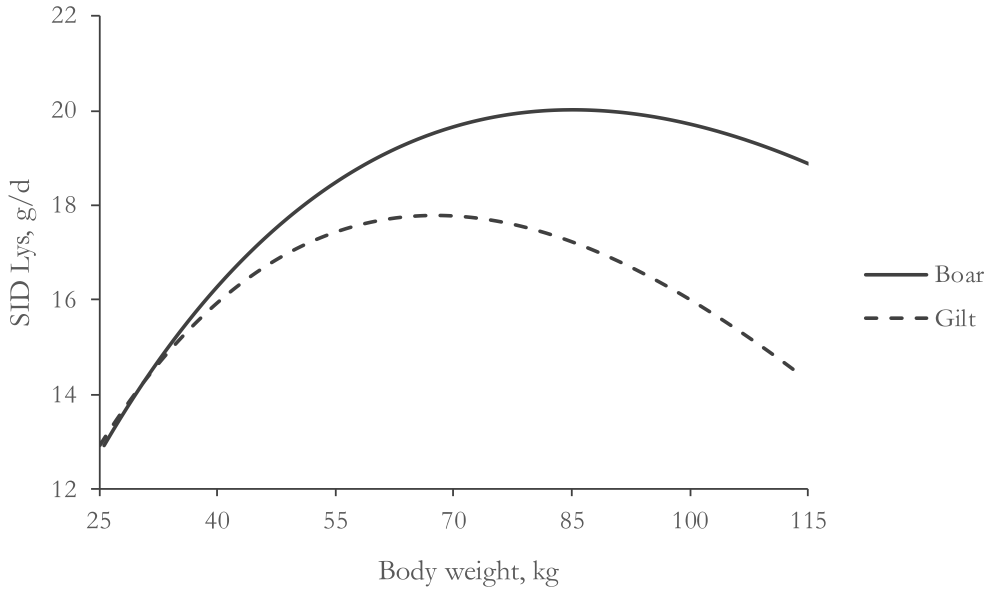

Figure 1.7. Evolution of the standardized ileal digestible lysine (SID Lys) daily requirements for boars and gilts from 25 to 115 kg body weight. Results from Quiniou et al. (2010) were modelled using InraPorc software.

Some works have already studied the differential response to increasing dietary lysine in contexts of non-castration. Campbell et al. (1988) published one of the first studies comparing the response of boars and gilts to increasing protein intake, therefore, to increasing amino acid density in a context without crystalline amino acids. Boars required more protein or lysine than gilts to reach maximum performance, especially at heavier BW. Van Lunen and Cole (1996), in a similar study, did not find significant differences in nitrogen gain per day between boars and gilts, and consequently the response to dietary lysine was neither different. However, boars had a lower lipid gain than gilts (158.6 vs. 180.2 g/d) in the period from 25 to 90 kg BW. King et al. (2000) reported a greater protein and fat deposition for boars from 80 to 120 kg BW, but they did not found evidence of a different response to increasing dietary lysine. Finally, a more recent study from Rikard-Bell et al. (2013a) reported an interaction between dietary lysine and sex (boars vs. gilts) FCR. Whereas males FCR was reduced up to the higher dietary lysine level, gilts reached the lowest FCR at a lower dietary lysine level.

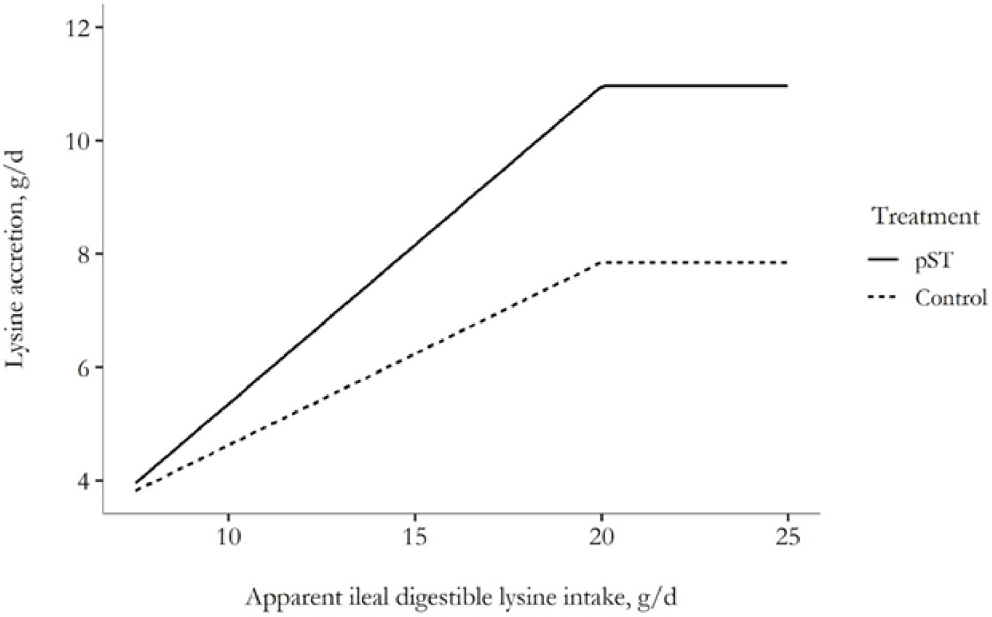

Figure 1.8. Effect of exogenous porcine somatotropin (pST) on the response to increasing apparent ileal digestible lysine intake on lysine accretion in gilts and barrows from 20 to 60 kg body weight. Broken- line linear regressions equations adapted from Krick et al. (1993).

Therefore, the current body of literature does not provide consistency on the response of boars and gilts to dietary lysine, although agrees in most cases that boars have a greater growth potential as a consequence of a greater lean tissue deposition (O'Connell et al., 2006; Moore et al., 2013). Coffey et al. (1995) propounded split-sex feeding of finishing barrows and gilts based on their different response to increasing dietary lysine. They underlined that this practice may only be feasible if the improvements exceed the extra costs associated. However, they expressed that the differences in growth suggested already that penning by sex was a reasonable practice to increase uniformity. Similarly, Tokach et al. (2007) mentioned that split-sex housing might be only feasible when the pig flow enables filling one sex barn in one week. Other authors have also studied the advantages of single versus mixed sex pens. For instance, mixed sex pens did not reduce performance of boars or gilts, but mixed females were sexually more mature (Andersson et al., 2005). However, in a previous study they found a lower ADG when boars and gilts were mixed, that they hypothesized that was a result of the greater sexual activity, and a tendency for lower skatole levels (Andersson et al., 1997).

1.2.3.1. A future without castration?

The increasing social concerns regarding pig castration will be one of the main drivers for the increasing relative importance of non-castrated pig production. In the European Union, the *Council Directive 2008/120/EC* already regulates how castration should be performed (Bee et al., 2015). The difficulties regarding who can perform it and in which conditions entails that the best alternative for most producers will be avoiding castration. Historically, boar production was only located in some specific European countries (British Isles, Spain or Portugal), and just accounted for a 20% of the pig production in 2006 (Fredriksen et al., 2009). As a result of the new regulations, in 2017 countries like Germany, the Netherlands and France already avoided castration in a considerable fraction of their pig production. Consequently, at that time boar production already represented a 34% of the European pig production (Kress et al., 2019).

The main concern when avoiding castration is a lower consumer acceptability related to boar taint, that results from compounds such as androsterone and skatole (Font-i-Furnols, 2012). Although the acceptability of meat with high androsterone varies depending on the country, a study performed in France, Spain and the United Kingdom showed that overall, 22.7% of the consumers had a high sensitivity towards this compounds (Blanch et al., 2012). Moreover, castration not only has negative impacts on welfare due to the surgical process itself, but it reduces welfare problems related to aggressive behaviors such as mounting when pigs get older (Von Borell et al., 2009). Regarding meat quality, the impact of castration may be considered positive or negative depending on the target product. It increases fat deposition, both subcutaneous and intramuscular, and consequently reduces carcass leanness (Gispert et al., 2010). Although a minimum subcutaneous fat thickness may be necessary for some high quality products such as dry-cured hams (Čandek-Potokar and Škrlep, 2012), consumers do generally prefer pork with a low fat cover

(Ngapo et al., 2007). Therefore, boars might be more suitable for pork production when boar taint is not a troublesome issue except for some specialties that require a minimum subcutaneous or intramuscular fat content.

Avoiding castration will also benefit pig producers since boars use feed more efficiently for growth than castrated males. Regarding growth rates, the results are more inconsistent. Those discrepancies could be related to different limitations in some nutrients when male pigs are castrated or not (Xue et al., 1997; Quiniou et al., 2010). For instance, as boars have a greater lean but lower fat deposition (Suster et al., 2006) and a lower ADFI (Quiniou et al., 2010), they require a greater amino acid density to reach their potential growth rate (Dunshea et al., 2013). The predominance of castration means that most research did only involve castrated males and entire females. Consequently, only a small fraction of the nutritional research has been done using non-castrated pigs, and it is difficult to find sufficient data on their nutritional requirements. Avoiding castration might not only be an option from the ethics perspective, but also to increase the sustainability of swine production systems by reducing the amount of feed needed to produce 1 kg meat. To achieve it, further research to feed boars more precisely to their requirements for maximum performance is needed.

CHAPTER 2

Background, hypothesis and objectives

The increasing demand in animal products requires a more efficient use of raw materials for feed production. Feed represents the greatest cost in swine production, with energy and AA being the more expensive constrains in feed formulation. Therefore, there is a need to periodically re-evaluate nutrient requirements and model the shape of the effects when those nutrient levels are modified.

The experiments that comprise this PhD. dissertation are part of a collaborative project between Vall Companys Group and the Animal Nutrition and Welfare Service from the Department of Animal and Food Science from Universitat Autònoma de Barcelona. In **Chapter 1**, the effect of factors (sire-line, body weight variability and sex) that modify growth performance and tissue deposition has been introduced. Besides, there is an increasing importance of **non-castrated male pigs** that demands more research focusing on nutrient requirements of those pigs considering their greater protein deposition potential. Consequently, it was hypothesized that pigs that are known to have a different potential of tissue deposition or feed intake might respond differently to varying nutrient levels. Therefore, the purpose of this thesis was to describe the responses to varying levels of AA and energy and determine whether the responses differ in groups of pigs with different growth performance or tissue deposition rates. A thorough analysis of these responses will be useful to improve the economic and environmental sustainability of swine production systems.

Several works have previously studied the benefits of precision feeding strategies over more conventional feeding systems like phase feeding. However, the application of such techniques is not economically feasible nowadays in large-scale swine operations. Therefore, the aim of this thesis was to investigate the potential of feeding strategies (**semi-precision feeding**) that are a step in between conventional and precision feeding strategies, which might be feasibly and easily applied in commercial operations.

The main objectives were:

1. To evaluate the effects of sex, genotype and body weight variability on growth performance and carcass composition
2. To determine whether there is a divergent response to increasing dietary amino acid intake between growing pigs classified in different initial body weight categories.
3. To determine whether there is a divergent response to increasing dietary amino acid intake between finishing boars and gilts.
4. To evaluate the effects of reducing dietary energy content in varying dietary amino acid concentrations.

Chapter 3 analyses the effects of sex, genotype and marketing day, the latter as a measure of body weight variability, on growth performance and carcass composition. Those effects are evaluated in an observational study. In **Chapter 4**, the effect of increasing SID Lys:NE is compared between growing pigs classified in different initial BW categories. Besides, the study provides SID Lys:NE requirements for 28-63 kg BW pigs. In **Chapter 5**, the effects of increasing SID Lys:NE on growth performance and carcass composition are compared between finishing boars and gilts (70-105 kg BW). In addition, the SID Lys:NE requirement to maximize ADG is provided for each sex. Similarly, **Chapter 6** evaluates the divergent response to increasing SID Lys:NE levels between boars and gilts, but in a meta-analysis approach from 70-100 kg BW, to corroborate the results in the previous chapter. Moreover, in **Chapter 7**, the effects of dietary net energy and SID Lys on growth performance and carcass composition in two swine production systems are evaluated. Finally, **Chapter 8** comprises a general discussion focused on the methodology to compare nutrient requirements between groups of pigs. In addition, it includes an evaluation of the responses to different nutrients in different AA and energy price scenarios.

CHAPTER 3

The effects of sire line, sex, weight and marketing day on carcass fatness of non-castrated pigs

The effects of sire line, sex, weight and marketing day on carcass fatness of non-castrated pigs

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Keywords: carcass composition, marketing day, carcass weight, growing pig.

3.1. Abstract

In the context of non-castrated pig production in the EU, it is important to quantify the different factors that affect carcass composition. In this study, a large-scale database was analyzed to assess the effect of two different lean sire lines (SL), sex, carcass weight (CW) and marketing day (MD) on carcass fatness of non-castrated pigs. Marketing day was introduced as a variable to quantify the effect of different growth rates within a farm on carcass composition. Thus, first pigs leaving the farm had a MD of 0. The results showed that the synthetic SL had a higher feed intake and average daily gain than the Pietrain SL, which lead to fatter carcasses. Females were fatter than males in both SL analyzed. For all SL and sexes there was a positive relationship between CW and carcass fatness variables, which was modified by SL and sex. Regarding MD, the results showed a negative relationship between MD and carcass fatness, which was also modified by SL and sex. Summarizing, there are relevant differences in productivity and carcass composition between lean SL, which might be related to changes in feed intake. Additionally, carcass fatness increases with CW and decreases with MD.

3.2. Introduction

Carcass weight and composition uniformity is an important requirement to reduce costs in the meat industry. In recent years, the production of entire pigs has increased in Europe at the expense of castrated animals, as a measure to improve animal welfare. Avoiding castration represents an opportunity to reduce carcass fatness and improve feed efficiency. However, it is necessary to quantify how different factors, both inter- and intra-genetically, influence carcass leanness. Sex is probably the most important intra-genetic factor that affects carcass fatness, with many studies reporting that castration increases carcass fatness (Gispert et al., 2010; Trefan et al., 2013; Carabús et al., 2017). Inter-genetic differences are also very important. The choice of a specific sire line (SL) partially determines the carcass composition of the progeny. For instance, Duroc SL are known to be fatter than Pietrain, whereas Landrace and Large White show intermediate fatness (Edwards et al., 2003; Gispert et al., 2007). Additionally, nutrition, mainly as the relation between ideal protein and energy content, also plays a role in the modification of the carcass composition (Szabó et al., 2001; Rodríguez-Sánchez et al., 2011).

Within the same herd, variability in weight is an important challenge in all-in-all-out systems. In order to slaughter all pigs at the same marketing weight, there can be differences of more than 30 marketing days (MD) between fast and slow growing pigs (Patience et al., 2004; López-Vergé et al., 2018a). Variability in slaughter weight also modifies carcass composition, with a positive relationship between slaughter weight and carcass fatness (Beattie et al., 1999; Latorre et al., 2004). Finally, differences in growth rates have been reported to modify carcass composition. Correa et al. (2006) showed that fast-growing pigs have fatter carcasses than slow-growing pigs, although this effect has not been broadly studied. Therefore, it is hypothesized that MD as a measure of intra-farm growth could have an effect on carcass fatness.

In the European context of non-castration, it is therefore necessary to quantify which differences in carcass composition can be expected due to factors as SL, sex, CW and MD. This study sought to: (1) determine the effect of two lean SL in the productive performance, (2) analyze their differences in carcass composition, the effect of sex and how the effect of CW is influenced by SL and sex, and (3) evaluate the effect of MD on carcass composition as affected by SL and sex.

3.3. Materials and Methods

All the procedures described in this work followed the EU Directive 2010/63/EU for animal experiments.

3.3.1. Dataset

The effects of SL, sex, CW and MD were analyzed in an observational study with 191,658 non-castrated growing pigs from 162 farm batches integrated in a Spanish company (Vall Companys Group), which were slaughtered at the same slaughterhouse (Cárnicas Cinco Villas, Ejea de los Caballeros, Spain). Two SL were evaluated: a Pietrain 100% (PNN) and a Synthetic mix (SYN; 40% Pietrain, 30% Duroc, 25% Large White and 5% Landrace). Both crossbred to Large white × Landrace sows.

Animals were managed within the same farm as a single farm batch (all-in all-out), which was composed of different marketing groups. Each marketing group consisted of pigs that reached the target slaughter weight at the same time and were transported in the same truck to the slaughterhouse. Within the same farm batch, the average period of time between the first marketing group and the last one averaged 33±8 days. To analyze the differences in carcass composition between marketing groups, a variable called MD was calculated. It was the amount of extra growing days in relation to the day when the first marketing group left to the slaughterhouse, which had a MD equal to 0.

The average size of a farm batch was 1932±797 pigs, and the average number of pigs per marketing group was 190±33. In the farm, both sexes, males and females, were housed in the same farm (50:50%). Therefore, it was not possible to differentiate the productive performance of males and females. Nevertheless, that differentiation was possible at the slaughterhouse level. After arrival at the slaughterhouse, pigs rested into lairage pens between 1 and 2 hours. They were stunned with CO2 (88%) for 150 seconds and subsequently scalded and peeled. Afterwards, pigs were eviscerated and splitted using an automatic robotic system with manual supervision.

From the initial dataset (264,520 pigs), only the data that fulfilled the following criteria was finally analyzed: (1) at least three marketing groups for each farm batch, (2) a minimum of 50 pigs for each marketing group and (3) for each marketing group, >70% of individually pigs with carcass composition measurements. Three datasets were created, one for each level analyzed, which was used as observational unit: farm batch, marketing group and individual carcass.

3.3.2. Live performance measurements

After the last marketing group left the farm, close-out data was obtained for each farm batch (all-in all out system). The measurements included average initial body weight (BW) and the amount of feed consumed by the whole herd. Also, the average final BW for each marketing group and the number of days that those pigs had been in the growing farm was measured. With those data, average daily gain (ADG), average daily feed intake (ADFI) and feed conversion ratio (FCR) were calculated. The marketing interval was calculated per farm batch as the difference between the minimum and maximum MD of the marketing groups in that batch. Carcass yield was calculated on a marketing group base, using the final BW and the average carcass weight of that group.

3.3.3. Slaughterhouse measurements

Carcass composition was individually measured in each pig by AutoFom III (Frontmatec Food Technology). The analyzed measurements were carcass leanness (CL), backfat thickness at P2 (BFT) and ham fat thickness at *gluteus medius* (HFT). Ham measurements were included in the analysis for their relevance in Spanish production for the dry-cured industry (Masferrer et al., 2018). Once splitted, paired half-carcasses were weighed together. The sex of the animals, entire males or females, was determined by an operator from the slaughterhouse. No control of boar taint was performed although the pigs were not castrated as it is not a marketing problem for fresh meat at the present slaughter weight in commercial conditions.

3.3.4. Statistical analyses

Live performance data was analyzed by comparing PNN and SYN farm batch data with a t-test for unequal variances. A two-way ANOVA was used to analyze the effect of sex and SL on individual carcass composition. The effect of CW on carcass composition was analyzed in a multiple regression with CW, SL and sex as main factors. The effect of MD in different productive and slaughterhouse measurements was analyzed by performing a multiple linear regression with MD and SL as main effects with marketing group as observational unit. Finally, the effect of

MD on carcass composition was analyzed in a multiple regression model with MD, SL and sex as main factors. In both multiple regression models, only the significant interactions were included in the models. Most of the analyses were carried out using the stats package in R 3.4.1 (R Core Team, 2017). However, slopes from the multiple regressions were calculated per SL or sex using the lsmeans package (Lenth, 2016). Statistical significance was considered at an alpha level of 0.05. Finally, the multiple regressions were used to produce a regression equation for each SL and sex combination to produce figures of BFT as influenced by CW or MD.

3.4. Results

3.4.1. Sire line and sex effects

The live performance of the two SL studied is summarized in **Table 3.1**. Synthetic pigs had a greater ADG than the PNN (+11.7%; *P* < 0.001). This result was related to a greater ADFI (+10.0%, *P* < 0.001) and a smaller improvement in the FCR (-1.5%; *P* < 0.01). Initial average BW was slightly different, but there were no differences in final BW. As SYN grew faster and had a higher initial BW than PNN, the average growing days for SYN pigs was 13 days lower. As expected PNN had a greater carcass yield than SYN (-1.0%; *P* < 0.001). The marketing interval was greater for SYN than PNN (+9.3%; *P* < 0.05).

Table 3.1. Productive performance of the evaluated sire lines (Pietrain and Synthetic)

Item	Pietrain	Synthetic	RMSE[1]	*P* -value	% difference
n (farm batches)[2]	93	69	-	-	-
Initial BW (kg)	19.0	19.9	1.5	<0.001	4.9
Final BW(kg)	111.5	112.5	5.0	0.215	0.9
Growing days (d)	129	116	5	<0.001	-10.4
ADG (g/d)	717	801	47.9	<0.001	11.7
ADFI (g/d)	1699	1869	119	<0.001	10.0
FCR (g/g)	2.371	2.334	0.082	<0.01	-1.5
Carcass yield (%)	79.9	79.1	0.6	<0.001	-1.0
Marketing interval (d)[3]	30	33	8	<0.05	9.3

[1] RMSE, root-mean-square error.

[2] The experimental unit was the average calculation for each farm batch.

[3] Average interval of days between first and last truck leaving the farm.

Table 3.2 provides the SL and sex effect on individual carcass composition. As hypothesized, PNN was leaner than SYN both for the whole carcass and the ham (*P* < 0.001). This result was related to a higher BFT and HFT for SYN (15.4±3.0 and 10.6±2.7 mm, respectively) compared to PNN (14.2± 2.7 and 9.6±2.4, respectively). Regarding sexes, there were significant differences for all the studied variables. Generally, female carcasses were heavier (90.0 vs 89.0 kg; *P* < 0.001) and fatter than males (*P* < 0.001) for all the variables analyzed. The difference between both sexes was of 1.5 and 0.6 mm for HFT and BFT, respectively.

Table 3.2. Effect of sire line (SL) and sex on individual carcass weight and composition

Item[2]	SL		Sex		RMSE[1]	SL	Sex
	Pietrain	Synthetic	Male	Female			
n (carcasses)	109,840	81,046	95,011	95,875	-	-	-
CW, kg	89.6	89.3	89.0	90.0	8.1	<0.001	<0.001
CL, %	64.5	62.6	64.1	63.3	2.6	<0.001	<0.001
HL, %	77.1	74.9	76.5	75.8	2.6	<0.001	<0.001
BFT, mm	14.2	15.4	14.4	15.0	2.8	<0.001	<0.001
HFT, mm	9.6	10.6	9.3	10.8	2.4	<0.001	<0.001

[1] RMSE= root-mean-square error.

[2] CW=carcass weight; CL=carcass leanness; HL=ham leanness; BFT=backfat thickness; HFT=ham fat thickness.

3.4.2. Carcass weight effect

The effects of CW on carcass fatness are reported in **Table 3.3**. As expected, carcass weight showed a negative relationship to CL, whereas a positive relationship with BFT and HFT. The effect was greater in magnitude for HFT than BFT. The relationship between CW and carcass fatness was modified by both SL and sex in the 3 variables analyzed (*P* <0.001). In **Figure 3.1** the BFT regressions lines for each SL and sex combination are plotted. The increase in HFT related to CW was higher in SYN than PNN (0.164 vs. 0.149 mm HFT/ kg CW) and in females than in males (0.172 vs. 0.141 mm HFT/ kg CW). The omission of the triple interaction in the three models for not being significant suggested that the relation between CW and carcass fatness was not affected in a synergistic way by SL and sex. Therefore, the difference in slopes between sexes was equal in both SL. For CL and BFT the interaction of CW with SL and with sex were the same. But for HFT the difference of CW effect was greater for sex than for SL. The carcass composition variable which could be better predicted was HFT (R^2=0.36) followed by BFT (R^2=0.26).

Table 3.3. The effect of carcass weight (CW) on carcass composition as affected by sire line and sex

	Carcass leanness (%)		Back fat thickness (mm)		Ham fat thickness (mm)	
Item	β_i ±SE	*P* -value	β_i ±SE	*P* -value	β_i ±SE	*P* -value
Intercept (β_0)[1]	70.7±0.11	<0.001	0.02±0.10	0.857	-4.43±0.09	<0.001
SYN	0.48±0.13	<0.001	-0.59±0.13	<0.001	-0.32±0.10	<0.01
Male	-1.78±0.13	<0.001	1.36±0.13	<0.001	1.41±0.10	<0.001
SYN * Male	0.11±0.02	<0.001	0.09±0.01	<0.001	-	-
CW effect (kg) [1]	-0.073±0.001	<0.001	0.160±0.001	<0.001	0.164±0.001	<0.001
SYN	-0.027±0.001	<0.001	0.020±0.001	<0.001	0.015±0.001	<0.001
Male	0.027±0.001	<0.001	-0.020±0.001	<0.001	-0.031±0.001	<0.001
SYN * Male	-	-	-	-	-	-
R^2	0.17		0.26		0.36	
p-value (F-test)	<0.001		<0.001		<0.001	

SYN, synthetic sire line; SE, standard error.

$$\mu_{\text{Sire Line, Sex}} = \beta_0 + \beta_{\text{SYN}} + \beta_{\text{Male}} + \beta_{\text{SYN*Male}} + CW^*(\beta_{CW} + \beta_{\text{SYN}} + \beta_{\text{Male}} + \beta_{\text{SYN*Male}})$$

[1] Reference was Pietrain female.

3.4.3. Marketing day effect

The effect of MD on productivity and carcass composition is shown in **Table 3.4**. As expected, the growing days increased and the calculated ADG decreased when MD increased ($P < 0.001$). Regarding carcass composition, HFT decreased ($P < 0.001$) with increasing MD and consequently leanness increased ($P < 0.001$). Final BW also decreased when MD increased ($P < 0.001$), and as there was no effect on carcass yield ($P = 0.509$), the same effect was shown for CW ($P < 0.01$). However, MD had a significant effect on carcass fatness, independently of CW reduction. Percentage of females was greater at greater MD ($P < 0.001$). The numeric difference in ADG between marketing groups in Week 1 and >Week 4 was 221 and 162 g/d for SYN and PNN, respectively, as supported by the interaction of MD and SL ($P < 0.001$).

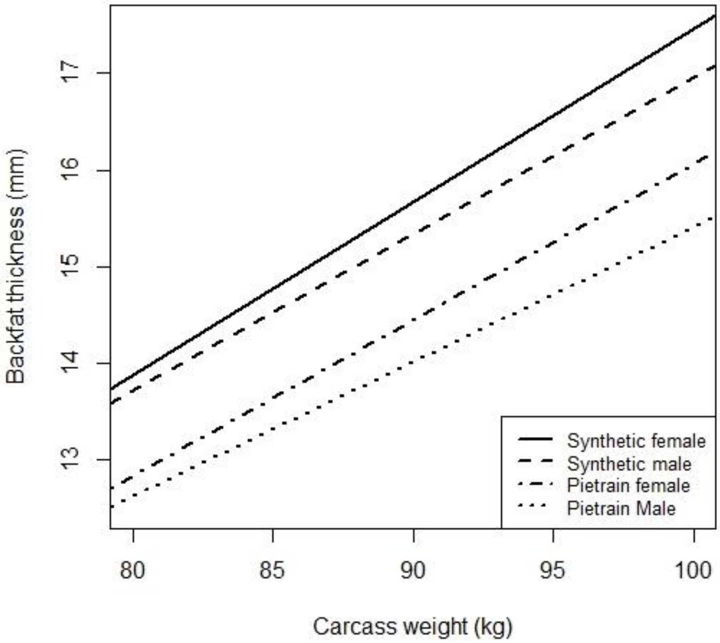

Figure 3.1. Effect of carcass weight on backfat thickness in different sire lines and sexes.

The outputs of the multiple regressions on individual carcass composition as affected by MD, SL and Sex are presented in **Table 3.5**. Regarding fat thickness variables, MD had a negative effect on both BFT and HFT ($P < 0.001$), which was significantly influenced by sex and SL (*P* < 0.001). The relationship between MD and BFT as affected by SL and sex is plotted in **Figure 3.2**. The decrease for PNN was 0.021 and 0.028 mm/day for BFT and HFT, respectively. But the effect of MD was greater in SYN pigs, decreasing 0.030 and 0.037 mm/day for BFT and HFT, respectively. The differences were slightly greater for sex in BFT than HFT. The negative effect of MD on BFT was 0.021 and 0.030 mm/day and on HFT at 0.029 and 0.035 mm/day, for females and males, respectively. Thus, the effect was greater for males compared to females. Finally, there was a positive relationship between MD and CL (*P* < 0.001). But this relationship was different for all sex and SL combinations, showed by a significant triple interaction between CW, sex and SL (*P* <0.001). SYN females were the most affected by MD on the CL (0.026%/MD; *P* <0.001). Generally, the decrease in carcass fatness due to increasing MD was greater in SYN pigs and in males. And the effect of MD was greater on HFT than in BFT.

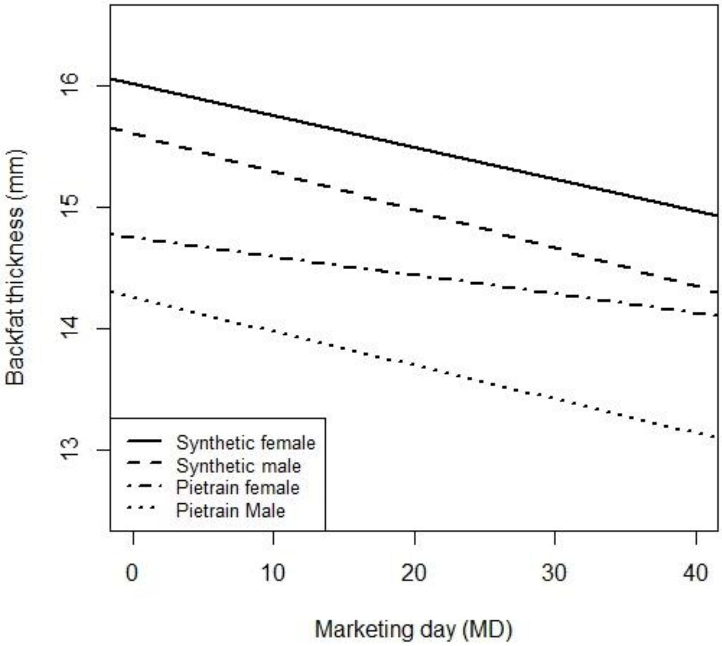

Figure 3.2. Effect of marketing day on backfat thickness in different sire lines and sexes.

Table 3.4. Effect of marketing day (MD) on productivity and carcass composition for two sire lines (SL)

	Pietrain					Synthetic					RMSE	*P*-value		
Item	W 1[3]	W 2	W 3	W 4	>W 4	W 1	W 2	W 3	W 4	>W 4		MD[4]	SL	MD * SL
n (marketing group)[1]	169	125	126	108	109	139	116	87	90	99				
Final BW (kg)	112.7	113.0	111.5	110.9	110.6	113.0	113.4	114.1	112.1	111.2	6.1	<0.01	0.235	0.580
Growing days (d)	117	126	131	137	143	103	111	116	124	132	6.7	<0.001	<0.001	<0.05
ADG (g/d)	823	769	725	691	661	934	866	833	766	713	61	<0.001	<0.001	<0.001
Carcass yield (%)	79.9	80.1	79.9	80.0	79.8	79.2	79.0	79.0	79.0	79.0	0.9	0.509	<0.001	0.620
Carcass weight (kg)	90.0	90.5	89.1	88.6	88.5	89.5	89.6	90.2	88.6	87.9	5.0	<0.01	0.438	0.662
Carcass leanness (%)	64.2	64.3	64.7	64.7	64.6	62.5	62.4	62.4	63.0	62.9	1.0	<0.001	<0.001	0.814
Ham fat thickness (mm)	9.9	9.9	9.4	9.2	9.4	10.8	10.8	10.7	10.2	10.1	1.1	<0.001	<0.001	0.561
Females (%)[2]	45.5	50.4	52.9	54.5	57.3	39.4	46.8	52.6	55.6	61.1	26.0	<0.001	<0.05	<0.05

BW = body weight; ADG = average daily gain; RMSE = root-mean-square error.

[1] The experimental unit was the average calculation per each marketing group.

[2] Percentage of females in each truck reaching the slaughterhouse.

[3] The table shows the results as numerical means per week (W), however the effect is analyzed with the MD continuous variable.

[4] Linear effect of the extra days that those pigs stayed in the growing farm compared to the first marketing group leaving the farm.

Table 3.5. The effect of marketing day (MD) on carcass fatness as affected by sire line (SL) and sex

Item	Carcass leanness (%)		Back fat thickness (mm)		Ham fat thickness (mm)	
	β_i ±SE	*P*-value	β_i ±SE	*P* -value	β_i ±SE	*P* -value
Intercept (β_0)[1]	63.94±0.02	<0.001	14.77±0.02	<0.001	10.77±0.02	<0.001
SYN	-2.15±0.03	<0.001	1.21±0.03	<0.001	1.07±0.02	<0.001
Male	0.61±0.03	<0.001	-0.55±0.02	<0.001	-1.50±0.02	<0.001
SYN * Male	0.34±0.04	<0.001	0.19±0.03	<0.001	0.09±0.02	<0.001
CW effect (kg) [1]	0.011±0.001	<0.001	-0.017±0.001	<0.001	-0.025±0.001	<0.001
SYN	0.015±0.002	<0.001	-0.007±0.001	<0.001	-0.008±0.001	<0.001
Male	0.012±0.001	<0.001	-0.009±0.001	<0.001	-0.007±0.001	<0.001
SYN * Male	-0.016±0.00	<0.001	-	-	-	-
R^2	0.13		0.06		0.14	
p-value (F-test)	<0.001		<0.001		<0.001	

SYN, synthetic sire line; SE, standard error.

$\mu_{\text{Sire line, Sex}} = \beta_0 + \beta_{\text{SYN}} + \beta_{\text{Male}} + \beta_{\text{SYN*Male}} + \text{MD}*(\beta_{\text{MD}} + \beta_{\text{SYN}} + \beta_{\text{Male}} + \beta_{\text{SYN*Male}})$

[1] Reference was Pietrain female .

3.5. Discussion

3.5.1. Sire line effect

The results showed that SYN pigs had a higher performance in terms of ADFI, ADG, and even a better FCR than PNN pigs. Those results are in agreement with Augspurger et al. (2002), who reported that a synthetic sire line that included Large white, Landrace, Duroc and Pietrain could grow faster, without differences in FCR, due to a higher ADFI compared to a Pietrain SL. In that study, the higher ADFI was explained by a higher feed intake per visit, and not for a higher number of visits to the feeder. Similarly, Pietrain pigs have been reported to have lower feed intake per visit compared to other sire lines (Quiniou et al., 1999). The lower FCR of SYN reported in this study can be explained by 13 days less to reach the same slaughter weight, which represent less energy needs for maintenance. However, maintenance requirements may differ depending on SL (Noblet et al., 1999). Finally, the lower carcass yield for SYN could be explained by the 60% of the SL which is composed by Duroc, Large white and Landrace breeds. Previous works have shown that those genetic lines have a lower conformation than Pietrain lines (Gispert et al., 2007).

Consistent with the literature, this study found that there are important differences in carcass composition between the SL studied. The BFT difference of 1.2 mm between SYN and PNN can be explained by the higher ADFI of SYN. Due to a limit in protein deposition capacity, a high ADFI can be related to a higher fat deposition, as a sink of the nutrients which are not used for protein deposition (Hermesch et al., 2000). The differences reported in the present study were similar to previous research, which found BFT differences of 1.0 mm in the last rib when comparing pure Pietrain and pure Duroc boars (Edwards et al., 2003). Therefore, the 30% of Duroc in the SYN SL could explain that SYN carcasses were fatter than PNN. Similarly, Gispert et al. (2007) compared 5 different SL, and showed that Duroc was the second fattest, only surpassed by Meshian SL, whereas Pietrain was the leanest. Landrace and Large white SL were intermediate between Pietriain and Duroc. As a summary, the inclusion of Duroc, Landrace and Large white breeds in a synthetic SL increases carcass fatness as a consequence of a higher feed intake. According to the literature, this increase in feed intake may be related to differences in the feeding behavior.

3.5.2. Sex effect

As expected, entire males were leaner than females (0.6 mm less BFT and 0.8% greater CL). Previous studies had reported BFT differences greater than 2 mm (Sather et al., 1991; Andersson et al., 2005). In our study, the difference was smaller probably because the analyzed SL's (SYN and PNN) were leaner than in those studies. The study from Cámara et al. (2014) also showed a significant difference for BFT of 1.3 mm but not for CL, although a numerical difference between sexes of 0.3 %. Those results are probably the most comparable to this study as the SL used was a crossbred of SYN and a PNN. Regarding HFT, Gispert et al. (2010) reported significant ($p<0.05$) differences in the minimum HFT over the *gluteus medius* between entire males and females (14.17 vs. 10.02 mm, respectively). However, that study could not report significant differences between females and entire males in BFT and CL, although there were numerical differences.

It may be the case that the low consistency of the sex differences in CL is related to the use of different equations to predict CL from AutoFom measurements (Schinckel and Rusk, 2012). Therefore, comparisons between different slaughterhouses should be carefully considered. It is worth to mention that the difference in subcutaneous fat thickness between sexes was greater in the ham than in P2. However, when comparing SL's, the difference was greater for BFT than for HFT. It can thus be suggested that the increase in fat deposition in females compared to entire males is more important in the ham than in the back. The work of Gispert et al. (2010) would support this hypothesis. As a summary, this study showed that females are fatter than entire males for BFT, HFT and CL.

3.5.3. Marketing day effect

The main result of the current study was that carcass fatness decreased at greater MD. The observed decrease in BFT and HFT with MD might be explained by the different growth rates within a farm. This results are in accordance with Correa et al. (2006), who reported that fast growing pigs were fatter than the slow growing ones. In our study, the differences in growth rate between fast and slow growing pigs were 221 and 162 g/d for SYN and PNN, respectively. Those differences were similar to Magowan et al. (2007), reporting a difference of 170 g/d between the top and bottom quartiles from 12 to 20 weeks of age. In addition, Patience et al. (2004) showed that the distribution of BW at the end of the growing period was almost normal, but there was a slight skewing towards the lower BW's. This may explain the decreased BW and CW at greater MD.

In the present study, the effect of MD on carcass leanness was different depending on SL and sex. HFT was more affected by MD than BFT in all SL and sexes. It shows that MD had a greater effect in SYN than in PNN, and in males than in females. For HFT, the decrease in SYN was 0.037 mm/day compared to 0.028 mm/day for BFT in PNN. The decrease in males was 0.035 mm/day compared to 0.029 mm/day in females. That yields a maximum decrease in HFT between fast and slow growing pigs (*Week 1* vs. >*Week 4*) of 0.7 mm. Correa et al. (2006) also reported that HFT was affected by growth rate, sex, and slaughter weight, with a difference of 1.8 mm between fast and slow growing pigs. The difference between the two studies can be explained by the sex, as barrows were used in that study whereas entire males in our work.

Carcass composition is known to be related to nutrient provision and growth potential (Kerr et al., 1995; van Milgen et al., 2000). Therefore, the differences in carcass composition related to MD in this study raises the possibility that pigs with different growth rates currently fed with the same feed have probably different requirements. Feeding them with different feeds according to their specific requirements could increase the efficiency of use of resources. However, these hypotheses should be checked in future research and analyze the potential benefits and drawbacks of a commercial application of split-feeding according to growth potential. As a summary, the current study indicates that there are important differences in carcass composition related to SL, sex, CW and MD in non-castrated pigs.

3.6. Conclusions

This research showed that there are important differences in productive performance between PNN and SYN lines. Synthetic pigs had a higher ADFI and ADG which lead to an increase in carcass fatness. Regarding sex, the study confirmed that females are fatter than entire males in lean SL. As expected, there was a positive relationship between carcass fatness and carcass weight. However, this effect was different for each SL and sex, being greater for SYN compared to PNN, and for females compared to males. The most obvious finding to emerge from this study is that carcass fatness decreases when MD increases, used as a measure of growth variability intra-farm. This effect was also different depending on the specific sire line and sex, with the effect being greater in males than in females.

CHAPTER 4

Increasing dietary lysine impacts differently growth performance of growing pigs sorted by body weight

Increasing dietary lysine impacts differently growth performance of growing pigs sorted by body weight

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Keywords: lysine, growing pig, body weight, requirements.

4.1. Abstract

An experiment was conducted analyzing whether growing pigs classified in different initial body weight categories (BWCAT) have a different response to increasing standardized ileal digestible lysine to net energy ratio (SID Lys:NE), to assess whether light pigs might benefit from being differentially fed. A total of 1170 pigs in pens of 13 were individually weighed, classified in 3 BWCAT (Lp: 32.1 ± 2.8 kg, Mp: 27.5 ± 2.3 kg, and Sp: 23.4 ± 2.9 kg), and afterwards pens were randomly allocated to 5 dietary SID Lys:NE treatments (3.25 to 4.88 g/Mcal) fed over 47 days. Results reported a greater linear improvement of growth and feed efficiency of Sp compared to Lp when increasing SID Lys:NE. Modelling the response to SID Lys:NE using quadratic polynomial models showed that the levels to reach 98% of maximum growth from day 0–47 were 3.67, 3.88, 4.06 g SID Lys/Mcal NE for Lp, Mp, and Sp, respectively. However, due to the overlapping SID Lys:NE confidence intervals at maximum performance, it was not possible to determine if requirements were different between BWCAT. Summarizing, the results suggested that feeding small pigs greater SID Lys:NE than large pigs can improve their performance and increase the efficiency of the overall production system.

4.2. Introduction

Pigs with a low body weight (BW) continue to be a major concern in all-in all-out swine production systems, as they have been associated with a longer time to reach marketing (Magowan et al., 2007; Beaulieu et al., 2010; He et al., 2016), a greater mortality rate (Larriestra et al., 2006; Magowan et al., 2007; He et al., 2016), and the resulting inefficiency of phase feeding strategies (Patience et al., 2004). The latter, being a widespread feeding system, aims to mimic the reduction in the optimal concentration of lysine in the diet required for growth with increasing BW (NRC, 2012; Pomar et al., 2014; Menegat et al., 2020b). Practical application of phase feeding programs consists in delivering a specific amount of each feed to the farm, aiming to fulfill the requirements of the average pig. However, as light pigs are known to have a lower feed intake than their heavier mates (Jones et al., 2012;

Douglas et al., 2014b; Paredes et al., 2014; van Erp et al., 2018), they might eat a lower amount of the first feeds, and therefore less lysine during the early stages both in the nursery and growing facilities. Even though phase feeding focuses on feeding pigs more precisely (Menegat et al., 2020b), the inherent BW variability of swine production systems (López-Vergé et al., 2018a) might represent that the requirements of the lightest pigs might not be fulfilled when applying this strategies (Brossard et al., 2009).

Inconsistent results regarding whether light pigs have a lower feed intake when expressed relative to metabolic BW (Jones et al., 2012; Paredes et al., 2014; van Erp et al., 2018) suggest that in addition to a lower BW, there might be other factors involved. Besides, contradictory results have been reported regarding whether lightweight pigs deposit more body fat as a consequence of their limited number of muscle fibers (Rehfeldt and Kuhn, 2006) or have a greater relative lean tissue content (Correa et al., 2006; Jones et al., 2012; Aymerich et al., 2018; López-Vergé et al., 2018b; Aymerich et al., 2019). The reduced feed intake might entail that a greater proportion of the ingested energy is retained as protein (Jones et al., 2012), but the issue might not be so straightforward if, as suggested by some studies, those pigs had an increased lysine catabolism (Moehn et al., 2004; Pilcher et al., 2015). Furthermore, Jones and Patience (2014) determined that there was a significant positive correlation between average daily gain (ADG) during nursery and nitrogen digestibility. Similarly, other authors have reported a greater lysine disappearance as a percentage of total intake at low energy intakes (Möhn et al., 2000). Consequently, most nutritional studies have focused on feeding high density diets, by increasing amino acid or energy concentrations during the nursery phase, as they considered that early interventions might be more effective (Wolter and Ellis, 2001; Magowan et al., 2011; Douglas et al., 2014b; Huting et al., 2019). However, other studies have also reported positive effects of dietary interventions during the grow-finishing phase (Liu et al., 2018; López-Vergé et al., 2018b; Hastad et al., 2020), and others reported no advantage (Beaulieu et al., 2009; Douglas et al., 2014a). Finally, modelling approaches also support the idea that low BW pigs would require a greater lysine concentration in the diets compared to heavier pigs (van Milgen et al., 2008; NRC, 2012). However, the majority of those studies are based on average population growth performance and requirements are calculated using factorial equations (Remus et al., 2019b). Thus, doubts arise about the use of these models to calculate different requirement for growing pigs within the same population (Pomar and Remus, 2019). Finally, practical application of different feeding plans for pigs from the same population would require one of the following strategies: split feeding of pigs (Tokach et al., 2007) or using precision feeding systems (Pomar and Remus, 2019).

The hypothesis of the present study was that small growing pigs within a batch might require diets with a higher lysine concentration to maximize lysine intake and therefore growth performance compared to their larger mates. Consequently, this study aimed to compare the effects of increasing standardized ileal digestible lysine to net energy ratio (SID Lys:NE) on growth performance among pigs classified in different body weight categories (BWCAT).

4.3. Materials and methods

All the procedures described in this work followed the EU Directive 2010/63/EU for animal experiments.

4.3.1. Experimental design and animals

In this study, the differential effect of SID Lys:NE between BWCAT on growth performance was analyzed in a dose-response trial. The experiment was conducted for 47 days in a commercial-experimental farm from Vall Companys Group (Alcarràs, Lleida), after a 10 day adaptation period. The day of arrival, a total of 1170 growing pigs [(Pietrain × (Landrace × Large white), half boars and half gilts] were grouped in pens of 13 pigs, with a total of 90 non-mixed sex pens, and individually pre-classified in 3 initial BWCAT. Pigs came from a weekly farrowing sow farm, and although were not followed from birth, maximum age difference was 7 days. The first day of the experiment pigs were reclassified, if necessary (e.g., a large pig in a pen of small pigs), as Large (Lp: 32.1 ± 2.8 kg), Medium (Mp: 27.5 ± 2.3 kg) or Small (Sp: 23.4 ± 2.9 kg). Each pen was randomly assigned by BW to one of the 5 treatments (3.25, 3.66, 4.07, 4.47 and 4.88 g SID Lys/Mcal NE), with 6 replicates per treatment and BWCAT, 3 of each sex. Each pen (3 × 3 m) had a half slatted concrete floor, 1 hole wet-dry feeder and an additional nipple waterer on the other side. Ad libitum access to feed and water was ensured during the whole trial. Pigs were individually weighed and monitored using electronic ear tags at the beginning of the trial, at day 26 and at day 47, at the end of the trial. In addition, pen feed intake was measured weekly by knowing the feed on offer and the amount of feed remaining in each trough and corrected if any pig died or was removed from the trial. The day after finishing the experiment, an ultrasound scan (Tecnoscan SF-1 Wi-Fi back fat probe; Tecnovet S.L., Centelles, Spain) was used to measure backfat thickness and loin depth on all pigs of 4 randomly selected Mp pens of each dietary treatment, 2 of each sex, representing a total of 251 pigs.

4.3.2. Feeding and analyses

Two isoenergetic diets (2460 kcal NE/kg) based on maize, wheat, and soybean meal (**Table 4.1**) were formulated to meet or exceed all nutritional requirements, except lysine. Essential amino acids (AAs) were formulated based on the ideal protein ratios (FEDNA, 2013). The low SID Lys:NE diet was 3.25 (Feed A) whereas the high one was 4.88 g SID Lys/Mcal NE (Feed B). Soybean meal inclusion was increased whereas maize inclusion was reduced to increase SID Lys:NE. In addition, the amount of crystalline AA in the diet was also modified. Feed was produced in successive blending batches (5000 kg). After pelleting, feed samples were collected for each blending batch and analyzed for crude protein (CP) (ISO 16634-2:2016) before used to ensure that levels were similar to the calculated. The 2 manufactured feeds were blended in 5 different proportions (**Table 4.2**) at the farm using a robotic feeding system to obtain the experimental treatments (DryExact Pro; Big Dutchman, Vechta, Germany). Furthermore, AA composition, by chromatography of hydrolyzed feed samples, and CP (Method 994.12) (AOAC

International, 2007) were analyzed in a blend of the different batches of the 2 manufactured feeds (**Table 4.3**).

Table 4.1. Ingredient and calculated composition (as fed basis) of the feeds used for blending the 5 dietary treatments.

Ingredient Composition, %	A	B	Calculated Composition [1]	A	B
Maize	45.36	38.35	Dry matter, %	87.56	87.84
Wheat	35.00	35.00	Crude Fiber, %	2.74	2.80
Soybean meal	13.70	19.20	Sugars, %	2.70	2.96
Choice white grease	1.90	2.30	Starch, %	48.90	44.42
Calcium carbonate	1.16	1.18	Ether extract, %	4.19	4.46
Dicalcium phosphate	0.70	0.61	Crude Protein, %	14.49	17.42
Sodium chloride	0.40	0.41	Total Lysine, %	0.89	1.30
Lysine sulphate	0.52	1.03	SID Lysine, %	0.80	1.20
L-Threonine	0.14	0.34	SID Met+ Cys/Lys ratio	0.60	0.60
DL-Methionine	0.07	0.27	SID Thr/Lys ratio	0.68	0.68
L-Valine	-	0.15	SID Trp/Lys ratio	0.20	0.20
L-Tryptophan	0.02	0.08	SID Val/Lys ratio	0.68	0.65
L-Isoleucine	-	0.06	SID Ile/Lys ratio	0.60	0.53
Phytase [2]	0.02	0.02	ME, kcal/kg	3266	3287
Liquid Acid mix [3]	0.30	0.30	NE, kcal/kg	2460	2460
Solid Acid mix [4]	0.40	0.40	SID Lys:NE, g/Mcal	3.25	4.88
Premix VIT-MIN [5]	0.30	0.30	Ashes, %	4.17	4.39
			Total Ca, %	0.68	0.68
			Total P, %	0.44	0.44
			STTD P, %	0.36	0.36
			Cl, %	0.28	0.28
			K, %	0.56	0.64
			Na, %	0.16	0.17

[1] SID: standardized ileal digestible; ME: metabolizable energy; NE: net energy; STTD: standardized total tract digestible.

[2] 6-phytase (750 FTU/kg).

[3] Blend of formic and lactic acid.

[4] Blend of medium chain fatty acids.

[5] Provided per each kg of feed: 4500 IU vitamin A, 2000 MIU vitamin D_3, 15 mg vitamin E, 0.7 mg vitamin K, 1.0 mg vitamin B_1, 4.0 vitamin B_2, 1.2 vitamin B_6, 0.02 vitamin B_{12}, 15 mg niacin, 12 mg pantothenic acid, 107 mg of choline from choline chloride, 90 mg Fe from iron sulphate, 100 mg Zn from zinc sulphate, 50 mg Mn from manganese oxide, 20 mg Cu from copper sulphate, 1.8 mg I from potassium iodide and 0.25 mg Se from sodium selenite.

4.3.3. Calculations and statistical analyses

Body weight, ADG, average daily feed intake (ADFI), feed to gain ratio (F/G), SID Lys/kg gain and feed cost per kg gain were measured and calculated for the 3 phases (Phase 1: 28 to 46 kg BW – d 0 to 26, Phase 2: 46 to 63 kg BW – d 26 to 47, Overall: 28 to 63 kg – d 0 to 47) for each pen. In addition, metabolic ADFI was calculated by correcting ADFI with the metabolic BW ($BW^{0.6}$) (Kil et al., 2013) at the middle of the phase to determine whether there were differences between BWCAT. Statistical analyses were carried out with R (R Core Team, 2019). Models and ANOVA were performed using the *nlme* package (Pinheiro et al., 2019), while contrasts and least square means were computed with the *emmeans* package (Lenth, 2020). The interactive effects between BWCAT and SID Lys:NE were analyzed in a linear mixed model using SID Lys:NE, BWCAT, their interaction and sex as fixed effects, while room was included as a random effect. Orthogonal polynomial contrasts for equally spaced treatments were implemented to evaluate if the linear or quadratic trends to increasing SID Lys:NE for each variable differed between BWCAT. In addition, orthogonal polynomial contrasts were implemented in the same model to each BWCAT. For all variables, a model with the triple interaction between SID Lys:NE, BWCAT and sex was tested, but as it was not significant for any variable, it was not included in the final model. Regarding ultrasound measures, a model without the BWCAT effect was built using the pig as experimental unit. It included SID Lys:NE, sex as fixed effects, individual BW at the end of the trial as a covariate, and room and pen within the room as random effects. Tables present least square means and standard errors computed with the *emmeans* package (Lenth, 2020). Results were considered significant when $P \leq 0.05$ and tendency when $0.05 < P \leq 0.10$.

Moreover, the effects of SID Lys:NE on ADG and feed efficiency were modelled for the *Overall* period modifying the models outlined by Robbins et al. (2006) (Robbins et al., 2006). Fitted statistical models included were the broken-line linear ascending (BLL), broken-line quadratic ascending (BLQ) and quadratic polynomial (QP). Models were built with the *nlme* package of R (Pinheiro et al., 2019), using room and BWCAT nested within the room as the grouping variables for ADG, whereas only BWCAT for feed efficiency as room did not improve the models fit. Models were fitted to predict ADG and gain to feed (G:F), which was preferred to F/G because enabled representing an ascending model. To improve the fitting process ADG was expressed in g and G:F in g/kg. As suggested by Pinheiro and Bates (Pinheiro and Bates, 2000), only fixed effects parameters that accounted by the between-subject variability were left in the random effects formula. The inclusion was based on comparing the Bayesian information criterion (BIC). Besides, a weights statement was included in the G:F models to account for the linear increase in the variance along with the fitted values observed in the residual plots. After fitting, the 3 fitted models were compared using the BIC. Confidence intervals (CI, 95%) for the optimum SID Lys:NE to maximize the response were computed with the *nlme* package for BLL and BLQ. For QP models, the CI of the SID Lys:NE at which the response was maximized were estimated using the delta method in the *msm* package (Jackson, 2011). Additionally, models were fit for the *Overall* period for each BWCAT to compare the estimated SID Lys:NE requirements. Only one model was used for each comparison depending whether the response was linear or quadratic for all the BWCAT. All the models included room as a random effect, and the same procedure as for the general model was used to decide which fixed parameters were included in the random formula.

Table 4.2. Blend ratios, calculated composition, and calculated price of the 5 dietary treatments (as-fed basis) averaged for the inclusion of each feed.

Item	SID Lys:NE g/Mcal [1]				
	3.25	3.66	4.07	4.47	4.88
Feed A, %	100	75	50	25	0
Feed B, %	0	25	50	75	100
SID Lys, %	0.80	0.90	1.00	1.10	1.20
NE, kcal/kg	2460	2460	2460	2460	2460
Cost, €/tn [2]	242.1	251.8	261.6	271.3	281.0

[1] Calculated standardized ileal digestible lysine to net energy ratio. [2] Formula cost.

Table 4.3. Analyzed (A) versus calculated (C) AA composition (%, as fed basis) of the feeds used for blending the 5 dietary treatments.

Item	Feed A		Feed B	
	A	C	A	C
Crude Protein	15.00	14.49	17.31	17.42
Lys	0.92	0.89	1.27	1.30
Met	0.27	0.28	0.48	0.50
Cys	0.26	0.27	0.28	0.30
Met + Cys	0.53	0.55	0.76	0.80
Thr	0.63	0.62	0.89	0.90
Val	0.67	0.64	0.86	0.88
Arg	0.57	0.55	0.69	0.71
His	0.37	0.36	0.40	0.42
Ile	0.57	0.55	0.69	0.71
Leu	1.17	1.16	1.24	1.30

4.4. Results

The analyzed AA content of the experimental feeds was close to the calculated composition (**Table 4.3**). Only significant differences in CP for Feed A were reported, but initial analysis of the different blending batches reported a 14.8 ± 0.16% CP, always below the 0.5 error assumed by the method. Thus, the authors were confident that feeds adequately met the expected composition. Moreover, one Mp observation was removed from *Phase 2* and *Overall*, because from d 26–47 half of the pigs had an ADG ≤ 0.600 kg whereas the average ADG of the other 2 entire male pens of the same SID Lys:NE was 0.901 kg. **Figure 4.1** summarizes the main effects of BWCAT on growth performance. Body weight was different between the 3 BWCAT throughout the experiment ($P < 0.001$), being 70.0, 62.7 and 55.6 kg at the end of the trial for Lp, Mp and Sp, respectively. Thus, the difference in BW between Lp and Sp increased from 8.7 to 14.4 kg, between day 0 and 47, as a result of a greater ADG ($P < 0.001$), and ADFI ($P < 0.001$) of Lp during the entire experiment. Although not reported in **Figure 4.1**, the effect of BWCAT on ADFI was still significant ($P = 0.001$) when the values were corrected by the metabolic body weight, being 0.157, 0.152 and 0.147 kg/kg $BW^{0.6}$, for Lp, Mp and Sp, respectively. Finally, BWCAT had a significant effect on F/G ($P < 0.001$), with Sp being the most efficient (2.06, 2.00 and 1.96 for Lp, Mp and Sp, respectively).

4.4.1. Interactive effects of SID Lys:NE between BW categories

The differential effect of SID Lys:NE between BWCAT is reported as the pairwise comparison of the linear and quadratic trends in each BWCAT. In addition, the same functional forms are reported separately for each BWCAT. The triple interaction n between SID Lys:NE, sex and BWCAT was initially tested reporting a $P > 0.100$ for all the response variables analyzed. Additionally, the linear and quadratic effects of SID Lys:NE on growth performance were compared between entire males and females. Only in *Phase 2* there was a significant interaction in the linear effect between sexes on ADG, F:G, SID Lys/kg gain, and feed cost/kg gain, and consequently also the *Overall* response was different for some variables between sexes. The interaction resulted from only reporting a linear effect of SID Lys:NE on growth performance for entire males. **Table 4.4** illustrates the interactive effects between BWCAT and SID Lys:NE on growth performance of *Phase 1* (28–46 kg). Increasing SID Lys:NE had a linear response ($P < 0.010$) on ADG in all BWCAT, but without a different effect between categories. Although increasing SID Lys:NE linearly reduced F/G in all BWCAT ($P < 0.001$), Sp pigs showed a greater linear reduction than Lp ($P = 0.042$). Similarly, SID Lysine used per kg gain increased more when increasing SID Lys:NE in Lp than in Sp ($P = 0.005$). Finally, the same interaction in the linear response to SID Lys:NE between Sp and Lp was also shown for feed cost per kg gain ($P = 0.019$), as it was linearly reduced in Sp whereas no significant linear effect was reported for Lp.

Interestingly, during *Phase 2* (46–63 kg) there were interactions between BWCAT and the linear effect of SID Lys:NE for almost all response variables except for ADFI, but not for the quadratic effect (**Table 4.5**). The linear increase in ADG as a response to increasing SID Lys:NE was greater for Mp ($P = 0.011$) and Sp ($P = 0.028$), both compared to Lp, for which there was no evidence of a linear effect ($P = 0.217$). Although there was no significant interaction on the effect on

ADFI, Lp showed linear reduction (*P* = 0.006) and Mp a quadratic response (*P* = 0.016) to increasing SID Lys:NE. Regarding F/G, there was an interaction in the linear response to SID Lys:NE between Lp and Mp (*P* = 0.008) and Lp and Sp (*P* = 0.019). Whereas Lp did not show a significant linear reduction on F/G when increasing SID Lys:NE (*P* = 0.540), both Mp and Sp did (*P* < 0.001). Similarly, SID Lys intake per kg gain greatly linearly increased in Lp compared to Mp (*p* = 0.008) and Sp (*P* = 0.019). Finally, increasing SID Lys:NE had a substantial linear negative impact on Lp pigs feed cost per kg gain compared to both Mp (*P* = 0.006) and Sp (*P* = 0.017).

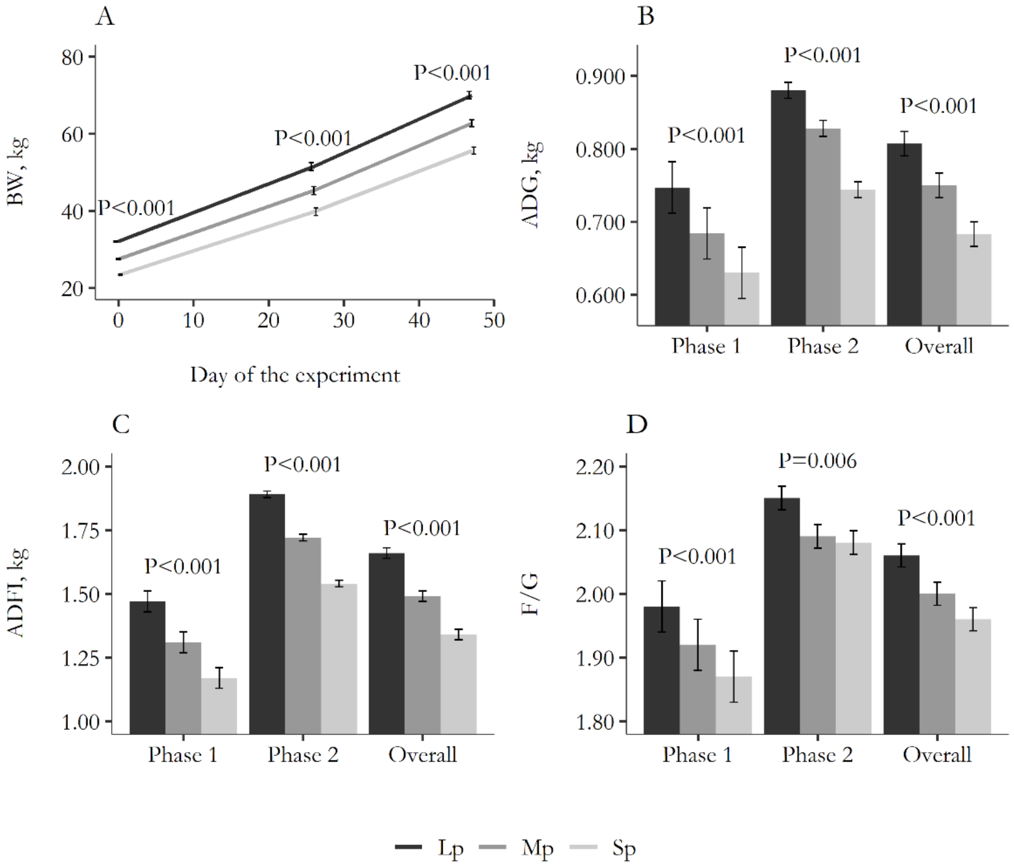

Figure 4.1. Effects of initial body weight category (Large = Lp; Medium = Mp; Small = Sp) on body weight (A), average daily gain (B), average daily feed intake (C) and feed to gain (D) of growing pigs in Experiment 1. Results in A are provided for the 3 weighing days. For B, C and D results are provided for Phase 1 (d 0–26), Phase 2 (d 26–47) and Overall (d 0–47). Error bars represent the standard error of the mean.

The interactive effects between BWCAT and SID Lys:NE on BW are presented in **Table 4.6**. Initially and at day 26, there was an interaction in the quadratic trend between Lp and Mp, explained by the slightly lower initial BW of Mp at 4.88 g SID Lys/Mcal NE, an unexpected effect from the randomization process. At day 26, increasing SID Lys:NE linearly increased BW in the 3 categories, and a quadratic response was shown by Mp. At the end of the trial, increasing SID Lys:NE increased linearly Sp BW ($P < 0.001$), whereas quadratically Mp ($P = 0.001$) and Lp ($P = 0.041$) BW. As there was no evidence of a linear effect on Lp ($P = 0.183$) BW, a tendency ($P = 0.055$) for a different linear response on final BW depending on SID Lys:NE between Lp and Sp was reported.

Results for the *Overall* period (**Table 4.6**) showed significant interactions between BWCAT and the linear effect of SID Lys:NE for all the response variables analyzed except for ADFI. Small pigs showed a greater linear increase ($P = 0.030$) in ADG when increasing SID Lys:NE than Lp whereas there was only a tendency for the same interaction between Mp and Lp ($P = 0.093$). A quadratic effect on Lp ADG was reported ($P = 0.018$) whereas for Mp and Sp both a linear ($P < 0.001$) and quadratic effect were reported ($P = 0.002$ and 0.047, for Mp and Sp, respectively). As in *Phase 1*, there was a tendency ($P = 0.057$) for a different quadratic response on ADFI between Mp and Sp. Increasing SID Lys:NE had a negative linear impact on Lp ADFI ($P = 0.014$), and a quadratic effect was reported for both Lp and Mp ($P = 0.028$ and 0.002, respectively). As expected from results in the other phases, Mp ($P = 0.006$) and Sp ($P = 0.002$) showed a greater linear reduction in F/G when increasing SID Lys:NE. Similarly, a significant interaction was also reported between Lp and Mp ($P = 0.004$) and Lp and Sp ($P < 0.001$) regarding the linear increase of SID Lys per kg gain. The reported value in the 3 BWCAT was numerically equal for the lower ratio (3.25 g/Mcal) but increased more in Lp compared to the Mp and Sp, both showing similar values across treatments. Finally, increasing SID Lys:NE showed a greater negative linear impact on feed cost per kg gain of Lp compared to Mp ($P = 0.004$) and to Sp ($P = 0.001$). Large pigs feed cost increased linearly (*P* < 0.001) whereas there was no evidence of an effect of SID Lys:NE on Mp, and a quadratic effect was reported for Sp (*P* = 0.007). What stands out in this table is that for all three SID Lys intake per kg gain, F/G and feed cost per kg gain the output for the lowest ratio was similar across BWCAT.

4.4.2.Effects of SID Lys:NE on backfat thickness and loin depth

A linear (*P* = 0.003) but not quadratic (*P* = 0.517) effect of increasing SID Lys:NE on backfat thickness of Mp at the end of the trial was observed (**Figure 4.2**). Backfat thickness was reduced from 6.25 to 5.50 mm comparing 3.25 and 4.88 g SID Lys/Mcal NE. Regarding loin depth, neither a linear (*P* = 0.261) or quadratic (*P* = 0.984) effect of SID Lys:NE were reported although it numerically increased from 47.8 to 49.3 mm between the lowest to highest SID Lys:NE tested. No evidence of an interaction (*P* ≥ 0.130) between SID Lys:NE and BW or sex was observed for backfat thickness.

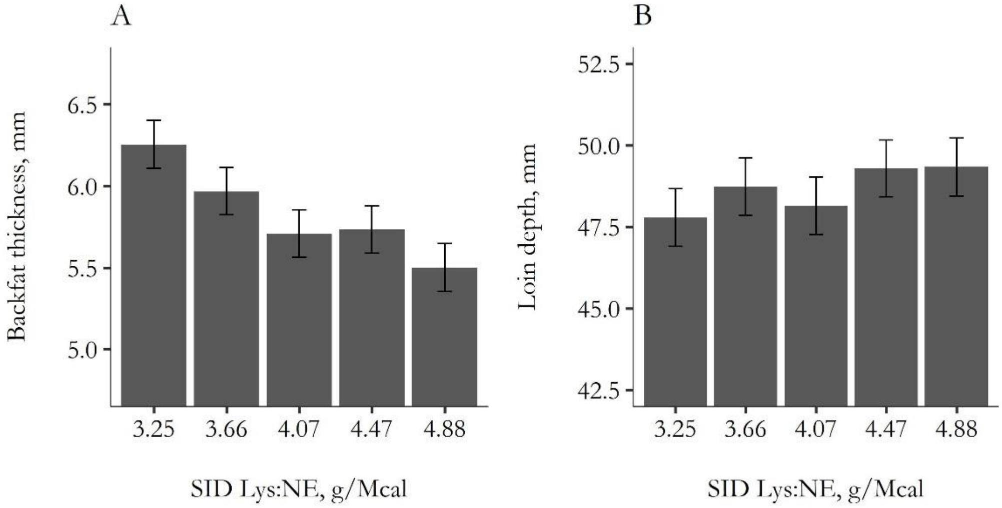

Figure 4.2. Effect of standardized ileal digestible lysine to net energy ratio (SID Lys:NE) on final backfat thickness and loin depth of medium body weight category pigs measured using an ultrasound scan at P2. (**A**) Backfat thickness was linearly (*p* = 0.004) reduced when increasing SID Lys:NE whereas there was no evidence of an effect of SID Lys:NE on (**B**) loin depth (*p* = 0.261).

Table 4.4. Interactive effects between initial body weight category (BWCAT) and standardized ileal digestible lysine to net energy ratio (SID Lys:NE) on growth performance on Phase 1 (d 0–26).

Item [3]	BWCAT [4]	SID Lys:NE, g/Mcal					SEM [5]	*P*-Value			
		3.25	3.66	4.07	4.47	4.88		L × BW [1]	Q × BW [1]	Linear [2]	Quadratic [2]
ADG, kg	Large	0.691	0.738	0.764	0.788	0.757	0.0389	-	Mp/Sp †	0.003	0.027
	Medium	0.622	0.669	0.732	0.713	0.684				0.006	0.001
	Small	0.565	0.631	0.628	0.652	0.676				<0.001	0.401
ADFI, kg	Large	1.46	1.52	1.48	1.50	1.41	0.048	-	Mp/Sp †	0.228	0.035
	Medium	1.30	1.33	1.36	1.32	1.23				0.094	0.007
	Small	1.17	1.21	1.16	1.16	1.17				0.427	0.916
F/G	Large	2.12	2.05	1.94	1.91	1.88	0.046	Lp/Sp *	-	<0.001	0.114
	Medium	2.10	1.99	1.86	1.86	1.80				<0.001	0.011
	Small	2.08	1.93	1.85	1.77	1.73				<0.001	0.021
Lys/gain, g/kg	Large	17.0	18.5	19.4	21.0	22.6	0.47	Lp/Sp **	-	<0.001	0.413
	Medium	16.8	17.9	18.6	20.4	21.6				<0.001	0.153
	Small	16.6	17.3	18.5	19.5	20.7				<0.001	0.319
Cost/gain, €/kg	Large	0.513	0.517	0.508	0.518	0.528	0.0121	Lp/Sp *	-	0.139	0.193
	Medium	0.509	0.502	0.486	0.503	0.507				0.882	0.033
	Small	0.503	0.485	0.483	0.481	0.485				0.063	0.068

Least square means.

[1] Pairwise comparison of the linear (L × BW) or quadratic (Q × BW) effect of SID Lys:NE between BWCAT: † $0.05 < P \leq 0.10$, * ≤0.05, ** ≤0.01.

[2] Orthogonal linear or quadratic contrasts on the effects of SID Lys:NE on each BWCAT.

[3] ADG: average daily gain; ADFI: average daily feed intake; F/G: feed to gain; Cost/gain: feed cost per kg gain.

[4] BWCAT: initial body weight category of the pen was large (Lp, 32.1 ± 2.8 kg), medium (Mp, 27.5 ± 2.3 kg) or small (Sp, 23.4 ± 2.9 kg).

[5] SEM: standard error of the mean.

Table 4.5. Interactive effects between initial body weight category (BWCAT) and standardized ileal digestible lysine to net energy ratio (SID Lys:NE) on growth performance on Phase 2 (d 26–47).

Item [3]	BWCAT [4]	SID Lys:NE, g/Mcal					SEM [5]	*P* -Value			
		3.25	3.66	4.07	4.47	4.88		L × BW [1]	Q × BW [1]	Linear [2]	Quadratic [2]
ADG, kg	Large	0.874	0.923	0.873	0.873	0.856	0.0225	Lp/Mp * Lp/Sp *	-	0.217	0.319
	Medium	0.766	0.847	0.827	0.855	0.846				0.018	0.124
	Small	0.686	0.764	0.751	0.763	0.754				0.057	0.072
ADFI, kg	Large	1.91	1.96	1.88	1.88	1.82	0.029	-	-	0.006	0.217
	Medium	1.69	1.77	1.74	1.75	1.66				0.340	0.016
	Small	1.53	1.58	1.56	1.52	1.53				0.490	0.415
F/G	Large	2.19	2.13	2.16	2.16	2.13	0.038	Lp/Mp ** Lp/Sp *	-	0.540	0.717
	Medium	2.22	2.09	2.11	2.05	1.97				<0.001	0.860
	Small	2.24	2.06	2.07	2.00	2.03				<0.001	0.024
Lys/gain, g/kg	Large	17.5	19.1	21.6	23.7	25.6	0.40	Lp/Mp ** Lp/Sp *	-	<0.001	0.877
	Medium	17.7	18.8	21.0	22.5	23.7				<0.001	0.654
	Small	17.9	18.6	20.7	22.0	24.4				<0.001	0.097
Cost/gain, €/kg	Large	0.530	0.535	0.564	0.585	0.600	0.0101	Lp/Mp ** Lp/Sp *	-	<0.001	0.777
	Medium	0.537	0.526	0.551	0.556	0.554				0.043	0.950
	Small	0.541	0.519	0.543	0.542	0.571				0.011	0.042

Least square means.

[1] Pairwise comparison of the linear (L × BW) or quadratic (Q × BW) effect of SID Lys:NE between BWCAT: * $P \leq 0.05$, ** ≤ 0.01.

[2] Orthogonal linear or quadratic (Quad.) contrasts on the effects of SID Lys:NE on each BWCAT.

[3] ADG: average daily gain; ADFI: average daily feed intake; F/G: feed to gain; Cost/gain: feed cost per kg gain.

[4] BWCAT: initial body weight category of the pen was large (L, 32.1 ± 2.8 kg), medium (M, 27.5 ± 2.3 kg) or small (S, 23.4 ± 2.9 kg).

[5] SEM: standard error of the mean. Different SEM for Medium at 4.07 g SID Lys/Mcal NE (1 observation removed). Values were 0.0246, 0.032, 0.042, 0.43 and 0.0110 for ADG, ADFI, F:G, Lys/gain and Cost/gain, respectively.

Table 4.6. Interactive effects between initial body weight category (BWCAT) and standardized ileal digestible lysine to net energy ratio (SID Lys:NE) on body weight (BW) and growth performance on the Overall experiment (d 0–47).

Item [3]	BWCAT [4]	SID Lys:NE, g/Mcal					SEM [5]	*P*-Value			
		3.25	3.66	4.07	4.47	4.88		L × BW [1]	Q × BW [1]	Linear [2]	Quadratic [2]
BW d0, kg	Large	32.0	32.2	31.8	32.2	32.1	0.22	-	Lp/Mp *	0.597	0.679
	Medium	27.3	27.6	27.7	27.7	27.1				0.596	0.015
	Small	23.5	23.3	23.6	23.4	23.3				0.778	0.796
BW d26, kg	Large	50.0	51.3	51.7	52.7	51.8	1.15	-	Mp/Sp *	0.006	0.073
	Medium	43.5	45.0	46.7	46.2	44.9				0.031	<0.001
	Small	38.1	39.7	40.0	40.4	41.1				<0.001	0.475
BW d47, kg	Large	68.3	70.8	70.0	71.1	69.7	1.12	Lp/Sp †	-	0.183	0.041
	Medium	59.7	62.9	63.9	64.2	62.8				0.002	0.001
	Small	52.7	55.7	55.9	56.7	57.0				<0.001	0.073
ADG, kg	Large	0.773	0.822	0.813	0.826	0.800	0.0210	Lp/Mp † Lp/Sp *	-	0.195	0.018
	Medium	0.689	0.750	0.773	0.777	0.759				<0.001	0.002
	Small	0.621	0.690	0.687	0.706	0.712				<0.001	0.047
ADFI, kg	Large	1.66	1.72	1.66	1.67	1.59	0.029	-	Mp/Sp †	0.014	0.028
	Medium	1.48	1.52	1.52	1.51	1.42				0.096	0.002
	Small	1.33	1.38	1.34	1.32	1.33				0.349	0.591
F/G	Large	2.15	2.08	2.04	2.02	2.00	0.027	Lp/Mp ** Lp/Sp **	-	<0.001	0.172
	Medium	2.16	2.04	1.97	1.94	1.88				<0.001	0.065
	Small	2.15	1.99	1.95	1.87	1.86				<0.001	0.002
Lys/gain, g/kg	Large	17.2	18.8	20.4	22.3	24.0	0.29	L/M ** L/S ***	-	<0.001	0.565
	Medium	17.2	18.3	19.7	21.4	22.5				<0.001	0.795
	Small	17.2	17.9	19.5	20.6	22.4				<0.001	0.053
Cost/gain, €/kg	Large	0.520	0.525	0.532	0.548	0.561	0.0071	L/M ** L/S ***	-	<0.001	0.266
	Medium	0.522	0.513	0.514	0.527	0.528				0.149	0.166
	Small	0.520	0.500	0.509	0.509	0.524				0.417	0.007

Least square means.

[1] Pairwise comparison of the linear (L × BW) or quadratic (Q × BW) effect of SID Lys:NE between BWCAT: † $0.05 < P \leq 0.10$, * ≤0.05, ** ≤0.01.

[2] Orthogonal linear or quadratic (Quad.) contrasts on the effects of SID Lys:NE on each BWCAT.

[3] ADG: average daily gain; ADFI: average daily feed intake; F/G: feed to gain; Cost/gain: feed cost per kg gain.

[4] BWCAT: initial body weight category of the pen was large (L, 32.1 ± 2.8 kg), medium (M, 27.5 ± 2.3 kg) or small (S, 23.4 ± 2.9 kg).

[5] SEM: standard error of the mean. Different SEM for Medium at 4.07 g SID Lys/Mcal NE (1 observation removed). Values were 0.0219, 0.030, 0.028, 0.31 and 0.0075 for ADG, ADFI, F:G, Lys/gain and Cost/gain, respectively.

4.4.3.Modelling the response to SID Lys:NE

The best fitting BLL, BLQ and QP models to describe the effect of SID Lys:NE on ADG and G:F for the entire population from 28–63 kg BW are plotted in **Figure 4.3** (see **Appendix A** for specific equations). Regarding ADG, each model provided different optimum SID Lys:NE to maximize performance. Those were 3.72 g/Mcal (95% CI: [3.58, 3.86]), 3.91 g/Mcal (95% CI: [3.55, 4.27]) and 4.40 g/Mcal (95% CI: [4.21, 4.59]) for BLL, BLQ and QP, respectively. In addition, maximum ADG was reported at 760, 755 and 770 g, and BIC was 911, 905 and 905 for BLL, BLQ and QP, respectively. Therefore, according to the BIC output BLQ and QP were the best fitting models, while BLL showed a slightly poorer fit. With respect to G:F, BLL reported the optimum at 4.29 g/Mcal (95% CI: [4.04, 4.53]), BLQ at 4.77 g/Mcal (95% CI: [4.27, >4.88]), and QP > 4.88 g/Mcal (95% CI: [4.25, >4.88]). As the optimum for the QP model was outside the range of the experiment, it was just considered to be greater than the maximum SID Lys:NE level. Nevertheless, when comparing the CI, the 3 models optimums were overlapped, with the lower boundary between 4.04–4.27 g/Mcal. Finally, BIC was 785 for the BLL, and 774 for both BLQ and QP models. Thus, both quadratic models fitted better the data although a lower CI was reported for the BLL model.

Having modeled the response for the overall population, models were fitted for each BWCAT with the aim to compare the requirements to optimize growth performance in each category. Results presented in **Table 4.6** showed that there was no linear response for Lp pigs, and therefore fitting BLL models to that group was not possible. Consequently, requirements for ADG were compared using QP models, as a significant quadratic trend was reported for all BWCAT. The QP models (**Figure 4.4**) reported that Lp pigs maximized their ADG at 4.29 g/Mcal (95% CI: [3.91, 4.67]), Mp at 4.33 g/Mcal (95% CI: [4.13, 4.53]) and Sp at 4.60 g/Mcal (95% CI: [4.02, >4.88]) (see **Appendix B** for specific equations). As all the CI were overlapped, it was not possible to conclude whether the estimated requirements were different between categories. Although there were not differences in the optimum between Lp and Mp pigs, when comparing the requirements to reach 98% of the maximum ADG those were 3.67, 3.88 and 4.06 for Lp, Mp and Sp, respectively. This might be explained by the different marginal efficiency of increasing SID Lys:NE on each category, greater for Mp than for Lp.

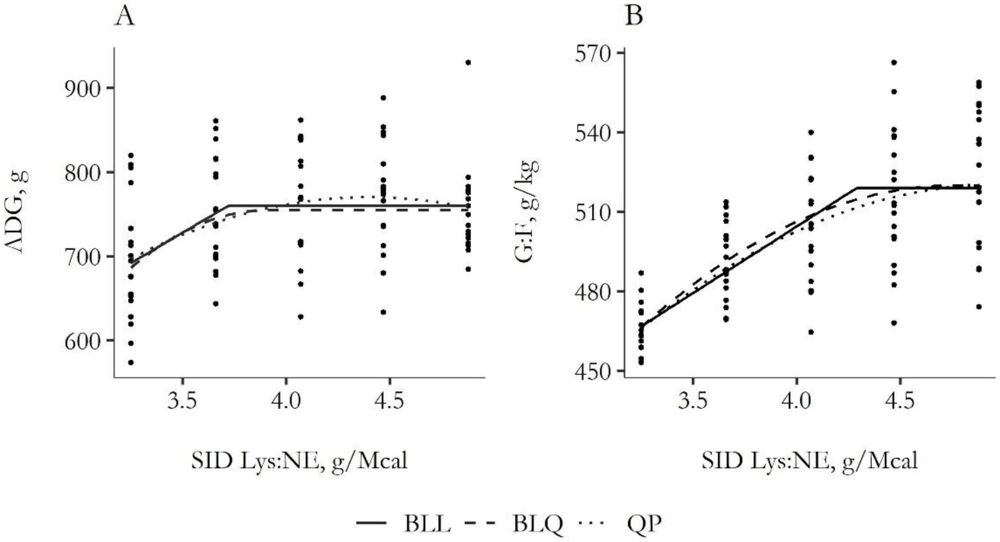

Figure 4.3. Fitted broken-line linear (BLL), broken-line quadratic (BLQ) and quadratic polynomial (QP) regressions models to optimize (**A**) average daily gain (ADG) and (**B**) gain to feed (G:F) as a function of standardized ileal digestible lysine to net energy ratio (SID Lys:NE) from 28–63 kg (Overall phases). For ADG, the BLL model estimated the optimum at 3.72 g/Mcal (95% CI: [3.58, 3.86], BIC = 908), the BQL at 3.91 g/Mcal (95% CI: [3.55, 4.27], BIC = 905) and the QP at 4.40 g/Mcal (95% CI: [4.21, 4.59], BIC = 905). Regarding G:F, BLL estimated the optimum at 4.29 g/Mcal (95% CI: [4.04, 4.53], BIC = 785), BLQ at 4.77 g/Mcal (95% CI: [4.27, >4.88], BIC = 774) and QP > 4.88 g/Mcal (95% CI: [4.25, >4.88], BIC = 774), both outside the range of the experiment.

Regarding feed efficiency, as there was a linear response in all BWCAT, BLL models were preferred to compare the requirements to maximize G:F. Large pigs maximized their feed efficiency at 4.29 g/Mcal (95% CI: [3.68, >4.88]), Mp at 4.75 g/Mcal (95% CI: [4.21, >4.88]) and Sp at 4.36 g/Mcal (95% CI: [4.00, 4.73]). Thus, there were no apparent differences in the requirement to maximize G:F, as the 3 CI were overlapped. Nevertheless, the plateau of maximum G:F was higher for Sp and Mp pigs, 536 g/kg (95% CI: [524, 548]) and 532 g/kg (95% CI: [517, 547]), respectively, compared to 499 g/kg (95% CI: [486, 512]) for Lp. Confirming, as indicated by the previous results comparing the linear and quadratic responses for each variable, that there is a greater range of improvement when increasing SID Lys:NE in Sp and Mp than in Lp.

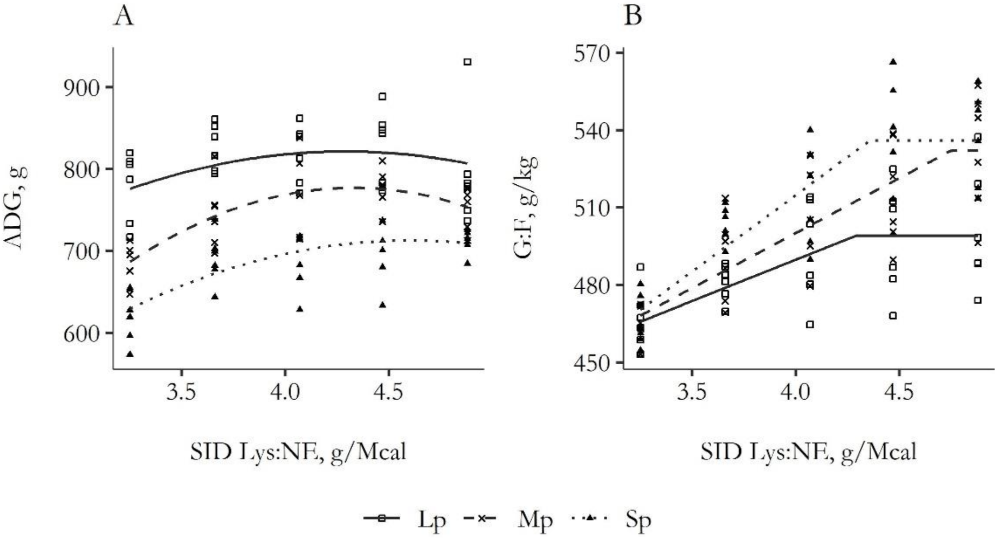

Figure 4.4. Fitted regressions models to optimize (**A**) average daily gain (ADG) using quadratic polynomial models (QP) and (**B**) gain to feed (G:F) using broken-line linear (BLL) models as a function of standardized ileal digestible lysine to net energy ratio (SID Lys:NE) from 28–63 kg (Overall phases) for each body weight category (Large = Lp; Medium = Mp; Small = Sp) in Exp 1. For ADG, the QP models estimated the optimum of Lp at 4.28 g/Mcal (95% CI: [3.91, 4.67]), of Mp at 4.33 g/Mcal (95% CI: [4.13, 4.53]), and of Sp at 4.60 g/Mcal (95% CI: [4.02, >4.88]). Regarding G:F the BLL models estimated the optimum of Lp at 4.29 g/Mcal (95% CI: [3.68, >4.88]), of Mp at 4.75 g/Mcal (95% CI: [4.21, >4.88]), and of Sp at 4.36 g/Mcal (95% CI: [4.00, 4.73]).

4.5. Discussion

The widespread adoption of all-in all-out swine production systems has raised concerns on the issue of pigs with a low BW at marketing (Magowan et al., 2007; Beaulieu et al., 2010; He et al., 2016). Those pigs, which are already smaller at the nursery exit (He et al., 2016) make phase feeding strategies inefficient and inaccurate (Patience et al., 2004; Brossard et al., 2009). The large amount of literature available on this topic suggest that this is a multi-factorial problem, which cannot be confronted in a single strategy. The 9 kg BW difference between Sp and Lp when starting the experiment was greater than most available studies (Wolter and Ellis, 2001; Douglas et al., 2014a; López-Vergé et al., 2018b), but other works have even reported initial greater differences (He et al., 2016). Because of the great difference, it might be impossible for Sp to reach the same BW as Lp at a specific marketing time. Furthermore, a lightweight at the end of the nursery has been related with reduced ADG during the grow-finishing (He et al., 2016), but some degree of compensatory growth might be expected by those pigs if sufficient nutrients are provided (Douglas et al., 2013). Thus, worthwhile strategies to avoid increasing the differences in BW between Lp and Sp pigs might focus on maximizing ADG of low BW pigs (Brumm et al., 2002; Hastad et al., 2020).

Most studies have just focused on the effect of increasing AA and/or energy on low BW pigs using a single nutritional strategy (Douglas et al., 2014a; López-Vergé et al., 2018b). Consequently, no similar experiment was found in the literature regarding the divergent effect of increasing SID Lys:NE on pigs classified in different BWCAT. In this study, isoenergetic but not isoproteic diets were preferred to ensure that essential AA were not limiting, while avoiding that a great proportion of non-essential AA were in excess in the low SID Lys:NE diets, which would have to be deaminated. The differences in ADFI have been suggested as one of the main drivers for the reduced growth of low BW pigs. The reported 15% lower ADG and a 19% lower ADFI of Sp compared to Lp, was in agreement with several studies focusing mainly on the nursery stage (Jones et al., 2012; Douglas et al., 2014b; Paredes et al., 2014; van Erp et al., 2018). Douglas et al. (2014a) reported a similar reduction on ADG (17%) but contrarily to this study, it was a result of a 16% increase in F/G as no differences in ADFI were reported. Other studies suggested that when ADFI was corrected by the metabolic BW, there were no evidences of differences (Jones et al., 2012; Paredes et al., 2014). Although in this study the differences were reduced when expressed by metabolic BW, Sp had a 6% significantly lower feed intake, similar to the 4% lower energy intake reported by van Erp et al. (2018). Future works might aim to answer whether Sp, with a reduced feed intake, might respond also to greater energy densities or if just SID Lys intake limits their performance.

Phase feeding commercially widespread strategies consist in a feeding program in which the amounts that must be fed of each feed are decided focusing on the average pig, although a 10% security margin has been suggested by some authors (Brossard et al., 2009). Considering the results from *Phase 1*, the differences in ADFI would suppose that in 26 days Sp would eat 7.8 kg less feed and considering a 1% SID Lys feed, 78 g SID Lys less than Lp, which would be a reduction of a 20% compared to Lp. Consequently, when using phase feeding strategies those pigs might be limited in SID Lys available for growth compared to their heavier mates. López-Vergé et al. (2018b) showed that a strategy to provide the same amount of the initial grower feed to small pigs as the amount fed to the average population improved ADG during the grow-finishing period. However, as the diets were only tested on low BW pigs, doubts arise whether some response would have been observed on the heavier pigs. Although studies involving different phase-feeding strategies might give an indication if growth of small pigs is impaired or improved by different strategies, these effects have not been reported in those works (Pomar et al., 2014; Menegat et al., 2020b).

4.5.1. Effect of BWCAT on the response to SID Lys:NE

In this study, a different linear effect of SID Lys:NE was reported between pigs classified in the 3 BWCAT. Unexpectedly, only for *Phase 2* the response on ADG between Sp and Lp differed. It might be explained because SID Lys:NE did not limit growth performance of Lp throughout the second phase. Therefore, the statistical model was more powerful when comparing a BWCAT in which there was no linear effect with one with a linear effect, than when there was a linear effect in both BWCAT. Focusing on a range in which the Lp category might not show a response on growth performance whereas Sp might, would be a strategy for future works using a similar experimental design. The low F/G reached by Mp at the highest SID Lys:NE was considered by the authors the result of a lower ADFI rather than an improved performance. Thus, as expected, *Overall* results confirmed that the effect of SID Lys:NE was different between Lp and Sp for all growth performance variables studied, except for ADFI.

The greater response of Sp pigs to SID Lys:NE might be related to several factors, and therefore those will be further discussed. Although only some Mp were ultrasound measured, previous results have confirmed that last pigs harvested are leaner than the first ones (Aymerich et al., 2018; Aymerich et al., 2019). This might support the idea that the ratio between energy deposited as protein or lipids is greater in slow growing pigs (Jones and Patience, 2014), and therefore energy was more efficiently used for growth (Patience et al., 2015). For instance, Sp used feed more efficiently for growth only when pigs were allowed to eat a high SID Lys:NE diet. Therefore, as isocaloric diets were used, probably Sp were more efficient because a greater fraction of energy was being used for protein deposition (Patience et al., 2015). Similarly to the present study, Main et al. (2008) reported only a reduction of fat depth on 35–60 kg gilts when increasing SID Lys:NE, but not in longissimus muscle area. Further works might aim to determine if feeding higher SID Lys:NE to Sp and Mp increases the differences in carcass fatness observed without nutritional interventions (Correa et al., 2006; Aymerich et al., 2018; Aymerich et al., 2019).

The different linear response of entire males and females during *Phase 2* could be expected as entire males are known to have a greater potential for protein deposition (Giles et al., 2009). Thus, this study provided evidence of a different response between sexes to increasing SID Lys:NE starting around 50 kg. Although this trial with only pigs from one sex might have reduced the chance of confounding effects, the authors considered that employing both sexes gave a better indication of the expected outcomes in real commercial production systems. In addition, as the inclusion of the SID Lys:NE and sex interaction did not modify the conclusions from the results presented, the simplest model was preferred. Summarizing, in the context of current all-in all-out swine commercial production systems, more research is needed to corroborate the results presented, and confirm that split feeding pigs by BWCAT can improve the overall population performance and reduce associated costs.

4.5.2. Critical assessment of SID Lys:NE requirement models

The inconsistencies between nutrient requirement models have been underlined by many authors previously (Remmenga et al., 1997; Robbins et al., 2006; Pesti et al., 2009) and confirmed in the present study. Although some studies just published the best fitting model (Gonçalves et al., 2016), considering that model choice depends also on how nutritional requirements and marginal responses are understood (Pesti et al., 2009), we decided to publish the 3 different models. Besides comparing model fit, some authors have also mentioned the relevance of the CI, particularly when a break point is included in the model (Pesti et al., 2009). As expected, the BLL yielded the lowest requirement [50], but although showing the narrowest CI of the requirement, it fitted worst the observations. Reported requirements to maximize growth performance would be greater than NRC (2012), which were on average 3.70 g SID Lys/Mcal NE from 25–75 kg BW. Only BLL requirements for ADG would be similar to NRC, although that requirement was the average between ADG and feed efficiency. Recent studies have reported lower requirements for G:F, being around 4.5 g SID Lys/Mcal NE from 25–50 kg (Landero et al., 2016; Ho et al., 2019) and 3.6 from 50–75 kg (Landero et al., 2016). However, this might be affected by the different response for ADG and G:F reported in this study.

As nutritionists, we would expect from this study a different requirement for each BWCAT, which enables deciding whether Sp pigs should be fed 10 or 20% higher SID Lys:NE compared to Lp. However, the dose-response models fitted to each BWCAT suggest careful consideration in accordance with the lack of evidence of a different quadratic response. The QP models showed that Sp pigs maximized ADG at a higher SID Lys:NE, but the CI were overlapped for the 3 BWCAT. Nevertheless, the different linear response might suggest a reduced diminishing marginal productivity (Pesti et al., 2009) for those pigs. Regarding G:F, although requirements were not significantly different, the models confirmed the greater potential of Sp to efficiently use high SID Lys:NE diets. The wide CI reported indicates that a considerable larger number of replicates (Pesti et al., 2009) would be necessary to determine different requirements between BWCAT using the conventional dose-response modelling approaches.

Moreover, Goodband et al. (2014) suggested that although there are changes in the SID Lys:NE requirements along with genetic improvements, nursery pigs maximize their growth performance at around 19 g SID Lys intake per kg gain across different studies. Recent studies in growing pigs have also shown that growth performance between 30–60 kg is maximized between 19–21 g/kg (Main et al., 2008; Ho et al., 2019). If we consider that the same hypothesis applies to different BWCAT, then excess lysine above 19–20 g/kg might not be used for protein deposition and consequently deaminated (Bender, 2012). In the present study, it might be assumed that *Overall* ADG was numerically maximized at 3.66, 4.07 and 4.47 g SID Lys/Mcal NE, with an efficiency of use of SID Lys per kg of 18.8, 19.7 and 20.6 g SID Lys/kg gain for Lp, Mp, and Sp, respectively. Therefore, with those results, it might be impossible to conclude that pigs in different BWCAT maximize ADG at the same SID Lys per kg gain. Other studies have shown that increasing SID Lys reduces its efficiency of utilization (Ghimire et al., 2016), which might be related to changes in maintenance requirements or alterations of AA composition. Future studies might analyze the differences in lysine needed for maintenance and the differences in protein composition of pigs in different BWCAT. Nevertheless, independently of the requirement models for each BWCAT, the results presented confirmed that Sp and Mp pigs had a greater potential to improve their growth performance when fed increasing SID Lys:NE.

4.6. Conclusions

This work confirmed that a different response to SID Lys:NE can be expected from growing pigs (28–63 kg BW) sorted in different initial BW categories.

However, the traditional models to estimate nutrient requirements failed to give significant different results for each category. Thus, an applied perspective of these results might be based on the different diminishing marginal productivity of small pigs compared to large pigs when increasing SID Lys:NE. In addition, the results of modelling the general population showed that SID Lys:NE requirements might be greater than NRC, especially for maximizing gain to feed ratio. Important practical implications are that feeding pigs sorted by initial BW different SID Lys:NE during the growing phase might be feasible to maximize performance of small and medium pigs and reduce costs of large pigs.

4.7. Appendix A

In this section the fitted BLL, BLQ and QP equations for ADG and G:F are detailed. The BLL model predicted ADG with the following regression Equation (A1):

$$\begin{aligned} &\text{ADG, g} = 760 - 145\times(3.72 - \text{SID Lys:NE}); && \text{if SID Lys:NE} \leq 3.72, \\ &\text{ADG, g} = 760\,; && \text{if SID Lys:NE} > 3.72, \end{aligned} \qquad \text{(A1)}$$

The BLQ model described ADG as a function of SID Lys:NE as follows (A2):

$$\begin{aligned} &\text{ADG, g} = -1646+1231\times(\text{SID Lys:NE}) - 157\times(\text{SID Lys:NE})^2; && \\ & && \text{if SID Lys:NE} \leq 3.91, \\ &\text{ADG, g} = 755 && \text{if SID Lys:NE} > 3.91, \end{aligned} \qquad \text{(A2)}$$

The QP model represented ADG depending on SID Lys:NE in the following way (A3):

$$\text{ADG, g} = -296 + 485\times(\text{SID Lys:NE}) - 55.1\times(\text{SID Lys:NE})^2 \qquad \text{(A3)}$$

Regarding G:F, the BLL model reported the following regression Equation (A4):

$$\begin{aligned} &\text{G:F, g/kg} = 519 - 50.2\times(4.29 - \text{SID Lys:NE}); && \text{if SID Lys:NE} \leq 4.29, \\ &\text{G:F, g/kg} = 519; && \text{if SID Lys:NE} > 4.29, \end{aligned} \qquad \text{(A4)}$$

The BLQ model reported the following regression Equation (A5):

$$\begin{aligned}
&\text{G:F, g/kg} = -7.14 + 221\times(\text{SID Lys:NE}) - 23.2\times(\text{SID Lys:NE})^2; \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{if SID Lys:NE} \leq 4.77, \\
&\text{G:F, g/kg} = 520; \qquad\qquad\qquad\qquad\quad\; \text{if SID Lys:NE} > 4.77,
\end{aligned} \tag{A5}$$

The QP model also reported G:F explained by SID Lys:NE as follows (A6):

$$\text{G:F, g/kg} = 75.5 + 178\times(\text{SID Lys:NE}) - 17.8\times(\text{SID Lys:NE})^2 \tag{A6}$$

4.8. Appendix B

In this section, the equations of the models used to describe ADG and G:F depending on SID Lys:NE for each BWCAT throughout the *Overall* period are presented. Different QP regression models were fitted for Lp (A7), Mp (A8) and Sp (A9) to describe ADG as a function of SID Lys:NE:

$$\text{ADG, g} = +42.5 + 363\times(\text{SID Lys:NE}) - 42.3\times(\text{SID Lys:NE})^2 \tag{A7}$$

$$\text{ADG, g} = -678 + 672\times(\text{SID Lys:NE}) - 77.6\ (\text{SID Lys:NE})^2 \tag{A8}$$

$$\text{ADG, g} = -252 + 419\times(\text{SID Lys:NE}) - 45.5\times(\text{SID Lys:NE})^2 \tag{A9}$$

Regarding feed efficiency, BLL models were fitted for Lp (A10), Mp (A11) and Sp (A12) to describe the effect of SID Lys:NE on G:F:

$$\begin{aligned}
&\text{G:F, g/kg} = 499 - 32.0\times(4.29 - \text{SID Lys:NE}); \text{ if SID Lys:NE} \leq 4.29, \\
&\text{G:F, g/kg} = 499; \qquad\qquad\qquad\qquad\qquad\quad \text{if SID Lys:NE} > 4.29
\end{aligned} \tag{A10}$$

$$\begin{aligned}
&\text{G:F, g/kg} = 532 - 42.6\times(4.75 - \text{SID Lys:NE}); \text{ if SID Lys:NE} \leq 4.75, \\
&\text{G:F, g/kg} = 532; \qquad\qquad\qquad\qquad\qquad\quad \text{if SID Lys:NE} > 4.75
\end{aligned} \tag{A11}$$

$$\begin{aligned}
&\text{G:F, g/kg} = 536 - 59.1\times(4.36 - \text{SID Lys:NE}); \text{ if SID Lys:NE} \leq 4.36, \\
&\text{G:F, g/kg} = 536; \qquad\qquad\qquad\qquad\qquad\quad \text{if SID Lys:NE} > 4.36
\end{aligned} \tag{A12}$$

CHAPTER 5

Interrelationships between sex and dietary lysine on growth performance and carcass composition of finishing boars and gilts

Interrelationships between sex and dietary lysine on growth performance and carcass composition of finishing boars and gilts

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Keywords: finishing pig, boars, gilts, lysine, requirements.

5.1. Abstract

The main goals of this study were to determine whether boars and gilts respond differently to the standardized ileal digestible lysine to net energy ratio (SID Lys:NE) and model the response to optimize growth performance. A total of 780 finishing pigs, 390 boars and 390 gilts [Pietrain NN × (Landrace × Large White)], with an initial individual body weight of 70.4±9.2 for boars and 68.7±8.0 kg for gilts, were used in a 41 day dose-response experiment. Pens (13 pigs/pen) were randomly allocated to a dietary treatment (2.64, 3.05, 3.46, 3.86, 4.27 g SID Lys/Mcal NE) by block and sex, with six replicates per treatment and sex. Two isoenergetic diets (2,460 kcal NE/kg), representing the extreme SID Lys:NE, were formulated and then mixed. Pigs were individually weighed at day 0, 22 and 41, when the experiment finished. The differential effect of SID Lys:NE on growth performance and carcass composition between sexes was analyzed with orthogonal polynomial contrasts to compare the linear and quadratic trends in each sex. In addition, broken-line linear (BLL) models to optimize average daily gain (ADG), including average daily feed intake (ADFI) as a covariate, were fitted when possible. As expected, boars had a greater ADG and feed efficiency (G:F) ($P < 0.001$) than gilts, but there was no evidence of differences in ADFI ($P = 0.470$). Increasing SID Lys:NE had a greater linear impact on boars ADG ($P = 0\ .087$), G:F ($P = 0.003$) and carcass leanness ($P = 0.032$). In contrast, gilts showed a greater linear increase in SID Lys intake per kg gain ($P < 0.001$) and feed cost per kg gain ($P = 0.005$). The best fitting BLL models showed that boars maximized ADG at 3.63 g SID Lys/Mcal NE (95% CI: [3.32-3.94]), although another model with a similar fit, compared with the Bayesian information criterion, reported the optimum at 4.01 g SID Lys/Mcal NE (95% CI: [3.60, 4.42]). The optimum to maximize ADG for gilts was estimated at 3.10 g SID Lys/Mcal NE (CI 95%: [2.74, 3.47]). Thus, the present study confirmed that boars and gilts have a different linear response to SID Lys:NE, explained by the greater protein deposition potential of boars. Likewise, BLL models indicated that boars require a higher SID Lys:NE to maximize ADG from 70-89 kg. These results

suggest that split feeding of finishing boars and gilts could be beneficial in terms of both performance and cost return.

5.2. Introduction

Historically, entire male pig production was common in some European countries such as Spain, the British Isles and Portugal (Bee et al., 2015). However, with the increasing pressure to ban castration in the EU and as a result of the *Council Directive 2008/120/EC*, in 2017 boars already accounted for 34% of the EU male pig population (Kress et al., 2019), representing around 45 million pigs (Agri-Food Data Portal – Pigmeat Productions; agridata.ec.europa.eu). As this has been a recent change, most of the studies conducted to determine lysine requirements for growth performance used barrows instead of boars (Szabó et al., 2001; Ettle et al., 2003; Main et al., 2008; Elsbernd et al., 2017). During recent decades, some works have already studied the differential response of boars compared to gilts (Campbell et al., 1988; Van Lunen and Cole, 1996; King et al., 2000; O'Connell et al., 2006; Moore et al., 2013), while others focused on the differences as a result of castration (Williams et al., 1984; Otten et al., 2013; Moore et al., 2016). In addition, there have been some modelling studies that compared lysine requirements based on growth and feed intake data (Quiniou et al., 2010; NRC, 2012; van der Peet-Schwering and Bikker, 2018).

Boars are known to have a greater potential for growth than gilts from 40-70 kg body weight (BW) until market weight (Campbell et al., 1988; Van Lunen and Cole, 1996; Moore et al., 2013; Cámara et al., 2014), resulting in a leaner body and carcass composition (Andersson et al., 2005; Giles et al., 2009; Gispert et al., 2010; Aymerich et al., 2019). As no evidence of differences in feed intake has been reported in the literature (Van Lunen and Cole, 1996; O'Connell et al., 2006; Moore et al., 2013; Cámara et al., 2014), theoretically the greater protein deposition potential of boars would represent a greater lysine requirement to maximize average daily gain (ADG). Most studies have found differences in requirements between boars and gilts in the finishing phase (Campbell et al., 1988; O'Connell et al., 2006); however, some studies have not (Van Lunen and Cole, 1996; King et al., 2000).

The available literature lacks research that compares the lysine requirements of boars and gilts in commercial conditions using low feed intake sire-lines, such as Pietrain. If, as hypothesized, boars have greater SID Lys:NE requirements than gilts, it might be productively and economically worthwhile to split-feed pigs by sex (Coffey et al., 1995) or use precision feeding systems (Pomar et al., 2010). Thus, the present work studied the effect of SID Lys:NE on the growth performance (70-106 kg) and carcass composition of finishing boars and gilts. The objectives of this work were (1) to determine whether boars and gilts respond differently to the standardized ileal digestible lysine to net energy ratio (SID Lys:NE); and (2) to model the response to SID Lys:NE in order to determine the SID Lys:NE requirement to maximize performance.

5.3. Materials and methods

All the procedures described in this work followed the EU Directive 2010/63/EU for animal experiments.

5.3.1. Experimental design and animals

In this study the differential response between finishing boars and gilts to increasing SID Lys:NE was analyzed in a 41-day dose-response experiment with five increasing levels. The trial was conducted in a commercial-experimental farm integrated into Vall Companys Group (Alcarràs, Spain). The study sample consisted of a total of 780 finishing pigs, 390 boars and 390 gilts [Pietrain NN × (Landrace × Large White)], with an initial individual BW of 70.4±9.2 for boars and 68.7±8.0 kg (mean ± SD) for gilts. When the pigs entered the growing-finishing facilities, they were separated into pens (13 pigs/pen) of similar weight based on visual observation. They were then weighed and large pigs that were in pens classified as small were exchanged with small pigs in pens classified as large, and vice versa, until we had three BW blocks (19.1±2.6, 21.9±2.6 and 24.7±2.6 kg, for small, medium and large categories, respectively). At the start of the experiment, the pens were randomly allocated by block to each treatment, and the resulting distribution was checked to avoid confounding effects related to barn location. Pen was used as an experimental unit, with six replicates per treatment and sex. Each pen had a half slatted concrete floor (3 x 3 m), 1-hole wet-dry Maxi Grow Feeder (Rotecna, Agramunt, Spain) and an additional nipple waterer at the opposite side. The farm was both naturally and semi-forced ventilated. Natural light was provided through the windows used for ventilation, and artificial light was only used when required by the farm care personnel. Although the trial was conducted during winter, the underfloor heating system was only used on the first days of the growing period, before starting the trial. A*d libitum* access to feed and water was ensured during the entire trial. Pigs were individually weighed and monitored using electronic ear tags at the beginning, at day 22 and before marketing the heaviest pigs (day 41 of the trial). The pigs came from a healthy sow farm and no relevant health issues were observed during the experiment. At day 41 of the experiment, pigs in the heaviest BW block were moved to the slaughterhouse (Patel S.A.U; L'Esquirol, Spain) and individual carcass composition was measured with AutoFom III (Frontmatec Food Technology, Kolding, Denmark). Measured parameters included hot carcass weight (HCW; head and feet on), carcass leanness (CL), backfat thickness (BFT) and ham fat thickness (HFT), whereas carcass yield (CY) was calculated afterwards. The same procedure was performed on medium and small BW block pigs at day 48 and 55, respectively.

5.3.2. Feeding

Two isoenergetic diets (2460 kcal NE/kg) were formulated based on maize, wheat and soybean meal (**Table 5.1**). Diets were formulated to meet or exceed the requirements for each nutrient, except lysine. The essential AA was formulated based on the ideal protein ratios (NRC, 2012; FEDNA, 2013). The high ratio diet was 4.27 g SID Lys/Mcal NE (Feed A) and the low ratio diet was 2.64 g SID Lys/Mcal NE (Feed B). To reduce SID Lys:NE, the amount of soybean meal included was decreased and the amount of wheat increased. In addition, the amount of crystalline amino acids included was also reduced ensuring that the ideal protein ratios were met in both diets. The two extreme feeds were mixed in five different proportions (Table 2) in the farm using a robotic feeding system (DryExact Pro; Big Dutchman, Vechta, Germany). Feed intake was measured weekly by determining the amount of feed remaining in each trough.

Table 5.1. Ingredient composition and calculated nutritional composition of the 2 diets used for blending the 5 dietary treatments (as-fed basis)

Ingredient composition (%)	Feed A	Feed B	Calculated composition[4]	Feed A	Feed B
Maize	45.00	45.00	Dry matter, %	87.56	87.42
Wheat	34.13	39.51	Crude Fiber, %	2.76	2.74
Soybean meal 47%	15.20	11.20	Sugars, %	2.68	2.54
Animal fat	1.60	1.50	Starch, %	47.90	51.03
Calcium carbonate	1.20	1.20	Ether extract, %	3.75	3.66
Dicalcium phosphate	0.20	0.20	Crude Protein, %	15.69	13.55
Sodium chloride	0.40	0.40	Total Lys, %	1.14	0.73
Lysine sulphate	0.91	0.33	SID Lys, %	1.05	0.65
L-Threonine	0.27	0.04	SID Met+ Cys/ Lys ratio	0.61	0.62
DL-Methionine	0.22	-	SID Thr/ Lys ratio	0.66	0.65
L-Valine	0.12	-	SID Trp/Lys ratio	0.21	0.21
L-Tryptophan	0.07	-	SID Val/Lys ratio	0.65	0.79
L-Isoleucine	0.06	-	SID Ile/Lys ratio	0.55	0.69
Phytase[1]	0.02	0.02	ME, kcal/kg	3,268	3,257
Acids mix[2]	0.30	0.30	NE, kcal/kg	2,460	2,460
VIT-MIN premix[3]	0.30	0.30	SID Lys:NE ratio, g/Mcal	4.27	2.64
			Ashes, %	3.74	3.57
			Total Ca, %	0.58	0.57
			STTD Ca, %	0.45	0.44
			Total P, %	0.36	0.35
			STTD P, %	0.30	0.30
			Cl, %	0.28	0.28
			K, %	0.58	0.52
			Na, %	0.16	0.16

[1] 6-phytase (750 FTU/kg).

[2] Blend of formic and lactic acid.

[3] Provided per each kg of complete feed: 4,500 IU vitamin A, 2,000 IU vitamin D_3, 15 mg vitamin E, 0.7 mg vitamin K, 1.0 mg vitamin B_1, 4.0 vitamin B_2, 1.2 vitamin B_6, 0.02 vitamin B_{12}, 15 mg niacin, 12 mg pantothenic acid, 107 mg coline, 90 mg Fe from iron sulphate, 100 mg Zn from zinc sulphate, 50 mg Mn from manganese oxide, 20 mg Cu from copper sulphate, 1.8 mg I from potassium iodide and 0.25 mg Se from sodium selenite.

[4] SID: Standardized ileal digestible; ME: Metabolizable energy; NE: Net energy; STTD: Standardized total tract digestible.

5.3.3. Diet sampling and analyses

After pelleting, feed samples were collected for each successive blending batch (5,000 kg) and CP was analyzed (ISO 16634-2:2016) to ensure that CP was within the range of the calculated composition. In addition, AA composition (Method 994.12, AOAC, 2007) was analyzed in a blend of all the different batches (**Table 5.3**).

Table 5.2. Blend ratios, calculated composition, and price for the 5 dietary treatments (as-fed basis)

Item[1]	T1	T2	T3	T4	T5
Feed A, %	0	25	50	75	100
Feed B, %	100	75	50	25	0
SID Lys, %	0.65	0.75	0.85	0.95	1.05
NE, kcal/kg	2,460	2,460	2,460	2,460	2,460
SID Lys:NE, g/Mcal	2.64	3.05	3.46	3.86	4.27
Formula cost, €/t[2]	223.4	231.0	238.5	246.1	253.6

[1] SID: standardized ileal digestible; NE: net energy.

[2] Calculated as a weighted average of the formula cost and inclusion of Feed A and B.

Table 5.3. Analyzed and calculated amino acid content of the experimental feeds (A and B) used for blending and obtain the 5 dietary treatments (%, as-fed basis)

Item	Feed A		Feed B	
	Calculated	Analyzed	Calculated	Analyzed
Crude Protein	15.7	15.9	13.6	13.7
Lysine	1.14	1.14	0.73	0.77
Methionine	0.44	0.40	0.21	0.21
Methionine+ Cysteine	0.71	0.65	0.47	0.45
Threonine	0.78	0.76	0.50	0.53
Valine	0.78	0.78	0.60	0.61
Leucine	1.21	1.21	1.11	1.10
Isoleucine	0.63	0.64	0.51	0.52
Histidine	0.38	0.37	0.35	0.34
Arginine	0.87	0.90	0.76	0.80

5.3.4. Calculations and statistical analyses

Pen BW, ADG, average daily feed intake (ADFI), feed efficiency (G:F), g SID Lys daily intake, g SID Lys intake per kg gain and feed cost per kg gain were measured and calculated for *Period 1* (day 0-22), *Period 2* (day 22-41) and *Overall* (day 0-41). In addition, HCW, CY, CL, BFT and HFT were calculated per pen using the individual data from pigs that could be traced at the slaughterhouse. The effect of SID Lys:NE on the studied productive parameters was initially analyzed in a linear model including SID Lys:NE, sex, initial BW block and all the interactions between factors as fixed effects. Interactions that were not significant ($P > 0.050$) and/or biologically meaningless for the *Overall* period were not included in the final model because simplification was prioritized. As not all pigs could be completely traced at the slaughterhouse, the number of pigs per pen was included as a weighting factor in the carcass trait models. In addition, CY, CL, BFT and HFT were linearly adjusted using HCW as a covariate. The differential effect of SID Lys:NE on growth performance between sexes was analyzed implementing orthogonal polynomial contrasts to compare the linear and quadratic trends in each sex. Afterwards, the model was conditioned to determine the linear or quadratic effect of SID Lys:NE on each sex. The models were performed using the *stats* package (R Core Team, 2019), ANOVA with the *car* package (Fox and Weisberg, 2019) and the effect of SID Lys:NE contrasted using the *emmeans* package (Lenth, 2020).

Broken-line linear (BLL) regression models were fitted when possible to determine the breakpoint at which ADG was maximized for each sex using the *stats* package (R Core Team, 2019). The models used were adapted from Robbins et al. (2006) by including ADFI as a covariate to improve the predictability of the model:

$$Y_{ij} = L + U * \ (R - X_i) + \pi * Z_{ij} + e_{ij}$$

if $X_i \leq R$, and when $X_i > R$ then

$$Y_{ij} = L + \pi * Z_{ij} + e_{ij}$$

where Y_{ij} is the response in ADG as a result of the difference between the breakpoint (R) and SID Lys:NE (X_i) times a factor (U) before reaching the plateau (L). In both equations, we assumed a linear effect (π) of ADFI (Z_{ij}) on the dependent variable. The models reported in the results section are the best fitting models achieved by iteratively modifying the initial parameter values and selecting the model with a lower Bayesian information criteria (BIC). Finally, the 95% CI for the BLL parameters (Venables and Ripley, 2002) was estimated with the *nlstools* package (Baty et al., 2015) to compare the requirements of boars and gilts. For all tests, results were considered significant when $P \leq 0.05$, and a tendency when $0.05 < P \leq 0.10$.

5.4. Results

The analyzed protein and AA content of the experimental feeds (**Table 5.3**) were consistent with the calculated composition of the diets. *Overall*, there was no evidence of significant interactions ($P > 0.050$) between block and treatment or sex. Only a tendency for an interaction between block and SID Lys:NE ($P = 0.051$) was observed for SID Lys per kg gain; however, as it represented a different effect only in medium category pigs, it was not considered biologically meaningful. Therefore, a model including only the interaction between SID Lys:NE and sex was preferred for the sake of simplification. An overview of the main effects of sex is presented in **Figure 5.1** for the main growth performance variables. Initially boars weighed 1.7 kg more than gilts (70.4 vs. 68.7 kg, $P = 0.001$), but this difference was even greater at day 22 (90.7 vs. 87.7 kg, $P<0.001$) and at the end of the trial (108.0 vs. 102.9 kg, $P < 0.001$). The increase in the difference in BW throughout the experiment was the result of a greater ADG of boars during *Period 1* ($P = 0.001$) and *Period 2* ($P < 0.001$). No evidence of differences in ADFI between boars and gilts was observed ($P > 0.100$), and therefore the greater growth was considered the result of an increased G:F of boars ($P < 0.001$). The *Overall* results reported a greater ADG (0.914 vs. 0.837 kg, $P < 0.001$) and G:F (0.421 vs. 0.388, $P < 0.001$) of boars, but no evidence of a difference in ADFI (2.17 vs. 2.16 kg, $P = 0.470$). As expected, the improved performance of boars was also reflected in a leaner carcass composition. Hot carcasses of boars were heavier (89.7 vs. 86.6 kg, *P* < 0.001) and CY was greater for gilts (77.2 vs. 78.7 %, *P* < 0.001). Boars had greater CL (64.4 vs. 63.5 %, *P* < 0.001) and lower BFT (14.1 vs. 14.7 mm, *P* = 0.009) and HFT (8.82 vs. 10.29 mm, *P* < 0.001).

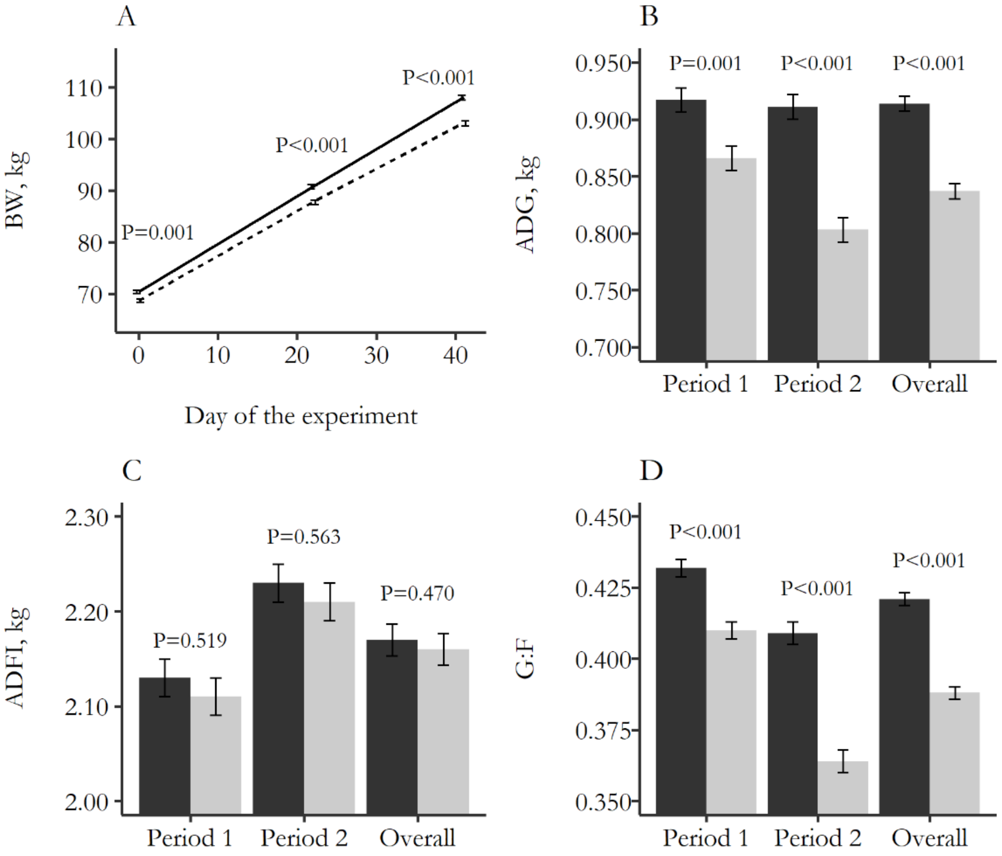

Figure 5.1. Effect of sex on body weight (A), average daily gain (B), average daily feed intake (C) and gain to feed (D) of finishing boars and gilts. For A, data represents the 3 weighing days. For B, C and D results are provided for Period 1(70-89 kg), Period 2 (89-106 kg) and the overall experiment (70-106 kg). Solid line and black bars represent boars whereas dashed line and grey bars represent gilts. Error bars represent the standard error of the mean.

5.4.1. Differential response to SID Lys:NE

In this section, the comparison of the linear and quadratic trends depending on SID Lys:NE between sexes is provided and used to determine whether there was a differential response between sexes. In addition, the effect of SID Lys:NE on each sex is also provided. Growth performance results of *Period 1* (70-89 kg) are summarized in **Table 5.4**. Strong evidence of a different linear response to SID Lys:NE was found for some performance variables. Nevertheless, there was no evidence of a different quadratic response to SID Lys:NE between boars and gilts for any of the variables analyzed. Regarding ADG, linear trends between sexes when SID Lys:NE was increased were not significantly different (*P* = 0.115). Nevertheless, boars showed a linear increase (*P* < 0.001), but gilts just a tendency (*P* = 0.100). The ADFI of both boars and gilts was not linearly or quadratically affected by SID Lys:NE. Although G:F increased linearly when SID Lys:NE was increased in both boars (*P* < 0.001) and gilts (*P* = 0.005), boars showed a greater linear increase than gilts (*P* = 0.003). Furthermore, there was a greater linear increase in SID Lys/kg gain (*P* = 0.001) and in feed cost per kg gain (*P* = 0.004) when SID Lys:NE was increased for gilts compared to boars.

In the second period (**Table 5.5**), from 89 to 106 kg BW, there were no significant interactions between sex and the linear or quadratic response to SID Lys:NE. Only a tendency for a different linear response to increased SID Lys was reported for SID Lys per kg gain. Neither boars (*P* = 0.328) nor gilts (*P* = 0.764) showed a linear increase in ADG when SID Lys:NE was increased. Moreover, boars' G:F linearly increased (*P* = 0.003) whereas gilts just showed a tendency (*P*=0.098). The difference between the response in ADG and G:F could be partly related to a tendency for ADFI to decrease in both boars (*P* = 0.052) and gilts (*P* = 0.089). As in the previous period, increasing levels of SID Lys:NE increased SID Lys per kg gain linearly in both boars and gilts (*P* < 0.001). However, gilts tended to show a greater linear increase than boars (*P* = 0.100).

Table 5.6 provides the experimental results on BW and growth performance for the *Overall* period. The top half of the Table shows that there was no evidence that increasing SID Lys:NE resulted in a greater linear increase in BW of boars at day 22 (*P* = 0.712) or day 41 (*P* = 0.591). However, when SID Lys:NE was increased boars showed a linear increase in BW at day 41 (*P* = 0.037), but the increase was not significant for gilts (*P* = 0.173). Regarding overall growth performance, there was evidence of a different response to SID Lys:NE between boars and gilts for most variables studied. Average daily gain tended to show a greater linear increase for boars than gilts (*P* = 0.087). Consistently, boars' ADG increased linearly (*P* < 0.001), while there was no significant effect for gilts (*P* = 0.103). As in *Period 1*, boars showed a greater linear increase in G:F (*P* = 0.003), whereas gilts showed an increase in SID Lys per kg gain (*P* < 0.001) and feed cost per kg gain (*P* = 0.005) when SID Lys:NE was increased.

The interactive effects between sex and SID Lys:NE on carcass characteristics are reported in **Table 5.7**. There was no significant interaction between sex and the linear (*P* = 0.151) or quadratic (*P* = 0.135) effect of SID Lys:NE on HCW. Nevertheless, boars' HCW increased linearly (*P* = 0.027), whereas there was no evidence of an increase for gilts (*P* = 0.821). Similarly, the CY of gilts was linearly (*P* = 0.042) reduced when SID Lys:NE was increased, whereas the CY of boars was not (*P* = 0.904); however, there was no significant interaction in the linear response (*P* = 0.180). In accordance with the results on growth performance, boars had a greater linear increase in lean tissue and a reduction in fat content when SID Lys:NE was increased. The interaction between sex and the linear effect of SID Lys:NE was significant for both CL (*P* = 0.016) and BFT (*P* = 0.026) but not for HFT (*P* = 0.230). Regarding boars, increasing SID Lys:NE led to a linear increase in CL (*P* < 0.001), and a linear decrease in BFT (*P* < 0.001) and HFT (*P* = 0.002). However, there was only a quadratic (*P* = 0.044) effect of SID Lys:NE on BFT, but no evidence of an effect on CL or BFT for gilts (*P* ≥ 0.129).

5.4.2. Estimation of SID Lys:NE requirements of boars and gilts

Dose-response BLL models were fitted to predict ADG for each sex and period. For the initial period, models could be fitted for each sex, and different responses were found. For boars, two models reported similar fits (BIC: 316.1 and 316.5). The best fitting model for boars was:

ADG (g) = 367 + 268 × ADFI (kg) -92.6 × (4.05 – SID Lys:NE); if SID Lys:NE ≤ 4.05,
ADG (g) = 367 + 268 × ADFI (kg) ; if SID Lys:NE > 4.05

in which ADG was transformed to g to facilitate the fitting process, and maximum growth was reached at 4.05 g SID Lys/Mcal NE (95% CI: [3.56, 4.54]). Whereas the other model gave an optimum for maximum growth of 3.71 g SID Lys/Mcal NE (95% CI: [3.30, 4.12]). The best fitting model for gilts (BIC=307.4) in the first period was modified because the intercept of the model was insignificant as it was close to 0; therefore, the model was fitted without an intercept as follows:

ADG (g) = 415 × ADFI (kg) -98.9 × (3.13 – SID Lys:NE); if SID Lys:NE ≤ 3.13,
ADG (g) = 415 × ADFI (kg); if SID Lys:NE > 3.13

with maximum growth reached at 3.13 g SID Lys/Mcal NE (95% CI: [2.74, 3.51]).

It was not possible to adjust a model in the second period for gilts. Fit was possible for boars but the slope (*U*) was not significant, and therefore the models were not considered.

Finally, models for the overall period could be fitted for both boars and gilts. Like in the first phase, for boars there were two models with similar fitting (BIC: 289.2 and 290.3). The best fitting model was the following:

ADG (g) = 405 + 249 × ADFI (kg) -92.6 × (3.63 – SID Lys:NE); if SID Lys:NE ≤ 3.63,
ADG (g) = 405 + 249 × ADFI (kg) ; if SID Lys:NE > 3.63

in which maximum growth was reached at 3.63 g SID Lys/Mcal NE (95% CI: [3.32, 3.94]). Contrastingly, the maximum growth in the model with just slightly the worst fit was reached at 4.01 g SID Lys/Mcal NE (95% CI: [3.60, 4.42]).

Table 5.4. Interactive effects between standardized ileal digestible lysine to net energy ratio (SID Lys:NE) and sex on growth performance and economics of finishing boars and gilts in Period 1 (70-89 kg)[1]

Item		SID Lys:NE, g/Mcal[2]					SEM	*P*-value			
		2.64	3.05	3.46	3.86	4.27		L x S[3]	Q x S[4]	Linear	Quadratic
ADG, kg	Boars	0.830	0.918	0.934	0.934	0.968	0.0235	0.115	0.626	<0.001	0.168
	Gilts	0.823	0.882	0.857	0.882	0.885				0.100	0.483
ADFI, kg	Boars	2.11	2.21	2.15	2.08	2.10	0.048	0.579	0.832	0.288	0.356
	Gilts	2.10	2.14	2.11	2.11	2.09				0.776	0.532
G:F	Boars	0.394	0.416	0.436	0.452	0.461	0.0072	0.003	0.612	<0.001	0.303
	Gilts	0.392	0.412	0.406	0.417	0.424				0.005	0.751
SID Lys/gain, g/kg	Boars	16.5	18.1	19.5	21.1	22.8	0.36	0.001	0.757	<0.001	0.779
	Gilts	16.6	18.2	21.0	22.9	24.8				<0.001	0.875
Feed cost/gain, €/kg	Boars	0.568	0.557	0.547	0.547	0.550	0.0100	0.004	0.594	0.146	0.323
	Gilts	0.570	0.561	0.588	0.592	0.599				0.007	0.811

[1] A total of 780 pigs [Pietrain NN × (Landrace × Large white)] in pens of 13, with six replicates per treatment and sex.

[2] Calculated SID Lys:NE.

[3] Interaction between sex and the linear response to SID Lys:NE.

[4] Interaction between sex and the quadratic response to SID Lys:NE.

Table 5.5. Interactive effects between standardized ileal digestible lysine to net energy ratio (SID Lys:NE) and sex on growth performance and economics of finishing boars and gilts in the Period 2 (89-106 kg)[1]

Item		SID Lys:NE, g/Mcal[2]					SEM	*P*-value			
		2.64	3.05	3.46	3.86	4.27		L x S[3]	Q x S[4]	Linear	Quadratic
ADG, kg	Boars	0.875	0.918	0.933	0.906	0.920	0.0254	0.630	0.505	0.328	0.296
	Gilts	0.783	0.836	0.781	0.802	0.812				0.764	0.915
ADFI, kg	Boars	2.27	2.25	2.29	2.16	2.17	0.044	0.853	0.971	0.052	0.525
	Gilts	2.21	2.34	2.18	2.17	2.17				0.089	0.559
G:F	Boars	0.386	0.408	0.408	0.420	0.425	0.0092	0.314	0.494	0.003	0.535
	Gilts	0.356	0.357	0.360	0.372	0.374				0.098	0.727
SID Lys/gain, g/kg	Boars	16.9	18.5	20.9	22.6	24.8	0.55	0.100	0.537	0.000	0.773
	Gilts	18.4	21.1	23.7	25.8	28.2				0.000	0.559
Feed cost/gain, €/kg	Boars	0.580	0.568	0.585	0.586	0.600	0.0154	0.409	0.476	0.236	0.556
	Gilts	0.631	0.649	0.665	0.667	0.680				0.021	0.674

[1] A total of 780 pigs [Pietrain NN × (Landrace × Large white)] in pens of 13, with six replicates per treatment and sex.

[2] Calculated SID Lys:NE.

[3] Interaction between sex and the linear response to SID Lys:NE.

[4] Interaction between sex and the quadratic response to SID Lys:NE.

Table 5.6. Interactive effects between standardized ileal digestible lysine to net energy ratio (SID Lys:NE) and sex on body weight, growth performance and economics of finishing boars and gilts in the overall experiment (70-106 kg)[1]

		SID Lys:NE, g/Mcal[2]					SEM	*P*-value			
Item		2.64	3.05	3.46	3.86	4.27		L x S[3]	Q x S[4]	Linear	Quadratic
BW d0, kg	Boars	70.4	70.7	70.4	70.4	70.4	0.79	0.563	0.844	0.879	0.912
	Gilts	68.4	68.6	68.5	68.8	69.1				0.506	0.867
BW d22, kg	Boars	88.7	90.9	91.0	90.9	91.8	1.00	0.712	0.693	0.055	0.461
	Gilts	86.5	87.9	87.4	88.2	88.6				0.156	0.857
BW d41, kg	Boars	105.3	108.6	108.5	108.2	109.2	1.11	0.591	0.492	0.037	0.259
	Gilts	101.3	103.8	102.2	103.2	104.0				0.173	0.871
ADG, kg	Boars	0.851	0.918	0.933	0.921	0.946	0.0149	0.087	0.348	<0.001	0.049
	Gilts	0.804	0.861	0.822	0.845	0.851				0.103	0.497
ADFI, kg	Boars	2.18	2.23	2.21	2.11	2.14	0.038	0.651	0.878	0.084	0.353
	Gilts	2.15	2.23	2.14	2.14	2.13				0.268	0.476
G:F	Boars	0.390	0.412	0.423	0.437	0.444	0.0051	0.003	0.326	<0.001	0.196
	Gilts	0.375	0.386	0.384	0.396	0.400				<0.001	0.925
SID Lys/gain, g/kg	Boars	16.7	18.2	20.1	21.8	23.7	0.27	<0.001	0.465	<0.001	0.663
	Gilts	17.3	19.5	22.2	24.0	26.3				<0.001	0.549
Feed cost/gain, €/kg	Boars	0.573	0.561	0.565	0.564	0.572	0.0074	0.005	0.314	0.965	0.210
	Gilts	0.596	0.600	0.622	0.622	0.634				<0.001	0.867

[1] A total of 780 pigs [Pietrain NN × (Landrace × Large white)] in pens of 13, with six replicates per treatment and sex.

[2] Calculated SID Lys:NE.

[3] Interaction between sex and the linear response to SID Lys:NE.

[4] Interaction between sex and the quadratic response to SID Lys:NE.

Table 5.7. Interactive effects between standardized ileal digestible lysine to net energy ratio (SID Lys:NE) and sex on carcass weight and composition of finishing boars and gilts (70-106 kg)[1]

		SID Lys:NE, g/Mcal[2]					SEM	*P*-value			
Item		2.64	3.05	3.46	3.86	4.27		L x S[3]	Q x S[4]	Linear	Quadratic
Hot carcass weight, kg	Boars	87.2	90.0[6]	90.6[6]	89.6	90.9[6]	0.95	0.151	0.135	0.027	0.197
	Gilts	86.7	87.1[6]	85.7	86.5	87.3[6]				0.821	0.405
Carcass yield, %	Boars	77.2[7]	77.0	77.4[6]	77.2[7]	77.1[6]	0.28	0.180	0.836	0.904	0.649
	Gilts	79.2	78.5	79.0[6]	78.6	78.3[7]				0.042	0.869
Carcass leanness, %	Boars	63.7	63.5[7]	64.8[6]	64.8	65.5[6]	0.31	0.016	0.320	<0.001	0.688
	Gilts	63.1	63.5	63.5[7]	63.8	63.6				0.181	0.305
Backfat thickness, mm	Boars	14.7[7]	14.7	13.8[6]	13.8[7]	13.3[6]	0.30	0.026	0.142	<0.001	0.933
	Gilts	15.1[7]	14.6	14.4[6]	14.3	14.9[7]				0.396	0.044
Ham fat thickness, mm	Boars	9.25	9.30[6]	8.60[6]	8.69	8.28[7]	0.23	0.174	0.484	0.002	0.903
	Gilts	10.61	10.37	10.17[6]	10.12	10.18				0.129	0.377

[1] A total of 780 finishing pigs [Pietrain NN × (Landrace × Large white)] in pens of 13 were used in a 41 days growth trial, with 2 periods, including 6 pens per treatment and sex. All pigs reaching marketing were transported to a commercial slaughter and packing plant (Patel, Spain) to collect individual data on carcass composition, but only 650 pigs could be completely traced. Observations per pen were weighted using the number of pigs per pen for which carcass data was available.

[2] Calculated SID Lys:NE.

[3] Interaction between sex and the linear response to SID Lys:NE.

[4] Interaction between sex and the quadratic response to SID Lys:NE.

[5] Adjusted for HCW.

[6] SEM was 0.97 for HCW,0.29 for CY, 0.33 for CL, 0.31 for BFT and 0.24 for HFT in the indicated means.

[7] SEM was 0.27 for CY, 0.32 for CL, 0.029 for BFT, and 0.25 for HFT in the indicated means.

For gilts, the model that best described growth (BIC: 296.2) depending on the SID Lys:NE and feed intake was:

$$\text{ADG (g)} = 270 + 267 \times \text{ADFI (kg)} - 82.3 \times (3.10 - \text{SID Lys:NE}); \text{ if SID Lys:NE} \leq 3.10,$$

$$\text{ADG (g)} = 270 + 267 \times \text{ADFI (kg)}; \qquad \text{if SID Lys:NE} > 3.10$$

in which maximum growth was achieved at 3.10 g SID Lys/Mcal NE (95% CI: [2.74, 3.47]). The two best fitting models in the overall period are shown in **Figure 5.2**.

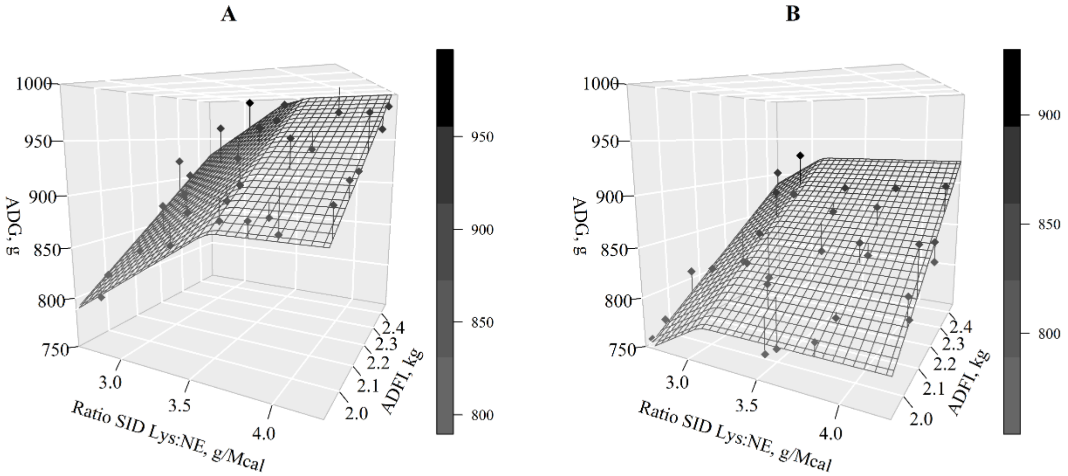

Figure 5.2. Fitted broken-line linear models to predict ADG as a function of increasing the standardized ileal digestible lysine to net energy ratio (SID Lys:NE) and ADFI. Maximum ADG was estimated for boars (A) at 3.63 g SID Lys/Mcal NE (95% CI: [3.32, 3.94] g SID Lys/Mcal NE) and for gilts (B) at 3.10 g SID Lys/Mcal NE (95% CI: [2.74, 3.47] g SID Lys/Mcal NE).

5.5. Discussion

In the context of an increasing production of entire males, this study focused on determining whether boars and gilts respond differently to SID Lys:NE, and modelling their response to optimize growth performance. Consistent with the literature, this study observed that boars have a greater ADG and G:F than gilts and a similar ADFI. The greater ADG of boars has been related to a higher potential for lean tissue deposition (Hendriks and Moughan, 1993; Rikard-Bell et al., 2013b) starting around 50-70 kg BW (Whittemore et al., 1988; Giles et al., 2009; Carabús et al., 2017). Studies analyzing growth data have observed that gilts' ADG compared to boars' ADG starts to decline around 40-70 kg BW (Campbell et al., 1988; Quiniou et al., 2010; Cámara et al., 2014). In addition, boars greater G:F might be explained by their greater growth potential and considering that there was no evidence of differences in ADFI (O'Connell et al., 2006; Cámara et al., 2014). Moreover, in agreement with the literature, boars were generally leaner than gilts (Cámara et al., 2014; Carabús et al., 2017) and had a reduced carcass yield, which might be partly attributed to the removal of the testicles (Gispert et al., 2010). The differences in BFT were in agreement with Rikard-Bell et al. (2013b). However, the small difference compared to HFT might explain why other authors did not obtain this result (Gispert et al., 2010; Trefan et al., 2013). Finally, as genetic improvements during the last decades could be responsible for part of the differences between studies, reference values should be carefully considered.

5.5.1. Differential response to SID Lys:NE

These results confirmed the different productive performance response of boars and gilts to SID Lys:NE. As mentioned in the introduction, some works have already studied this response in recent decades (Campbell et al., 1988; Van Lunen and Cole, 1996; King et al., 2000; O'Connell et al., 2006; Moore et al., 2013; Rikard-Bell et al., 2013a). However, so far there is no single experiment in the literature that compares the linear or quadratic trends between sexes in one statistical model. Most authors just report the effect of dietary lysine on each sex. As recently shown by Aymerich et al. (2020b), comparing the linear or quadratic response in a single model gives an indication of how certain we can be that the effect of SID Lys:NE differs between categories of a factor. However, being linear or quadratic should be considered carefully as this could be strongly influenced by the range of SID Lys:NE in which the experiment evaluated the effects on pig performance. Throughout the discussion, as most experiments used a ratio between SID Lys and ME or DE, a ratio of 0.71 between NE and DE, and 0.74 between ME and NE is assumed to make comparisons with the results from other studies possible (Noblet and van Milgen, 2004).

The current study reports evidence that boars and gilts respond differently to increasing SID Lys:NE, although due to the great variability only a tendency was found for ADG. The response of boars up to a higher SID Lys:NE is explained because more lysine is needed to reach their greater protein deposition potential. Thus, as the experiment was in accordance with previous literature that shows no significant differences in ADFI between boars and gilts (O'Connell et al., 2006; Cámara et al., 2014), boars responded to diets that are more concentrated in dietary lysine to maximize performance. The response for ADG was different to Moore et al. (2013), who found linear and quadratic effects of dietary lysine in both finishing boars and gilts in a SID Lys:NE range from 2.3 to 4.6 g/Mcal. However, Rikard-Bell et al. (2013a) reported that boars have a response in ADG up to a higher SID Lys:NE than gilts in a range from 2.4 to 4.2 g SID Lys/Mcal NE. It is possible that the SID Lys:NE range in our study was not sufficient to significantly limit growth in gilts. Using a lower bottom SID Lys:NE boundary might have provided a better understanding of the form of the different responses between sexes.

A reduction in ADG and G:F at the highest lysine levels has been reported in other studies (Van Lunen and Cole, 1996; O'Connell et al., 2006; Moore et al., 2013). This outcome differs from the findings presented here, in which ADG did not decrease at lysine levels above the requirement. A hypothesis is that the reduction in growth at high lysine levels is explained by an increase in heat production when CP levels are above the requirement for growth. Le Bellego et al. (2001) showed that reducing CP while using synthetic AA to fulfill ideal protein requirements increased the efficiency of ME and NE use. Otherwise excess AA has to be deaminated, which has an energy cost (Bender, 2012). Hence, it could conceivably be hypothesized that the high CP diets used in the high lysine treatments of some of the works reviewed, most of them above 17% (Campbell et al., 1988; Van Lunen and Cole, 1996; King et al., 2000; O'Connell et al., 2006; Moore et al., 2013), might explain why there was a reduction in feed efficiency and ADG.

The carcass composition results corroborated the findings of Moore et al. (2013), reporting a linear effect of SID Lys:NE only on the backfat thickness of boars, while there was no linear effect on gilts. Similarly, Lambe et al. (2013) showed that fatness of entire male Pietrain sire-line pig carcasses increased only when the lysine content of the diet was reduced, and not for a lower CP. In addition, Rikard-Bell et al. (2013b) showed that when SID Lys:NE was increased from 3.3 to 3.8 g/Mcal, there was only a significant increase in boars' lean tissue deposition. The different linear effect between sexes reported in this experiment, supports the different linear responses observed in growth performance results. It confirmed that the greater response of boars to increasing SID Lys:NE entailed an increase in carcass leanness. Therefore, at the lower ratios, SID Lys intake was limiting boars' protein deposition, and consequently energy was used for fat deposition, increasing BFT. However, the results also suggest that gilts cannot increase lean deposition when offered more SID Lys. Nevertheless, the inconsistency with some of the available literature might be a result of different statistical analyses, experimental diet formulation strategies or genetic lines.

5.5.2. Modelling SID Lys:NE requirements

Several studies have aimed to model the results from a dose-response trial to determine an optimum for different parameters such as ADG or G:F. It is widely acknowledged that the model used (broken-line linear, quadratic polynomial, broken-line quadratic) is a major factor in determining the optimum level (Pesti et al., 2009). In the present study, BLL was preferred because quadratic trends were not reported for almost any variable. The objective of the fitted models was to describe the differential response to SID Lys:NE on ADG of boars and gilts reported in the results section. Although models could be fitted, having a lower bottom SID Lys:NE level would have made the fitting process easier. For instance, Robbins et al. (2006) suggested that a minimum of four points below the requirement are needed to fit the shape of a quadratic response.

Including ADFI as a covariate in the model, which explained 0.40-0.60 of the ADG variability, enabled fitting a BLL model to predict the ADG of gilts depending on SID Lys:NE, although there was only one level that theoretically limited growth. As a result, both dose-response broken-line linear models for gilts and boars could be fitted for *Period 1* and *Overall*, and the requirements between sexes were compared using the CI of the break-point, the SID Lys:NE at which ADG was maximized. From 70-89 kg BW boars showed a response in ADG up to a higher SID Lys:NE compared to gilts. Nevertheless, in the *Overall* period, the CIs were overlapped considering the best fitting model; however, if the boars' second best fitting model, with a similar BIC, is considered, then the CI would not be overlapped because it reported a higher break-point. Therefore, in agreement with the different linear effects of SID Lys:NE on growth performance, boars required greater dietary SID Lys:NE, mainly for the period 70-89 kg, to maximize growth performance.

The greater requirements for boars compared to gilts corroborate the findings of some previous studies (O'Connell et al., 2006; Rikard-Bell et al., 2013a), contradict other studies (Van Lunen and Cole, 1996; King et al., 2000), and some studies did not show relevant differences (O'Connell et al., 2006; Moore et al., 2013). However, most of these studies did not report a CI for the requirement estimates, and thus, doubts arise about comparisons of requirements of the two sexes. For instance, the requirement for boars to optimize ADG from 70-106 kg (3.63-4.01 g SID Lys/Mcal NE) was slightly lower to that reported by Rikard-Bell et al. (2013a) (>4.24 g SID Lys/Mcal NE), whereas it was slightly higher than that reported by Moore et al. (2016) (3.4 g SID Lys/Mcal NE) using BLL models. The requirement for gilts, although low compared to some studies (O'Connell et al., 2006; Shelton et al., 2011; Moore et al., 2013) was similar to Rikard-Bell et al. (2013a) (3.2 g SID Lys/Mcal NE) and greater than Main et al. (2008) (2.6 g SID Lys/Mcal NE).

These results suggest that the requirements for boars were 117% higher than gilts or even more, whereas the review in Dunshea et al. (2013) suggested that they were only 108%. However, Williams et al. (1984) suggested that the requirements for boars might be 125% the requirements of barrows, considering that barrows and gilts have similar requirements (Main et al., 2008). The differences in requirements might be partly due to the potential ADG, which in this study was 11% greater for boars (940 vs. 844 kg), assuming a 2.15 kg ADFI. However, data from studies in which the SID Lys:NE of the diets fed to pigs could have been limiting boars' growth should be used carefully to model requirements. Furthermore, as suggested by Lerman and Bie (1975), dose-response growth models need to be linked to lysine cost models to determine exactly which is the best level from an economic standpoint. The present models are a first step for determining which are the economically optimal diets for each sex. Nevertheless, the results already suggest that feeding gilts with an optimal diet for boars may increase the production cost of gilts.

In conclusion, the different responses in growth performance and carcass composition of boars and gilts to increasing SID Lys:NE along with the modelling outcomes indicate that finishing boars (70-110 kg) have a greater SID Lys:NE requirement than gilts to maximize growth performance and carcass leanness. This is explained by the greater protein deposition and therefore growth potential of boars starting from 50-70 kg to market weight, when there are no evident differences in ADFI. Therefore, the present work suggests that feeding boars and gilts diets with different SID Lys:NE during the finishing period might be beneficial from both the performance and cost-return perspectives.

CHAPTER 6

Lysine requirements of 70 to 100 kg boars and gilts: A meta-analysis

Lysine requirements of 70 to 100 kg boars and gilts: A meta-analysis

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Submitted to *Animal*.

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6.1. Abstract

The expected increase in boar (pig entire male) production while societal concerns for castration increase requires good estimations of their nutrient requirements. For this meta-analysis, data from 14 different studies analysing the effect of increasing dietary lysine on growth performance of finishing pigs, 70 to 100 kg average body weight (BW), were extracted from 11 publications. Those studies represented 6,654 pigs (1,588 boars and 5,066 gilts) in 128 different treatments (53 for boars and 75 for gilts). Diets were reformulated based on NRC (2012) ingredient values to calculate standardized ileal digestible lysine to net energy ratio (SID Lys:NE) and daily SID Lys intake using average daily feed intake (ADFI). As expected, no evidence for differences in ADFI ($P = 0.287$) was observed between boars and gilts. However, boars grew faster ($P < 0.001$) and had higher gain to feed (G:F; $P < 0.001$). The divergent effect of SID Lys:NE on average daily gain (ADG) and G:F was analysed in a quadratic polynomial model showing different parameters for each sex ($P < 0.001$). Although performance between sexes was similar at low SID Lys:NE, differences were greater at higher SID Lys:NE. Furthermore, broken-line linear (BLL), broken-line quadratic (BLQ) and quadratic polynomial (QP) models were fitted to each sex to determine SID Lys:NE and SID Lys daily intake requirements to maximize ADG and G:F. Overall, QP were the best fitting models, and reported that to reach maximum ADG 3.70 (95% CI:[3.43-3.97]) or 4.23 (95% CI:[3.81-4.65]) g SID Lys/Mcal NE was required for gilts and boars, respectively. However, boars ADG was best fitted by BLQ using SID Lys daily intake as independent variable, with the requirement for maximum ADG at 24.2 (95% CI:[21.3-27.2]) g SID Lys/day. The three models reported wide confidence intervals for the requirements at maximum performance, and consequently those were overlapped when comparing boars and gilts. Maximum boars' productive performance when dietary lysine was not limiting was 116% of gilts, and at those levels the amount of SID Lys intake required per kg gain was similar between both sexes. Thus, because ADFI and Lys efficiency of gain was similar, the requirement

differences were driven by the increased growth rate and gain to feed ratio between boars and gilts.

6.2. Introduction

Increasing societal pressure in some countries to stop surgical castration of male pigs will increase the relative production of entire male pigs in future years (Bee et al., 2015). Male pigs that are not castrated have improved feed efficiency and leaner carcasses than barrows (Dunshea et al., 2013), and better feed efficiency than gilts (Cámara et al., 2014) because of a greater lean deposition potential (King et al., 2000; Giles et al., 2009). Several studies have shown that growth differentiation between boars and gilts starts around 40-70 kg body weight (BW) (Campbell et al., 1988; Moore et al., 2013; Cámara et al., 2014). Because lysine is the first limiting amino acid for lean tissue deposition, modelling indicates boars need more lysine intake than gilts to maximize growth performance. Whereas these modelling studies have assumed a lower average daily feed intake (ADFI) for boars than for gilts (NRC, 2012; Dunshea et al., 2013; van der Peet-Schwering and Bikker, 2018), other work has not found evidence of these ADFI differences (Moore et al., 2013; Rikard-Bell et al., 2013a; Aymerich et al., 2020a). Furthermore, those works reported greater differences in average daily gain (ADG) than the assumed inputs in the models when sufficient lysine was available. For instance, NRC (2012) assumed that entire males ADG was only 2.8% greater than gilts between 75-100 kg BW whereas Aymerich et. al. (2020) reported on average a 9.2% greater ADG in the period 70-105 kg and O'Connell et al. (2006) a 17.6% greater ADG.

Available studies comparing lysine requirements of boars and gilts to maximize growth performance have indicated inconsistent results (O'Connell et al., 2006; Moore et al., 2013; Rikard-Bell et al., 2013a). It could be that differences in BW range or genetic lines are partly responsible for this inconsistency. In addition, the different models used to describe the response to the dietary standardized ileal digestible lysine to net energy ratio (SID Lys:NE) in each study might also be responsible for the inconsistencies (Pesti et al., 2009). In a situation of lack of clarity in individual studies, meta-analysis are considered a reasonable and powerful tool to improve the understanding of the response (Kelley and Kelley, 2019) and determine nutritional requirements (van Milgen et al., 2012a). Therefore, the aims of this meta-analysis were to compare the response to increasing dietary lysine between finishing boars and gilts (65 to 100 kg BW), and, if different, determine dietary SID Lys:NE and SID Lys intake requirements for each sex to maximize growth performance.

6.3. Material and methods

This study did not require ethical approval as the data was collected from studies already published in the literature. The methodology outlined by Kelley and Kelley (2019) for meta-analysis in nutrition research was used as a reference to develop a protocol for obtaining meta-data (Supplementary Material S1). Thus, the following section was divided in study eligibility, data sources, study selection, data abstraction, and statistical analyses.

6.3.1. Study eligibility

Only randomized controlled dose-response experiments analysing the effects of dietary lysine on growth performance of finishing boars or gilts were included. The literature search was limited to articles from 2000 onwards to limit differences related to genetic improvements and nutrition advances. In addition, only studies in which initial BW was between 50-85 kg and final BW was between 85-120 kg were considered. Publications were excluded when there were less than 4 dietary lysine levels. Other reasons for exclusion were not meeting amino acid ratios (ideal protein) after reformulation, based on NRC (NRC, 2012), or only providing mixed sex data.

6.3.2. Data sources

The literature search was performed on April 18, 2020, by searching with PubMed and Web of Science using pre-specified search terms like lysine and pig and boar or gilt (see Supplementary Material S1). References in the identified eligible articles were checked and some authors were contacted for further information if data was only available as figures. In addition, one work which at the date of search was not publicly available was also included (Aymerich et al., 2020a). Finally, a publication detected after revising cross references in the selected articles was also included, although not published in a peer-reviewed journal (Moore et al., 2015).

6.3.3. Study selection

A total of 1,473 publications were initially identified after removing the duplicates between both data sources. To determine if studies fulfilled the eligibility criteria, first, the title was checked to discard studies focusing on other topics. Afterwards, the abstracts of the remaining studies were carefully analysed, and if sufficient data was not provided there, the full text was also checked. At the end, there were only 11 publications that fulfilled all inclusion criteria, including 9 studies for boars and 13 for gilts, of which 8 included results for both sexes.

6.3.4. Data abstraction

The data from the selected studies represented 6,654 pigs (1,588 boars and 5,066 gilts) in 128 different treatments (53 for boars and 75 for gilts). Diet information in each study was entered into a single database to reformulate the diets based on NRC (2012) ingredient values to avoid differences related to different ingredient composition. Next, a database was created including: (1) study reference (first author name, year of publication, locations and experiment number), (2) animal characteristics (sex, genetics, initial BW and final BW), (3) experimental design characteristics (pigs per treatment, replicates per treatment), (4) diet characteristics (main energy and protein sources, crude protein, metabolizable energy, net energy, SID Lys and SID Lys:NE, after reformulation), (5) growth performance (ADG, ADFI and gain to feed), and (6) measures of variability for the response variables (standard error of the mean, standard error of the difference, standard deviation or the coefficient of variation). The latter were recorded to provide a measure of the consistency of the means to be used as weights in the regression model (St-Pierre, 2001). All variability measures were transformed to standard error of the mean (SEM). Each row in the dataset corresponded to a treatment of one specific sex.

The ADFI and SID Lys content of the diet were used to calculate daily SID Lys intake.

6.3.5. Statistical analyses

A complete dataset including boars and gilts data was analysed to compare performance of both sexes. The highly suspected heterogeneity was corroborated comparing null models and heterogeneity models using the Bayesian information criteria (BIC). Initially, growth performance of both sexes was compared in a linear mixed model including sex as a fixed effect and study as a random effect using the *nlme* package (Pinheiro et al., 2019) of R (R Core Team, 2019). In addition, the SEM of the specific variable tested was specified as a variance covariate using the *VarPower* function in the weights statement (Pinheiro and Bates, 2000), representing the inverse of the variance as suggested by St-Pierre (2001). Finally, model validity was examined using standardized residual scatterplots to observe if the distribution of residuals was more homogeneous after accounting for the random study effect and the variance covariate adjustment (Supplementary Figure S2). The sex effect significance was determined by the F-test in the ANOVA when *P* value was ≤ 0.05. Least square means and SEM were estimated with the *emmeans* package (Lenth, 2020). Furthermore, the differential response to SID Lys:NE between boars and gilts was analysed in a quadratic polynomial function ($Y_i = L_{QP} + B_{QP} \times X_i + A_{QP} \times X_i^2$) in which the parameters L_{QP}, B_{QP} and A_{QP} were interacted with sex. Posteriorly ANOVA with F-tests was used to assess the significance of the interactions, and only the ones that reduced BIC were considered for the final model.

Next, each sex was modelled independently to determine the response to dietary lysine on growth performance. Regression models to predict growth performance, ADG or gain to feed (G:F), depending on SID Lys:NE and SID Lys daily intake were built using the nlme package (Pinheiro et al., 2019). Broken-line linear (BLL), broken-line quadratic (BLQ), and quadratic polynomial (QP) models were built following Robbins et al. (2006). Furthermore, the quadratic parameter of the BLQ model (A_{BLQ}) was included as a function of B_{BLQ} and the requirement at maximum performance (R_{BLQ}):

$$A_{BLQ} = -B_{BLQ}/\left(R_{BLQ} \times 2\right)$$

Initially, a random component was included for all fixed effects parameters using a diagonal variance-covariance structure to determine which did not account for the between subject model variability. The parameters which had a near zero standard deviation (SD) were removed starting by the one with the lower SD and a model with a general positive variance-covariance structure was fitted. Subsequently, the complex and simpler models were compared using BIC, and the one with the lowest BIC was selected. Over parametrization was assessed analysing the correlation between random parameters in the model, and if present, the model was tested with and without each parameter, selecting the model with the lowest BIC. Only the best fitting model, the ones reporting the lowest BIC, were finally considered. Ninety-five percent confidence intervals (CI) of the fixed effects were calculated for the parameter estimates of the models. The CI of the parameters representing the level at which maximum performance was achieved in BLL and BLQ models were used to compare requirements of boars and gilts. Furthermore, the CI at the inflection point in the QP models was estimated using the delta method in the msm package (Jackson, 2011).

6.4. Results

6.4.1. Study characteristics

The 14 studies included in the meta-analysis are summarized in **Table 6.1**. Initial BW ranged from 49.6 to 84.1 kg, whereas final BW from 86.2 to 120 kg. The minimum SID Lys:NE was 1.59 for gilts and 1.89 for boars whereas the maximum was 5.14 g/Mcal for both sexes. Net energy ranged from 2.32 to 2.80 Mcal/kg, but the diets with higher energy density (> 2.54 Mcal NE/kg) were only from gilts studies (Main et al., 2008; Shelton et al., 2011). The NE range within some studies was related to formulating diets based on digestible energy or metabolizable energy, instead of NE, and to using different ingredient composition tables than NRC (2012). Median year of publication was 2008, and of the 14 studies, 5 were from Australia, 4 from Europe, 4 from North America and 1 from South America. Finally, the median number of replicates per study was 6 and 7, for boars and gilts, respectively.

6.4.2. Sex differences

The effect of sex on growth performance and carcass composition variables is reported in **Table 6.2**. The effects of sex on BW were not statistically analyzed because for some studies BW data was only reported as mixed sex, while others only reported the study average initial and final BW. Nevertheless, on average initial BW was 68.1 and 68.9 kg, average BW was 85.1 and 85.4 kg, and final BW was 102.2 and 101.8 kg, for boars and gilts, respectively. As expected, boars compared to gilts had greater ADG ($P < 0.001$) that was the result of better G:F ($P < 0.001$) with no evidence for differences in ADFI observed ($P = 0.287$). In addition, **Figure 6.1** shows the variation in ADFI between treatments within each study by sex and visually confirms the similar ADFI between boars and gilts. Regarding carcass composition, only backfat thickness was abstracted from the studies because it was the most frequently reported parameter. As expected, backfat thickness was greater in gilts than in boars (11.6 vs. 10.9 mm, $P < 0.001$).

To assess if the response to increasing SID Lys:NE differed between boars and gilts, a quadratic model including the interaction between sex and each of the 3 parameters was built and each interaction was evaluated. The best fitting models to predict ADG and G:F accounting for the interactions are shown in **Figure 6.2**. Best fitting models for both ADG and G:F included a different slope (B_{QP}) and intercept (L_{QP}) for each sex ($P < 0.001$), but a different quadratic parameter (A_{QP}) was not significant and did not improve model fit, therefore it was not included. Summarizing, both ADG and G:F models confirmed a different response to increasing SID Lys:NE between boars and gilts.

Table 6.1. Summary of the studies included in the meta-analysis to predict the effect of sex on the growth performance response to dietary lysine of finishing boars and gilts

Study	Publication – Experiment (Exp.)	Sex	Average BW (kg)		Dietary treatments	Dietary range	
			Initial	Final		SID Lys:NE[1]	NE[2]
1	Aymerich et al. (2020a)	Boars/Gilts	69.6	105.5	5	2.65-4.17	2.54-2.54
2	Cline et al. (2000)	Gilts	53.6	116.4	5	2.60-4.87	2.41-2.54
3	Kill et al. (2003)	Gilts	66.3	95.5	4	2.71-3.83	2.51-2.53
4	King et al. (2000)	Boars/Gilts	80.0	120.0	6	1.89-3.84	2.41-2.51
5	Main et al. (2008) - Exp. 2	Gilts	59.8	86.2	6	2.11-3.86	2.67-2.77
6	Main et al. (2008) - Exp. 3	Gilts	78.4	102.9	6	1.59-3.12	2.71-2.80
7	Moore et al. (2013) - Exp. 2	Boars/Gilts	49.6	103.3	5	2.30-4.70	2.39-2.47
8	Moore et al. (2015)	Boars/Gilts	63.6	100.5	7	2.50-4.70	2.32-2.43
9	Moore et al. (2016)	Boars	60.1	105.1	5	1.91-4.45	2.37-2.45
10	O'Connell et al. (2006) - Exp. 1	Boars/Gilts	60.0	91.0	6	2.85-4.71	2.34-2.46
11	O'Connell et al. (2006) - Exp. 2	Boars/Gilts	81.0	102.0	8	2.47-5.14	2.32-2.48
12	O'Connell et al. (2006) - Exp. 3	Boars/Gilts	80.0	99.0	6	2.47-4.57	2.37-2.48
13	Rikard-Bell et al. (2013a)	Boars/Gilts	60.0	90.0	5	2.32-4.67	2.34-2.46
14	Shelton et al. (2011) - Exp. 3	Gilts	84.1	110.5	6	1.91-3.27	2.62-2.70

BW = body weight;

[1] Standardized ileal digestible lysine to net energy ratio (SID Lys:NE, g/Mcal) calculated after reformulating the diets (NRC, 2012).

[2] Net energy (NE, Mcal/kg) calculated after reformulating the diets (NRC, 2012).

Table 6.2. The effects of sex (boars vs. gilts) on growth performance and carcass composition of finishing pigs from the 14 studies included in the meta-analysis

Item	Boars	Gilts	*P*-value
n (observations)	53	75	-
Initial BW, kg[1]	68.1	68.9	-
Average BW, kg[1]	85.1	85.4	-
Final BW, kg[1]	102.2	101.8	-
Average daily gain, g	1,012 ± 21.5	900 ± 20.5	<0.001
Average daily feed intake, g	2,498 ± 42.3	2,483± 41.7	0.287
Gain to feed, g/kg	406 ± 9.0	363 ± 8.6	<0.001
Backfat thickness, mm[2]	10.9 ± 0.71	11.6 ± 0.71	<0.001

Least square means ± standard error of the mean.

[1] For body weight (BW) the value represents the arithmetic mean of all the observations.

[2] Replicates were 33 and 32, for boars and gilts, respectively.

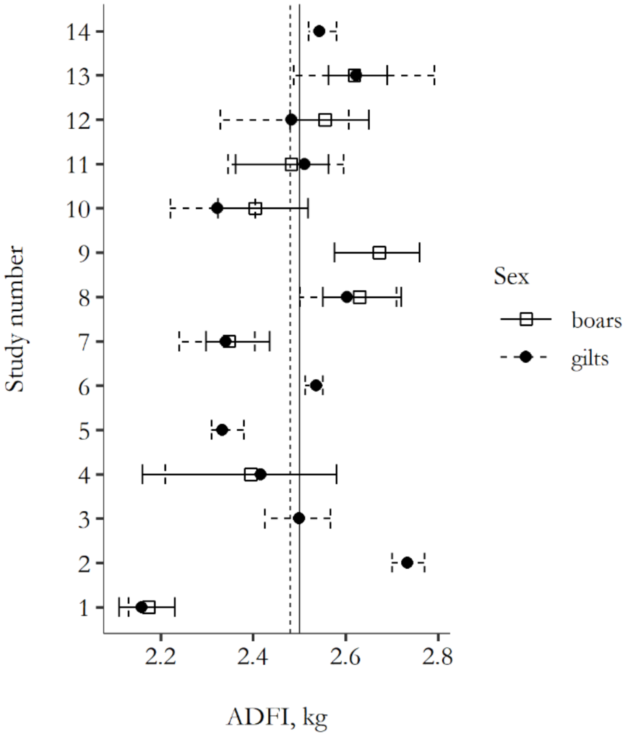

Figure 6.1. Variation in average daily feed intake (ADFI) within each study and sex. Error bars represent the minimum and maximum reported values while the vertical dashed and solid lines represent the mean of each sex.

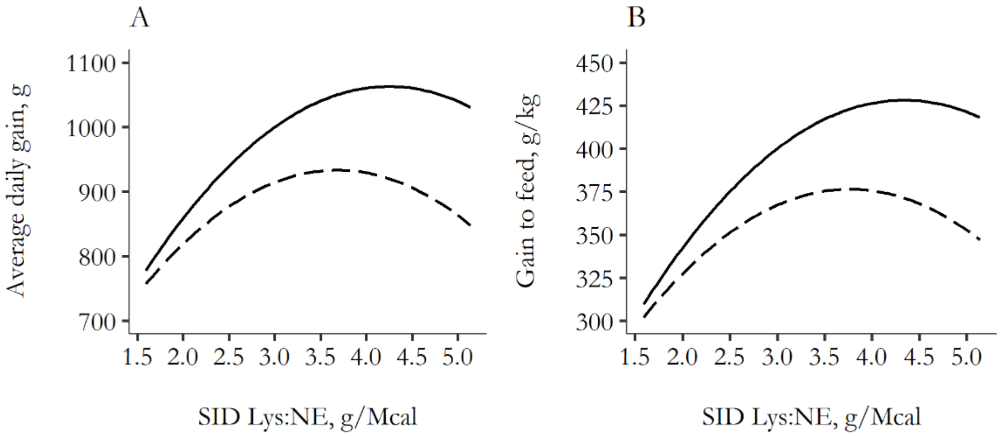

Figure 6.2. Best fitting quadratic polynomial models to predict average daily gain (a) and gain to feed (b) from dietary standardized ileal digestible lysine to net energy ratio (SID Lys:NE) for boars (—) and gilts (--). The regression equations for growth were $Y = -40.3 \times X^2 + 342 \times X + 336$ and $Y = -40.3 \times X^2 + 297 \times X + 387$, for boars and gilts, respectively. The regression equations for feed efficiency (b) were $Y = -15.7 \times X^2 + 136 \times X + 133$ and $Y = -15.7 \times X^2 + 118 \times X + 154$, for boars and gilts, respectively.

6.4.3.Lysine requirements by sex

The different response to SID Lys:NE between boars and gilts suggested fitting models to determine the requirements to maximize performance for each sex separately. The best fitting BLL, BLQ and QP regression equations to describe the effect of SID Lys:NE and SID Lys intake in boars and gilts ADG and G:F and each model BIC are reported in **Table 6.3**. In addition, the final models in response to SID Lys:NE and the observations from each study are illustrated in **Figure 6.3**. Similarly, Figure 4 illustrates the models explaining the effect of SID Lys intake on ADG and G:F and all the observations included in the meta-analysis. Quadratic polynomial models were the best fitting ones except for boars ADG, that was best predicted by BLQ using SID Lys intake as explanatory variable. Nevertheless, the differences in BIC between boars BLQ and QP for both ADG and G:F were at most 2 units with SID Lys:NE as explanatory variable.

Table 6.3. Parmeter estimates of different models to predict average daily gain (ADG, g) and gain to feed (G:F, g/kg) from the dietary standardized ileal digestible lysine (SID Lys) to net energy (NE) ratio and SID Lys daily intake for boars (B) and gilts (G)

Explanatory variable	Response variable	Sex	Parameter estimates[1]			BIC[2]
Broken-line linear[3]			L_{BLL}	U_{BLL}	R_{BLL}	
SID Lys:NE (g/Mcal)	ADG	B	1050 [979,1112]	203 [145, 259]	3.08 [2.94, 3.23]	581
		G	913 [871, 956]	90.8 [55.1, 126.6]	2.99 [2.74, 3.25]	795
	G:F	B	429 [408, 450]	46.9 [35.5, 58.4]	3.69 [3.44, 3.94]	478
		G	371 [352, 390]	32.5 [18.6, 46.5]	3.08 [2.78, 3.37]	667
SID Lys/day (g/day)	ADG	B	1060 [988, 1135]	20.3 [12.7, 27.9]	21.9 [20.4, 23.4]	587
		G	915 [873, 957]	14.4 [8.9, 19.8]	19.2 [17.7, 20.7]	793
	G:F	B	431 [408, 454]	7.31 [5.53, 9.10]	22.9 [21.1, 24.7]	484
		G	371 [352, 390]	4.95 [2.93, 6.96]	19.5 [17.8, 21.2]	667
Broken-line quadratic[4]			L_{BLQ}	B_{BLQ}	R_{BLQ}	
SID Lys:NE (g/Mcal)	ADG	B	109 [-239, 458]	487 [259, 715]	3.88 [3.46, 4.30]	574
		G	490 [295, 685]	233 [94, 372]	3.65 [3.05, 4.25]	791
	G:F	B	117 [23, 210]	145 [89, 201]	4.32 [3.81, 4.84]	468
		G	174 [83, 265]	114 [49, 178]	3.45 [2.95, 3.95]	663
SID Lys/day (g/day)	ADG	B	79.2 [-191, 349]	81.5 [52.3, 110.6]	24.2 [21.3, 27.2]	573
		G	424 [181, 668]	43.5 [16.2, 70.9]	22.6 [19.1, 26.2]	789
	G:F	B	127 [24, 230]	22.9 [12.7, 33.1]	26.6 [22.7, 30.5]	478
		G	174 [65, 283]	18.0 [5.7, 30.3]	21.8 [18.2, 25.4]	665
Quadratic polynomial[5]			L_{QP}	B_{QP}	A_{QP}	
SID Lys:NE (g/Mcal)	ADG	B	260 [71, 450]	380 [272, 487]	-44.9 [-60.6, -29.1]	575
		G	407 [278, 536]	280 [205, 355]	-37.9 [-48.7, -27.0]	774
	G:F	B	131 [57, 206]	135 [93, 177]	-15.3 [-21.2, -9.3]	467
		G	165 [106, 224]	110 [78, 143]	-14.5 [-19.2, -9.7]	657
SID Lys/day (g/day)	ADG	B	235 [42, 429]	64.6 [46.2, 83.1]	-1.27 [-1.73, -0.81]	581
		G	393 [250, 536]	46.5 [32.4, 60.5]	-1.02 [-1.38, -0.66]	789
	G:F	B	147 [59, 235]	20.7 [12.4, 29.1]	-0.375 [-0.573, -0.177]	487
		G	207 [157, 257]	14.3 [9.8, 18.7]	-0.308 [-0.412, -0.205]	673

[1] Estimate [95% confidence interval].

[2] Bayesian information criteria.

[3] Broken-line linear: $Y_i = L_{BLL} + U_{BLL} \times (R_{BLL} - X_i); \quad if\ R_{BLL} \leq X_i$

$Y_i = L_{BLL}; \quad if\ R_{BLL} > X_i$

[4] Broken-line quadratic:

$$Y_i = L_{BLQ} + B_{BLQ} \times X_i - B_{BLQ} \times X_i^2/(R_{BLQ} \times 2); \quad if\ R_{BLL} \leq X_i$$
$$Y_i = L_{BLQ} + B_{BLQ} \times R_{BLQ} - B_{BLQ}/2; \quad if\ R_{BLL} > X_i$$

[5] Quadratic polynomial: $Y_i = L_{QP} + B_{QP} \times X_i + A_{QP} \times X_i^2$

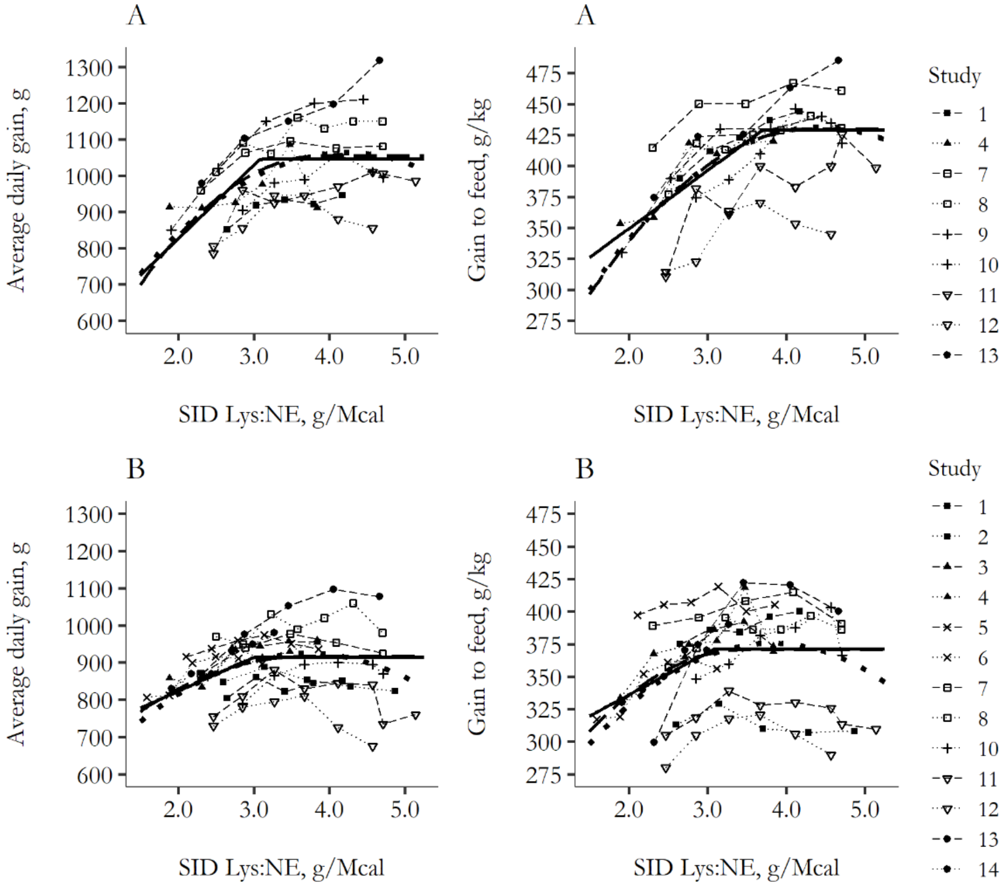

Figure 6.3. Best fitting broken-line linear (BLL, —), broken-line quadratic (BLQ, ---) and quadratic polynomial (QP, ⋯) models to predict boars (a) and gilts (b) growth performance from the dietary standardized ileal digestible lysine to net energy ratio (SID Lys:NE). Each number represents a different study, as summarized in Table 6.1.

As expected, the 3 models reported different SID Lys:NE and SID Lys intake to maximize growth performance, with the lowest being always the BLL. Although the 95% confidence intervals of the requirement (R_{BLL}) were overlapped between sexes, the slope of the effect of increasing SID Lys:NE on ADG was greater in boars than in gilts. Besides, maximum performance (L_{BLL}), for both ADG and G:F, was greater in boars than in gilts regardless of the explanatory variable used. On average boars' maximum performance using BLL was 16% greater than gilts. Broken-line quadratic models did neither report different SID Lys:NE or SID Lys intake requirements (R_{BLQ}) because of the wide confidence intervals. However, boars' requirement was always numerically greater than gilts. For instance, boars required 3.88 g SID Lys/Mcal NE (95% CI: [3.46, 4.30]) or 24.2 g SID Lys/d (95% CI: [21.3, 27.2]) to maximize ADG whereas gilts required 3.65 g SID Lys/Mcal NE (95% CI: [3.05, 4.25]) or 22.6 g SID Lys/d (95% CI: [19.1, 26.2]).

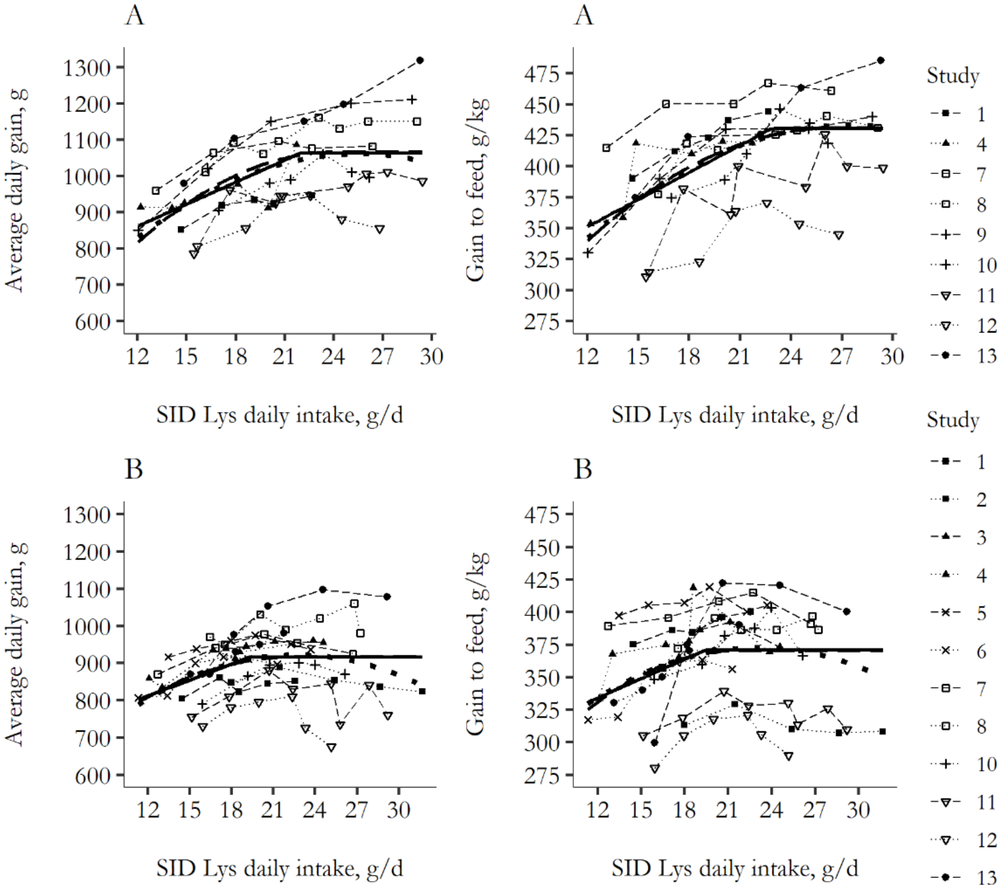

Figure 6.4. Best fitting broken-line linear (BLL, —), broken-line quadratic (BLQ, ---) and quadratic polynomial (QP, ···) models to predict boars (a) and gilts (b) growth performance from the standardized ileal digestible lysine (SID Lys) daily intake. Each number represents a different study, as summarized in Table 6.1.

The QP models reported the highest requirement to reach the maximum performance, calculated at the inflection point of the function. Regarding boars, maximum ADG and G:F were reached at 4.23 and 4.44 g SID Lys/Mcal NE, whereas gilts at 3.69 and 3.79 g SID Lys/Mcal NE, respectively. **Table 6.4** shows the dietary SID Lys required to reach different relative target performances (95-100%) in 2,500 kcal NE/kg diets. To increase 1 point of relative performance between 95-99 % of the maximum performance, dietary SID Lys had to increase around 0.03-0.05%, whereas to increase from 99% to 100%, it required 0.12-0.13% higher dietary SID Lys. Although QP and BLQ SID Lys:NE models fitted similarly for boars, QP reported a greater requirement for maximum ADG that could be related to maximum ADG being slightly greater in the QP than in the BLQ (1063 vs. 1054 g). Finally, as for the BLL, QP reported boars maximum ADG and G:F to be 116% of gilts.

Table 6.4. Dietary standardized ileal digestible lysine (%) required to reach target average daily gain (ADG) and gain to feed (G:F) in relation to their maximum for 65 to 100 BW boars and gilts using quadratic polynomial models[1]

	% of maximum performance					
Item	95	96	97	98	99	100
ADG						
Boars	0.79	0.82	0.85	0.89	0.94	1.06
Gilts	0.65	0.68	0.71	0.75	0.80	0.92
G:F						
Boars	0.81	0.84	0.88	0.92	0.98	1.11
Gilts	0.67	0.70	0.73	0.77	0.82	0.95

[1] Standardized ileal digestible lysine (SID Lys) calculated assuming a diet with 2,500 kcal net energy/kg.

6.5. Discussion

The increasing importance of entire male production requires good estimations of their nutrient requirements. As lysine is the first limiting AA for protein deposition (NRC, 2012) and boars have a greater potential for protein deposition than gilts (King et al., 2000; Giles et al., 2009), this study focused on the differential response of boars and gilts to increasing SID Lys:NE ratio. In the last decade, the publication of different nutrient requirements for boars and gilts evidenced the increasing concern on this issue. For instance, NRC (2012) provided different requirements for boars and gilts, whereas the previous version did not (NRC, 1998). Similarly, more recent work also gave different requirements for each sex (van der Peet-Schwering and Bikker, 2018). These publications were based on models which consider ADFI and ADG or protein deposition as input parameters. Although these approaches might provide reliable estimations, it is necessary to validate the values provided by these models with experimental data to determine whether those approaches are valid or need further revision.

Consistent with the literature, this meta-analysis confirmed that boars grow more rapidly and with a better feed efficiently than gilts, similar to results reported by Cámara et al. (2014), and without evidence of differences in ADFI as reported by Van Lunen and Cole (1996). The variation in ADFI between studies could be related to the differences in dietary NE concentration or to the feed intake potential of the genotype used. The reduction in BFT for boars might be the result of less energy available for fat deposition as a greater fraction is used for protein deposition (Moore et al., 2013). Nevertheless, some publications have not reported evidence for different BFT between boars and gilts (Gispert et al., 2010; Moore et al., 2013; Trefan et al., 2013) whereas others have (Cámara et al., 2014; Aymerich et al., 2019).

The different requirements to maximize ADG and G:F reported by BLL, BLQ and QP models might be the result of the model itself (Pesti et al., 2009), but also for which fixed effects parameters a random component was included in the model (Robbins et al., 2006). Moreover, as the meta-data only included studies in a specific BW range, it was not considered necessary to account for the variation in requirements related to BW as implemented by van Milgen et al. (2012a). The different slope before reaching the plateau in the BLL models for ADG suggested that although the requirement estimate was not different for those models, the marginal efficiency was greater for boars. The low requirement for boars ADG could be related to the requirements underestimation of BLL model outlined by some authors.

Commonly, models with a quadratic shape are preferred for being "biologically meaningful" (Remmenga et al., 1997) or because they better represent the "diminishing marginal productivity". However, the concept of a nutritional requirement consists in assuming that a plateau is reached, and therefore, models which combine a plateau but with an ascending quadratic part (BLQ) might be a good combination of both concepts. However, the greater standard error for the requirement estimate of BLQ models as outlined by Pesti et al. (2009) might rise concerns around the precision of that estimate. Generally, the best fit in this study was provided by the QP models, probably related to accounting for the reduction in performance at dietary lysine above the requirement. This reduction could be the result of a reduced energy available for fat deposition, as part of it is used to deaminate excess amino acids (Bender, 2012).

The outputs of the QP models showed that to increase the performance of both boars and gilts from 99 to 100%, the required increase in dietary SID Lys was of similar magnitude to that required to increase performance from 96 to 99%. Therefore, in some price contexts it might not be economically feasible to feed finishing boars and gilts at their maximum performance. Nutritionist can use the QP equations provided to decide the most optimal diet for their production goal and whether it is feasible or not to feed boars and gilts separately. For instance, to reach 99% of maximum ADG it would be necessary to feed diets with 3.75 or 3.20 g SID Lys/Mcal NE for boars and gilts, respectively. Similarly, in the 2,500 kcal NE/kg diet example, boars required between 0.14-0.16% more dietary SID Lys than gilts to reach between 95-100% of maximum ADG or G:F.

Models describing the effect of SID Lys intake could be more useful for practical feed formulation when feed intake is well characterized, but because feed intake is difficult to predict, SID Lys:NE is usually preferred. Moreover, in this meta-analysis, BLQ was the best fitting model for boars ADG when using SID Lys intake as explanatory variable, but gilts fit was rather poor. The BLQ predicted a requirement for maximum ADG at 24.2 g and 22.6 g SID Lys/d, for boars and gilts, respectively. Both values were relatively high compared to NRC (2012) between 50 to 100 kg BW, 18.2 and 18.0 g SID Lys/d, for boars and gilts, respectively. In addition, they reported no differences between both sexes. This could be the result of assuming that boars ADG would be only 102% of gilts, and with lower average performance than the maximum in this meta-analysis.

The SID Lys intake models might also be used to calculate the efficiency of use of SID Lys per kg gain at the maximum performance. Main et al. (2008) found a constant efficiency of around 20 g total ileal digestible Lys/kg gain was for grow-finishing pigs at the level at which growth performance was maximized. In the present study, considering the SID Lys intake and the performance at the breakpoint (BLL and BLQ) or the inflection point (QP), there were some differences between models, but the value was similar between sexes. Sex related variation in lysine efficiency was between 20.7-21.0 for BLL, 22.7-24.6 for BLQ, and 24.1-24.7 g SID Lys/kg gain for QP, for boars and gilts, respectively. Thus, relevant differences in SID Lys efficiency of utilization for growth at maximum performance between sexes were only reported by BLQ. Unexpectedly, boars did not require more SID Lys per kg gain, although protein deposition represents a greater fraction of their growth. This results would be further supported by Heger et al. (2009), that suggested that there was no evidence of differences on SID Lys utilization between pigs with different protein deposition potential. Future studies might aim to compare SID Lys digestibility and maintenance requirements of finishing boars and gilts.

The relative maximum performance of boars for the different SID Lys:NE models was around 115-116% of gilts, for both ADG and G:F. If there are no differences in SID Lys efficiency for growth between sexes, then the requirements of boars relative to gilts would be directly related to their relative performance. Therefore, assuming finishing boars SID Lys requirement to be around 115% of gilts might be useful for practical feed formulation. Dunshea et al. (2013) suggested that SID Lys:NE requirements of boars relative to gilts might be 108% from 50 to 95 kg BW and 114% from 95 to 125 kg BW when modelled with InraPorc (van Milgen et al., 2008) using previously published data (Quiniou et al., 2010) as inputs. Thus, the relative requirements were the result of the observed differences in performance, which were small during the first 42 days in the grow-finishing facilities. In addition, the single phase diet used in that study might have been initially limiting boars growth.

Summarizing, this study provided evidence of a different response of finishing gilts and boars to increasing dietary lysine. In this meta-analysis, the maximum performance of boars relatively to gilts when dietary lysine was not limiting was around 115-116% between 65-100 kg BW. Thus, the requirements of boars can be expected at around 115% of gilt requirements until further studies compare the efficiency of use of lysine between sexes. However, basing boar requirements on gilts requires good estimates of gilts dietary lysine requirements. The equations provided in this work, especially the quadratic polynomial, can be used to evaluate the effects of different dietary strategies in boars and gilts in the body weight range studied.

CHAPTER 7

The implications of nutritional strategies that modify dietary energy and lysine for growth performance in two different swine production systems

The implications of nutritional strategies that modify dietary energy and lysine for growth performance in two different swine production systems

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Keywords: lysine, energy, growing pig, finishing pig, castration.

7.1. Abstract

This work aimed to determine the impacts of lowering dietary net energy (NE) density in two swine production systems that produce pigs with different carcass traits. To ensure that dietary lysine was not limiting growth, two studies were conducted in a 2 x 2 factorial arrangement with NE and standardized ileal digestible lysine (SID Lys) as experimental factors. A total of 1,248 pigs were used in each study, Pietrain (Exp. 1, males non-castrated) or Duroc (Exp. 2, males castrated) sired. Reducing NE resulted in a greater feed intake; however, this was not sufficient to reach the same NE intake. Whereas in Exp. 1 a 3.2% lower NE intake did not impair average daily gain (ADG; $P = 0.220$), in Exp. 2 a 4.7% lower NE intake reduced ADG by 1.4% ($P = 0.027$). Furthermore, this effect on ADG entailed a reduced ham fat thickness ($P = 0.004$) of the first marketed pigs. Increasing SID Lys only had a positive effect in Exp. 1, but no significant interaction between NE and SID Lys was reported ($P \geq 0.100$). Therefore, dietary NE can be reduced without impairing growth performance when pigs can increase feed intake sufficiently, and thus, limit energy deficiencies.

7.2. Introduction

It is necessary to have a thorough understanding of the consequences of modifying dietary energy and lysine in each specific pig production context because energy and amino acids are the most expensive constraints in feed formulation. In Europe, the swine industry involves two main production systems depending on the sire line used and the entire/castrated status of males. These systems result in carcasses with different fat /lean depositions and qualities in relation to the requirements of the packing and curing industries (Bonneau and Lebret, 2010). For the market that requires high lean carcasses, highly conformed sire lines such as Pietrain (Edwards et al., 2003; Gispert et al., 2007) without male castration are preferred. In contrast, for the market that requires a minimum fat deposition (Masferrer et al., 2018), high feed intake sire lines (Duroc or synthetic lines) are used, with males usually castrated (Čandek-Potokar and Škrlep, 2012; Daza et al., 2016).

Thus, to maximize performance and pork quality while meeting the processors' requirements, each sire line and sex combination (Augspurger et al., 2002; Carabús et al., 2017; Aymerich et al., 2019) needs tailored nutritional programs (Pettigrew and Esnaola, 2001; Čandek-Potokar and Škrlep, 2012).

Adjusting dietary energy density is a common practice for dealing with the price volatility of high energy ingredients (fats and oils) (Avalos, 2014). When it is necessary to minimize the cost of feed, it is possible to reduce energy density without negatively impacting average daily gain (ADG) because, pigs increase their average daily feed intake (ADFI) to reach a similar energy intake (Schinckel et al., 2012; Li and Patience, 2017). However, in some conditions, pigs cannot completely compensate for the reduced energy density, especially younger animals (Oresanya et al., 2007; Quiniou and Noblet, 2012; Smit et al., 2017) or low-weight pigs (Hastad et al., 2020) with a limited ADFI (Aymerich et al., 2020b). Under these circumstances, the lower energy intake may impair ADG by limiting protein (Urynek and Buraczewska, 2003; Ferreira et al., 2019) or fat deposition (Apple et al., 2004; Beaulieu et al., 2009; Cámara et al., 2014), depending on whether pigs are in the energy or amino acid dependent phase (Möhn et al., 2000). In the systems for producing lean carcasses the effects of reducing dietary energy density could be problematic when protein deposition is limited; however, in systems requiring a minimum fat deposition the effect may be a problem when fat deposition is reduced. In a meta-regression analysis, Nitikanchana et al. (2015) showed that increasing dietary energy density resulted in greater ADG if dietary lysine was not limiting. Therefore, it is relevant to work at the amino acids levels which do not limit growth performance if we want to evaluate the energy effects. Marçal et al. (2019) suggested that energy trials should formulate diets based on the standardized ileal digestible lysine to net energy ratio (SID Lys:NE) instead of SID Lys, to report effects on ADG. However, when pigs cannot completely compensate for a reduced energy density (Quiniou and Noblet, 2012), then the lower energy intake will entail a reduced SID Lys intake (Hinson et al., 2011) that may limit growth performance (Rodríguez-Sánchez et al., 2011).

The hypothesis of the present work was that reducing net energy (NE) will not impact growth performance when SID Lys intake is not limiting if pigs are able to match the same NE intake in the two abovementioned systems. Therefore, the aim of this work was to determine the effects of reducing dietary net energy (NE) and their interaction with dietary SID Lys on growth performance in two different swine production systems targeting specific products.

7.3. Materials and Methods

7.3.1. Experiment 1: *Pietrain*

The aim of this experiment was to determine whether reducing NE had an impact on growth performance of lean pigs (20-40 kg) and evaluate if dietary SID Lys modified the possible effects. Furthermore, evaluate the carryover effects when lean pigs are fed a common diet (40-110 kg).

7.3.1.1. Experimental design and animals

In this study, the effects of dietary NE and SID Lys on growth performance of lean growing pigs was analyzed in a 2 x 2 factorial arrangement. The treatments represented the factorial combination of one of two SID Lys levels (1.00 vs. 1.20 %) and NE levels (2,360 vs. 2,550 kcal NE/kg). At arrival, a total of 1,248 pigs [Pietrain × (Landrace × Large white), half boars and half gilts] were grouped by body weight (BW) in 96 non-mixed sex pens of 13 pigs. After a 9 day adaptation period, pigs were individually weighed (19.7±3.8 and 20.0±4.1 kg, mean±SD, boars and gilts, respectively) and each pen was allocated to one of the four dietary treatments, with twenty-four replicates per treatment. Pens were classified in one of three BW blocks (large, medium, or small). Each pen (3x3 m) had a half slatted concrete floor, 1-hole wet-dry Maxi Grow Feeder (Rotecna, Agramunt, Spain) and an additional nipple waterer on the other side. Ad libitum access to feed and water was ensured during the entire trial. Pigs were individually weighed and monitored using electronic ear tags at the beginning of the trial, and at day 14, 26, 68 and 116, when the experiment finished. Feed intake was measured weekly on a pen basis considering the feed offered and measuring the remaining feed in each feeder. In addition, when a pig was removed due to illness or death, the feed intake was corrected for the days in the week that the pig was not in the pen.

7.3.1.2. Feeding and analyses

The pigs were fed a common commercial diet (1.17% SID Lys and 2,500 kcal NE/kg) in the nine days prior to starting the experiment. Afterwards, during the first 26 days of the experiment, pigs were fed the four experimental diets, based on maize, wheat and soybean meal (**Table 7.1**). To reduce dietary NE, animal fat inclusion was reduced whereas wheat middlings were increased. In addition, SID Lys was increased by modifying the inclusion of crystalline amino acids. Feed was produced in successive blending batches (5,000 kg), and 2% animal fat was added post-pelleting to ensure a good quality pellet. After pelleting, feed samples were collected for each blending batch and analyzed for crude protein (ISO 16634-2:2016) and crude fat (Commission Regulation (EC) No 152/2009 of 27 January 2009) before used to ensure no relevant deviations from the calculated values. Furthermore, the AA composition (Method 994.12)(AOAC International, 2007) was posteriorly analyzed in a blend of the different batches of each experimental feed. From day 26 onwards, all pigs were fed the same feeds. One feed (0.95% SID Lys and 2,440 kcal NE/kg) from day 26 to 68 and the other feed (0.84% SID Lys and 2,450 kcal NE/kg) from day 68 to 116. During the entire trial, feeds were distributed in the different pens using an automatic feeding system (DryExact Pro; Big Dutchman, Vechta, Germany). For the low SID Lys diets, the cost of feed ingredients was 253 and 268 €/t for the low and high energy treatments, respectively. For the high SID Lys feed, the cost of feed ingredients was 265 and 280 €/t for the low and high energy treatments, respectively. The cost of feed ingredients in the common feed phases was 225 €/t for the period 26-68 , whereas the last period (68-116) was 215 €/t.

Table 7.1. Ingredient, calculated and analyzed composition (as fed basis) of the feeds used in Experiment 1

	1.00 % SID Lys[1]		1.20 % SID Lys	
Net energy, kcal/kg	2,360	2,550	2,360	2,550
Ingredient composition ,%				
Maize	37.15	35.01	36.01	33.68
Wheat	35.00	35.00	35.00	35.00
Wheat middlings	2.80	-	2.04	-
Soybean meal	19.50	21.00	20.60	21.50
Animal fat	1.00	4.50	1.00	4.50
Calcium carbonate	0.64	0.63	0.66	0.63
Dicalcium phosphate	1.24	1.27	1.25	1.27
Sodium chloride	0.42	0.42	0.42	0.42
Lysine sulphate	0.65	0.60	0.98	0.96
L-Threonine	0.18	0.17	0.30	0.29
DL-Methionine	0.15	0.15	0.26	0.27
L-Valine	0.02	-	0.13	0.13
L-Tryptophan	0.01	0.01	0.05	0.05
L-Isoleucine	-	-	0.05	0.05
Phytase[2]	0.01	0.01	0.01	0.01
Acids mix[3]	0.70	0.70	0.70	0.70
VIT-MIN premix[4]	0.55	0.55	0.55	0.55
Calculated composition[1]				
Dry matter, %	87.96	88.39	88.05	88.49
Crude fiber, %	3.01	2.73	2.95	2.72
Neutral detergent fiber,	10.06	8.92	9.77	8.86
Starch, %	44.68	42.72	43.82	41.89
Crude fat, %	3.23	6.57	3.18	6.54
Crude protein, %	16.71	16.77	17.59	17.51
SID Lys, %	1.00	1.00	1.20	1.20
Net energy, kcal/kg	2,360	2,550	2,360	2,550
Total Ca	0.62	0.62	0.63	0.63
STTD P	0.38	0.38	0.39	0.38
Analyzed composition, %				
Crude fat	3.3	6.2	3.3	6.5
Crude protein	16.5	17.0	17.1	17.5
Lysine	1.12	1.11	1.32	1.28
Methionine + Cysteine	0.66	0.66	0.79	0.78
Threonine	0.76	0.77	0.91	0.88
Valine	0.77	0.79	0.90	0.89
Isoleucine	0.68	0.71	0.73	0.75

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[1] SID: standardized ileal digestible; STTD: standardized total tract digestible.

[2] 6-phytase (750 FTU/kg).

[3] Blend of formic and lactic acid with medium chain fatty acids [4]Provided per each kg of feed: 6,000 IU vitamin A, 2,000 MIU vitamin D_3, 20 mg vitamin E, 0.7 mg vitamin K, 1.0 mg vitamin B_1, 4.0 vitamin B_2, 1.2 vitamin B_6, 0.02 vitamin B_{12}, 15 mg niacin, 12 mg pantothenic acid, 120 mg choline from choline chloride, 90 mg Fe from iron sulphate, 100 mg Zn from zinc sulphate, 50 mg Mn from manganese oxide, 90 mg Cu from copper sulphate, 1.8 mg I from potassium iodide and 0.25 mg Se from sodium selenite.

7.3.1.3. Calculations and statistical analyses

Pen BW, ADG, ADFI, NE daily intake, SID daily intake, feed to gain ratio (F/G), NE efficiency per kg gain (NEE), SID Lys efficiency per kg gain (LysE), and feed cost per kg gain were calculated per pen for the initial phases (*Phase 1*: 20-29 kg BW – d 0 to 14, *Phase 2*: 29-38 kg BW – d 14 to 26). In addition, BW, ADG, ADFI and F/G were calculated for the period when pigs were fed a common diet. The average ADG and ADFI were calculated for *Phases 1 - 2* , and *Overall* weighting according to the number of days in each subphase. The other variables were then recalculated using the ADG and ADFI. Statistical analysis was carried out with R (R Core Team, 2019). Linear mixed models, initially including SID Lys, NE, BW block and sex, and all the possible interactions, were initially fitted using the *nlme* package (Pinheiro et al., 2019) considering room as a random effect. The models were assessed using type III ANOVA. Only interactions that were significant ($P \leq 0.05$) for at least one variable were included in the final model. The *emmeans* package (Lenth, 2020) was used to calculate the least square means.

7.3.2. Experiment 2: *Duroc*

The aim of experiment 2 was to determine the effects of reducing NE in different dietary SID Lys levels on the growth performance of Duroc pigs, which have a high feed intake capacity, and the effects of NE on carcass composition. The experiment was divided in two subphases (30-75 and 75-120 kg BW) in which the main differences were the SID Lys levels tested and the low NE value.

7.3.2.1. Experimental design and animals

We used a 2 x 2 factorial design to analyze the effects of NE and SID Lys. From 30 to 75 kg BW pigs were fed either 0.94 or 1.04% SID Lys and 0.80 or 0.90 % SID Lys from 75 to 120 kg BW. Regarding NE, pigs were fed either 2,450 kcal NE/kg or a low energy diet that was 2,200 and 2,230 kcal NE/kg, for the first and second subphase, respectively. A total of 1,248 pigs [Duroc × (Landrace × Large white), half barrows and half gilts] were randomly grouped in non-mixed sex pens of 13 animals according to their initial body weight. After a 10 day adaptation period, pigs were individually weighed (33.5±5.0 and 31.4±4.9 kg, mean±SD, barrows and gilts, respectively) and the pens were randomly allocated to one of the four dietary treatments, with twenty-four replicates per treatment, and classified in three BW blocks. Each pen (3x3 m) had a half slatted concrete floor, 1-hole wet-dry Maxi Grow Feeder (Rotecna, Agramunt, Spain) and an additional nipple waterer on the other side. *Ad libitum* access to feed and water was ensured during the entire trial. Pigs were individually weighed and monitored using electronic ear tags at day 0, 23, 43, 72 and 85, when the experiment finished. Feed intake was measured weekly on a pen basis considering the feed offered and measuring the remaining feed in each trough. In addition, when a pig was removed due to illness or death, the feed intake was corrected for the days in the week that the pig was not in the pen. The day after the experiment finished, a total of 380 pigs (half barrows and half gilts) from the large BW block, representing the first marketing group, were moved to the slaughterhouse (Cárnicas Cinco Villas, Ejea de los Caballeros, Spain). Pigs of each sex were divided into two groups, depending on whether they came from the high or low NE treatments. Individual carcasses were weighed, and carcass composition was measured using Autofom III (Frontmatec Food Technology, Kolding, Denmark). The measured parameters included hot carcass weight (HCW), carcass leanness (CL), backfat thickness (BFT) and ham fat thickness (HFT). Carcass leanness (%) was automatically calculated from 9 measurements provided by the 16 ultrasound transducers using the official equations for grading carcasses in Spain (2012/384/UE).

7.3.2.2. Feeding and analyses

During the 10 day adaptation period pigs were fed a common commercial diet (1.08% SID Lys diet and 2,475 kcal NE/kg). The experiment was divided into two phases, one from day 0 to 43 (Growing phase) and one from day 43 to 85 (Finishing phase). In both phases the pigs remained in the same treatment, that is, one of the combinations of high or low SID Lys and high or low NE. In the Growing phase dietary treatments, SID Lys was increased using crystalline AA. To reduce NE the inclusion of animal fat was reduced while part of wheat was replaced by wheat middlings and barley. Similarly, in the Finishing diets, dietary NE was limited by reducing the amount of palm oil included, while maize was replaced by barley and wheat middlings, and part of the soybean meal by sunflower meal. As in the initial feeds, differences in dietary SID Lys were the result of modifying the inclusion of crystalline AA (**Table 7.2**). Feed was produced in successive blending batches (5,000 kg), and in the high NE diets a 2.0-1.5% of the fat source, for Growing and Finishing feeds, respectively, was applied post-pelleting to ensure a good quality pellet. After pelleting, feed samples were collected for each blending batch and crude protein (ISO 16634-2:2016) and crude fat (Commission Regulation (EC) No 152/2009 of 27 January 2009) were analyzed before use to ensure that levels were similar to those calculated. Furthermore, AA composition (Method 994.12)(AOAC International, 2007) was analyzed in a blend of the different batches of each feed (**Table 7.3**). During the entire trial, feeds were distributed in the different pens using an automatic feeding system (DryExact Pro; Big Dutchman, Vechta, Germany).

7.3.2.3. Calculations and statistical analyses

Pen BW, ADG, ADFI, NE daily intake, SID daily intake, F/G, NEE, LysE, and feed cost per kg gain were calculated per pen for four phases (days 0-23, 23-43, 43-72, 72-85). Data from days 0-43 (*Growing phase*) were combined because there was a health challenge that increased the variability in the results after the first 23 days. In addition, data from days 43-85 days were also combined in a single period (*Finishing phase*) because of the short duration of the last period. The average ADG and ADFI were calculated for each phase weighting by the number of days in each subphase. The other variables were then recalculated using the ADG and ADFI. Statistical analyses were carried out with R (R Core Team, 2019). Linear mixed models initially including SID Lys, NE, BW block, sex, and all the possible interactions were initially fitted using the *nlme* package (Pinheiro et al., 2019) considering room as a random effect. Afterwards, interactions that were never significant ($p > 0.05$) were removed from the final models. Then, type III ANOVA was performed using the same package for each variable. The *emmeans* package (Lenth, 2020) was used to calculate least square means. The effect of NE on carcass traits of first marketed pigs was analyzed using linear models (R Core Team, 2019). To predict CL, BFT and HFT, HCW was included as a covariate in the model. The interaction of HCW with NE was initially tested, and if not significant ($P > 0.050$), it was included just as a linear predictor of carcass traits.

Table 7.2. Ingredient composition (as fed basis) of the feeds used in Experiment 2

	Growing phase (d 0-43)				Finishing phase (d 43-85)			
SID Lysine, %[1]	0.94		1.04		0.80		0.90	
Net energy, kcal/kg	2,200	2,450	2,200	2,450	2,230	2,450	2,230	2,450
Ingredient composition ,%								
Maize	30.00	30.50	30.00	30.50	25.00	40.50	25.00	40.50
Wheat	15.00	30.00	15.00	30.00	25.00	25.00	25.00	25.00
Barley	21.55	14.46	22.01	13.82	26.79	15.33	27.31	15.35
Wheat middlings	12.00	-	12.00	-	8.00	-	8.00	-
Soybean meal 47%	10.90	11.80	10.00	12.00	3.50	7.50	2.50	7.00
Sunflower meal	6.00	6.00	6.00	6.00	8.00	6.00	8.00	6.00
Animal fat	1.00	3.60	0.85	3.55	-	-	-	-
Palm oil	-	-	-	-	0.80	2.80	0.80	2.80
Calcium carbonate	1.26	1.24	1.26	1.24	1.28	1.22	1.26	1.22
Dicalcium phosphate	0.10	0.16	0.10	0.16	-	0.12	-	0.13
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Lysine sulphate	0.77	0.80	1.01	0.99	-	-	-	-
Lysine HCl	-	-	-	-	0.54	0.49	0.70	0.63
L-Threonine	0.19	0.19	0.28	0.26	0.18	0.16	0.26	0.24
Liquid MHA[2]	0.13	0.14	0.21	0.21	0.10	0.10	0.17	0.17
L-Valine	0.04	0.05	0.12	0.12	0.03	0.03	0.12	0.11
L-Tryptophan	0.02	0.03	0.04	0.04	0.02	0.02	0.05	0.04
L-Isoleucine	-	-	0.08	0.08	0.04	-	0.11	0.07
Phytase[3]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Acids mix[4]	0.30	0.30	0.30	0.30	-	-	-	-
VIT-MIN premix[5]	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32

[1] SID: standardized ileal digestible.

[2] Methionine hydroxy analogue

[3] 6-phytase (750 FTU/kg).

[4] Blend of formic and lactic acid with medium chain fatty acids

[5] Provided per each kg of feed in the growing phase: 4,500 IU vitamin A, 2,000 MIU vitamin D_3, 15 mg vitamin E, 0.7 mg vitamin K, 1.0 mg vitamin B_1, 4.0 vitamin B_2, 1.2 vitamin B_6, 0.020 vitamin B_{12}, 15 mg niacin, 12 mg pantothenic acid, 107 mg of choline from choline chloride, 90 mg Fe from iron sulphate, 100 mg Zn from zinc sulphate, 50 mg Mn from manganese oxide, 20 mg Cu from copper sulphate, 1.8 mg I from potassium iodide and 0.25 mg Se from sodium selenite.

Provided per each kg of feed in the finishing phase: 2,000 IU vitamin A, 1,500 MIU vitamin D_3, 7 mg vitamin E, 0.6 mg vitamin K, 0.8 mg vitamin B_1, 3.2 vitamin B_2, 1.0 vitamin B_6, 0.016 vitamin B_{12}, 12 mg niacin, 7 mg pantothenic acid, 107 mg choline from choline chloride, 72 mg Fe from iron sulphate, 80 mg Zn from zinc sulphate, 40 mg Mn from manganese oxide, 16 mg Cu from copper sulphate, 1.8 mg I from potassium iodide and 0.25 mg Se from sodium selenite. [6]STTD: standardized total tract digestible.

Table 7.3. Calculated and analyzed composition (as fed basis) of the feeds used in Experiment 2

	Growing phase (d 0-43)				Finishing phase (d 43-85)			
SID Lysine, %[1]	0.94		1.04		0.80		0.90	
Net energy, kcal/kg	2,200	2,450	2,200	2,450	2,230	2,450	2,230	2,450
Calculated composition								
Dry matter, %	88.1	88.5	88.1	88.3	88.6	88.5	88.7	88.5
Crude fiber, %	5.49	4.44	5.47	3.63	5.57	4.30	5.55	4.28
Neutral detergent fiber, %	16.1	12.0	16.1	10.7	16.1	11.8	16.1	11.8
Starch, %	41.1	44.2	41.3	45.2	45.8	48.0	46.1	48.0
Crude fat, %	3.20	5.54	3.05	4.79	2.90	4.94	2.90	4.93
Crude protein, %	15.6	15.1	15.7	15.7	13.4	13.3	13.4	13.4
SID Lys, %	0.94	0.94	1.04	1.04	0.80	0.80	0.90	0.90
Net energy, kcal/kg	2,200	2,450	2,200	2,450	2,230	2,450	2,230	2,450
Total Ca	0.60	0.60	0.60	0.60	0.57	0.57	0.56	0.57
STTD P[6]	0.31	0.30	0.31	0.30	0.29	0.29	0.29	0.29
Analyzed composition, %								
Crude fat	3.5	5.5	3.4	4.9	3.3	5.2	3.2	5.3
Crude protein	15.9	15.8	16.0	16.3	13.6	13.4	13.7	13.8
Lysine	1.04	1.07	1.19	1.18	0.91	0.87	0.99	0.97
Methionine + Cysteine[2]	0.61	0.64	0.70	0.71	0.56	0.54	0.61	0.60
Threonine	0.67	0.70	0.77	0.77	0.61	0.59	0.65	0.63
Valine	0.72	0.75	0.81	0.83	0.64	0.63	0.71	0.70
Isoleucine	0.55	0.60	0.63	0.68	0.50	0.49	0.55	0.54
Feed cost, €/t	220.2	232.8	231.1	249.0	204.0	212.6	219.8	228.6

[1] SID: standardized ileal digestible.

[2] Sum of Met and Cys from vegetal sources and synthetic Met from methionine hydroxy analogue.

7.4. Results

7.4.1. Experiment 1: *Pietrain*

The analyzed content of the feeds was close to that calculated, and only some small deviations in the CP content were reported for some dietary treatments; however, they were within the error of the analytical method (±0.50 % CP). In addition, the amino acid profile did not show any significant deviations in the amino acid composition of the feeds. Furthermore, the final statistical model only included the double interactions between SID Lys, NE, BW block and sex. Triple and quadruple interactions were not included as they were never significant ($P > 0.05$).

7.4.1.1. Effects on growth performance

The effects of dietary NE and SID Lys on growth performance are reported in **Table 7.4**. There was no evidence of an interaction between SID Lys and NE for any of the analyzed variables ($P \geq 0.100$). Pigs were 0.7 ($P = 0.003$) and 1.1 kg heavier ($P < 0.001$), on day 14 and 26, respectively, when SID Lys was increased, but no evidence of a NE effect on BW was observed ($P \geq 0.331$) from day 0 to 26. Pigs fed the high SID Lys diets showed a greater ADG in both initial phases ($P < 0.001$) due to a reduced F/G ($P < 0.001$), as no evidence of differences in ADFI ($P \geq 0.821$) were reported. Thus, increasing 20 % dietary SID Lys resulted in a 20 % greater SID Lys intake ($P < 0.001$) but only a 6.4 % increase in ADG overall Phases 1- 2. The NEE was also reduced ($P < 0.001$) in a similar proportion to F/G whereas LysE significantly increased ($P < 0.001$); thus, SID Lys efficiency for growth was worsened. Feed cost per kg gain was significantly reduced in Phase 1 ($P = 0.006$) but there was no evidence of a reduction in Phase 2 ($P = 0.266$). Reducing 190 kcal NE/kg by removing 3.5 % added animal fat did not impact significantly ADG in either of the experimental phases ($P \geq 0.220$). Although the ADFI of pigs in the low NE diet was on average 0.05 kg greater ($P < 0.001$) than the ADFI of pigs fed the high NE diet, the calculated NE intake was greater in the high NE diet ($P < 0.001$). As a result of the higher ADFI but lower NE intake, F/G improved whereas NEE was worsened ($P < 0.001$) when NE was increased. Similarly, feed cost per kg gain was lower for the 2,360 kcal NE/kg diets for each phase and overall ($P \leq 0.004$).

When fed a common diet, pigs previously in the high SID Lys treatments remained heavier at day 68 ($P = 0.023$), but the same difference was not significant at the end of the experiment ($P = 0.103$). Interestingly, although initially there was no evidence of a difference in BW in relation to NE ($P = 0.331$), at day 116 pigs that from day 0-28 had been fed the low NE diets were 1.3 kg heavier than pigs in the high NE diet ($P = 0.025$). The increased BW was the result of a greater ADFI ($P = 0.001$) and consequently a greater ADG ($P = 0.037$). A tendency for a poorer F/G in pigs previously fed the low SID Lys diets was also observed ($P = 0.059$). Similarly, a poorer F/G was reported for pigs previously fed the high NE diet ($P = 0.024$).

The effects of the initial dietary treatments were also evaluated in relation to the overall growth performance. Similarly, as for BW, increasing SID Lys from day 0 to 26 did not increase ADG significantly (0.787 vs. 0.780 kg; *P* = 0.106). However, a greater ADG was reported for pigs initially fed the low NE diet (0.789 vs. 0.778 kg; *P* = 0.020). Nevertheless, pigs initially fed the high NE diet showed an improved F/G (*P* < 0.001) due to a 0.050 kg lower ADFI (p < 0.001), which was a huge difference compared to the effect on ADG. Increasing SID Lys did not impact the overall ADFI (*P* = 0.491) and F/G (*P* = 0.162). However, a tendency for an interaction between SID Lys and NE on F/G (*P* = 0.100) was reported because in the high NE diet increasing SID Lys reduced feed efficiency (2.07 vs. 2.05; *P* = 0.033) whereas in the low NE diet it had no effect (2.09 vs. 2.09; *P* = 0.857). Finally, the overall results did not show any effect of initially fed SID Lys (*P* = 0.310) or NE (*P* = 0.454) on feed costs per kg gain.

Table 7.4. Effects of increasing dietary standardized ileal digestible lysine (SID Lys) and reducing net energy (NE) concentration on growth performance of Pietrain grow-finishing pigs when fed the experimental treatments or a common diet (Experiment 1)

	NE (kcal/kg)	2,360		2,550		SEM[2]	*P* -value[1]		
Item[3]	SID Lys (%)	1.00	1.20	1.00	1.20		Lys	NE	Lys x NE
Body weight, kg									
d 0		19.8	19.9	19.8	19.9	0.15	0.847	0.962	0.966
d 14[4]		28.6	29.4	28.6	29.2	0.64	0.003	0.556	0.741
d 26[5]		37.6	38.7	37.4	38.5	0.50	<0.001	0.331	0.968
d 68[5]		68.4	69.6	68.1	69.0	0.44	0.023	0.328	0.754
d 116[5]		109.7	110.	107.9	109.	0.70	0.103	0.025	0.450
Phase 1, d 0-14									
ADG, kg		0.630	0.68	0.625	0.66	0.0386	<0.001	0.293	0.621
ADFI, kg		1.000	1.01	0.964	0.96	0.0430	0.857	<0.001	0.617
SID Lys intake, g/d		10.0	12.1	9.6	11.5	0.47	<0.001	<0.001	0.405
NE intake, Mcal/d		2.37	2.38	2.46	2.45	0.105	0.870	0.003	0.615
Feed/gain		1.59	1.49	1.54	1.44	0.028	<0.001	0.001	0.730
NEE, Mcal/kg		3.76	3.51	3.93	3.68	0.068	<0.001	<0.001	0.967
LysE, g/kg		15.9	17.8	15.4	17.3	0.30	<0.001	<0.001	0.983
Feed cost/gain, €/kg		0.403	0.39	0.414	0.40	0.0074	0.006	0.004	0.979

Table 7.4. Continued

NE (kcal/kg)	2,360		2,550		SEM[2]	*P* -value[1]		
SID Lys (%)	1.00	1.20	1.00	1.20		Lys	NE	Lys x NE
Phase 2, d 14-26								
ADG, kg[5]	0.740	0.775	0.727	0.773	0.0122	<0.001	0.432	0.545
ADFI, kg	1.31	1.31	1.25	1.26	0.013	0.837	<0.001	0.898
SID Lys intake, g/d	13.1	15.8	12.5	15.1	0.14	<0.001	<0.001	0.775
NE intake, Mcal/d	3.10	3.10	3.20	3.21	0.031	0.831	0.002	0.890
Feed/gain[4]	1.77	1.70	1.72	1.63	0.024	<0.001	<0.001	0.442
NEE, Mcal/kg[4]	4.19	4.00	4.40	4.15	0.060	<0.001	<0.001	0.291
LysE, g/kg[4,6]	17.7	20.3	17.2	19.5	0.26	<0.001	<0.001	0.220
Feed cost/gain, €/kg[4]	0.449	0.449	0.462	0.455	0.0065	0.266	0.003	0.239
Phase 1 & *2*, d 0-26								
ADG, kg	0.681	0.724	0.672	0.715	0.0171	<0.001	0.220	0.993
ADFI, kg[4]	1.15	1.15	1.10	1.10	0.025	0.821	<0.001	0.826
SID Lys intake, g/d[4]	11.5	13.8	11.0	13.2	0.27	<0.001	<0.001	0.505
NE intake, Mcal/d[4]	2.70	2.71	2.80	2.80	0.060	0.825	<0.001	0.831
Feed/gain	1.68	1.59	1.63	1.53	0.008	<0.001	<0.001	0.837
NEE Mcal/kg	3.97	3.74	4.16	3.91	0.019	<0.001	<0.001	0.474
LysE, g/kg	16.8	19.0	16.3	18.4	0.09	<0.001	<0.001	0.397
Feed cost/gain, €/kg[7]	0.425	0.420	0.437	0.429	0.0020	0.001	<0.001	0.385
Common diet, d 26-116								
ADG, kg[6]	0.801	0.794	0.785	0.787	0.0055	0.695	0.037	0.371
ADFI, kg	1.79	1.79	1.74	1.75	0.013	0.491	0.001	0.843
Feed/gain	2.23	2.26	2.22	2.23	0.010	0.059	0.024	0.274
Overall d 0-116								
ADG, kg[5]	0.788	0.790	0.772	0.784	0.0045	0.106	0.020	0.265
ADFI, kg	1.64	1.65	1.60	1.61	0.014	0.491	<0.001	0.892
Feed/gain[5]	2.09	2.09	2.07	2.05	0.019	0.162	<0.001	0.100
Feed cost/gain, €/kg[7]	0.473	0.477	0.474	0.474	0.0016	0.310	0.454	0.145

Least square means.

[1] Statistical model included the effects of SID Lys, NE, initial BW block, sex, and all double interactions between these factors. Lys= SID Lys.

[2] SEM: standard error of the mean.

[3] ADG: average daily gain; ADFI: average daily feed intake; NEE: net energy efficiency per kg BW gain; LysE: SID Lys intake per kg gain.

[4] BW block x sex interaction ($P < 0.05$).

[5] NE x BW block interaction ($P < 0.05$).

[6] SID Lys x BW block interaction ($P = 0.036$).

[7] SID Lys x sex interaction ($P < 0.05$).

7.4.2. Experiment 2: *Duroc*

Crude protein, crude fat and amino acid analyzed composition were consistent with the calculated values, and only some deviations were observed for Met+Cys and Thr in the low SID Lys high NE diet in the *Growing* phase. The quadruple interactions were removed from all the final statistical models because those were not significant ($P \geq 0.247$) and only the triple interaction between SID Lys, BW block and sex was left in the model as it was significant for some variables in the *Growing phase* and *Overall.*

7.4.2.1. Effects on growth performance

Table 7.5 reports the factorial effects of NE and SID Lys density on growth performance. Increasing SID Lys had no significant effect on BW on any measurement day ($P \geq 0.644$); however, reducing NE reduced BW by 1.3 kg BW at day 72 ($P = 0.039$) and tended to reduce BW by 1.2 kg at the end of the experiment ($P = 0.077$). No evidence of an interaction between SID Lys and NE was reported for BW ($P \geq 0.194$). From day 0 to 43, a tendency for a significant interaction between SID Lys and NE was only reported for SID Lys intake ($P = 0.071$) because the effect of increasing SID Lys was greater in the low NE diets than in the high NE diets. However, no interaction was reported for ADG or F/G. Increasing SID Lys had no significant impact on growth performance, and only increased SID Lys intake ($P < 0.001$), SID Lys per kg gain ($P < 0.001$) and feed cost per kg gain ($P < 0.001$). In contrast, reducing NE did impact all analyzed variables ($P \leq 0.004$) except for ADG (0.963 vs. 0.978 kg; $P = 0.105$). As expected, when NE density was reduced, ADFI, F/G and LysE increased, whereas NE intake, feed cost per kg gain, and NEE decreased. In the *Finishing phase* (days 43-85), no interaction between SID Lys and NE was observed ($P \geq 0.141$). As reported in the *Growing phase*, SID Lys did not have a positive impact on growth performance, except for a greater SID Lys intake, LysE and feed cost per kg gain ($P < 0.001$). Similarly, reducing NE influenced all variables except ADG ($P = 0.220$). In contrast with the *Growing phase*, reducing NE negatively impacted feed cost per kg gain in the *Finishing phase* (0.608 vs. 0.630

€/kg; $p < 0.001$) as the differences in cost were smaller, but the increase in ADFI was greater than in *Growing phase*. As a result of the greater ADFI of barrows compared to gilts (3.32 vs. 3.00 kg; $p < 0.001$), the effect of increasing SID Lys on SID Lys intake was greater in barrows than in gilts ($p = 0.023$). Overall, there was no evidence that increasing SID Lys improved growth performance. Contrarily to the analysis by phases, reducing NE impaired ADG (1.030 vs. 1.045 kg; $p = 0.027$) with a greater feed cost per kg gain (0.560 vs. 0.553 €/kg; $p = 0.004$).

Table 7.5. Effects of increasing dietary standardized ileal digestible lysine (Lys) and reducing net energy (NE) concentration on growth performance of Duroc grow-finishing pigs (Experiment 2)

	day 0-43	2,200 kcal NE/kg		2,450 kcal NE/kg		SEM[2]	*P* -value[1]		
	SID Lys, %	0.94	1.04	0.94	1.04		Lys	NE	Lys × NE
	day 43-85	2,230 kcal NE/kg		2,450 kcal NE/kg					
Item[3]	SID Lys, %	0.80	0.90	0.80	0.90				
Body weight, kg									
d 0		32.5	32.4	32.4	32.5	0.13	0.890	0.939	0.601
d 23[4]		50.9	51.4	51.5	51.3	0.72	0.644	0.513	0.269
d 43		74.0	74.2	75.1	74.5	0.68	0.717	0.157	0.476
d 72		107	108	109	109	0.88	0.903	0.039	0.943
d 85[5]		120	121	122	122	1.16	0.714	0.077	0.867
Growing phase, d 0-43									
ADG, kg[6,7]		0.956	0.969	0.985	0.972	0.0135	0.992	0.105	0.213
ADFI, kg[5]		2.07	2.11	2.03	2.01	0.028	0.469	<0.001	0.102
SID Lys intake, g/d[5]		19.4	22.0	19.1	20.9	0.28	<0.001	<0.001	0.071
NE intake, Mcal/d		4.54	4.65	4.97	4.92	0.065	0.526	<0.001	0.111
Feed/gain[8]		2.16	2.18	2.06	2.07	0.011	0.295	<0.001	0.605
NE/gain, Mcal/kg		4.75	4.79	5.05	5.06	0.026	0.307	<0.001	0.645
SID Lys/gain, g/kg[5,8]		20.3	22.6	19.4	21.5	0.11	<0.001	<0.001	0.322
Feed cost/gain, €/kg[5,8]		0.475	0.503	0.479	0.514	0.0026	<0.001	0.004	0.166
Finishing phase, d 43-85									
ADG, kg		1.099	1.099	1.106	1.119	0.0136	0.570	0.220	0.555
ADFI, kg		3.25	3.28	3.05	3.08	0.034	0.296	<0.001	0.889
SID Lys intake, g/d[5]		26.0	29.5	24.4	27.7	0.30	<0.001	<0.001	0.811
NE intake, Mcal/d		7.25	7.31	7.46	7.55	0.078	0.287	0.002	0.849
Feed/gain		2.96	2.98	2.75	2.76	0.016	0.362	<0.001	0.482
NE/gain, Mcal/kg		6.60	6.65	6.74	6.75	0.037	0.380	0.001	0.510
SID Lys/gain, g/kg		23.7	26.9	22.0	24.8	0.14	<0.001	<0.001	0.141
Feed cost/gain, €/kg		0.604	0.656	0.585	0.630	0.0035	<0.001	<0.001	0.276
Overall, d 0-85									
ADG, kg[5,7,9]		1.027	1.033	1.045	1.044	0.0116	0.637	0.027	0.610
ADFI, kg[5]		2.65	2.69	2.53	2.54	0.028	0.250	<0.001	0.483
SID Lys intake, g/d[5]		22.7	25.7	21.7	24.3	0.26	<0.001	<0.001	0.249
NE intake, Mcal/d[5]		5.88	5.96	6.20	6.20	0.064	0.260	<0.001	0.516
Feed/gain		2.58	2.60	2.42	2.43	0.010	0.184	<0.001	0.668
NE/gain, Mcal/kg		5.72	5.77	5.93	5.95	0.024	0.192	<0.001	0.721
SID Lys/gain, g/kg		22.1	24.8	20.7	23.2	0.09	<0.001	<0.001	0.144
Feed cost/gain, €/kg		0.541	0.579	0.533	0.574	0.0025	<0.001	0.004	0.675

Least square means.

[1] Statistical model included the effects of Lys, NE, initial BW block, sex, all double interactions between these factors and the triple interaction between Lys, BW block and sex.

[2] SEM: standard error of the mean.

[3] ADG: average daily gain; ADFI: average daily feed intake; SID Lys: standardized ileal digestible lysine.

[4] BW block x sex interaction ($P < 0.05$).

[5] Lys x sex interaction ($P < 0.05$).

[6] NE x BW block interaction ($P < 0.05$).

[7] Lys x BW block x sex interaction ($P < 0.05$).

[8] NE x sex interaction ($P < 0.05$).

[9] Lys x BW block interaction ($P < 0.05$).

7.4.2.2. Effects on carcass traits

The results of the effects of dietary NE on carcass traits of first marketed pigs are shown in **Figure 7.1**. As expected, pigs fed the high NE diets were heavier ($P = 0.005$). In addition, reducing the NE content in the diet increased CL (61.1 vs. 59.9%). Increasing HCW reduced CL 0.105%/kg ($P < 0.001$) but there was no evidence that this effect was different between the two NE densities ($P = 0.314$). Reducing dietary NE concentration also reduced significantly BFT (19.4 vs. 20.4 mm; $P = 0.003$) and HFT (13.3 vs 14.1 mm; $P = 0.004$).

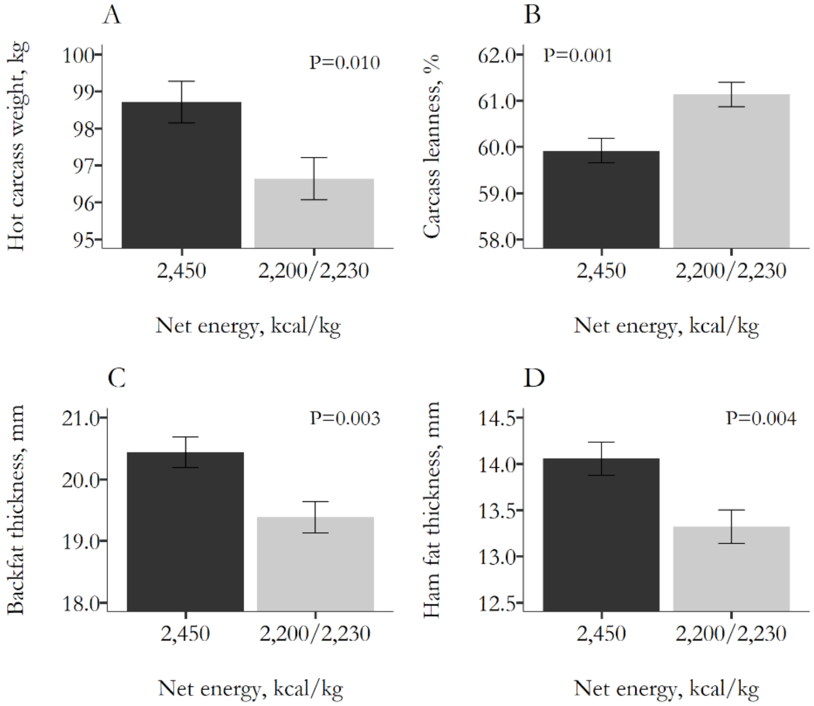

Figure 7.1. Least square means of the effect of dietary net energy (NE) on carcass traits measured on the 380 first marketed pigs at day 86 of Experiment 2. For B, C and D the response was adjusted using carcass weight (HCW) as a linear predictor. Error bars represent the standard error of the mean.

7.5. Discussion

Energy and amino acids represent the costliest constraints in feed formulation. It is necessary to determine the impact of reducing energy density on practical swine nutrition to ascertain the extent these constraints can be reduced without negatively impairing growth performance. Grow-finishing pigs can compensate a low energy density diet by increasing ADFI (Li and Patience, 2017). However, there are inconsistencies regarding whether reducing dietary energy density results in a reduced (Oresanya et al., 2007; Hinson et al., 2011; Zhang et al., 2011; Quiniou and Noblet, 2012) or similar energy intake (Beaulieu et al., 2009; Cámara et al., 2016a; Ferreira et al., 2019). If the energy value of feeds is correctly valued, and pigs can compensate for the reduced energy density, it would be expected that there would be no effect on ADG if there are no differences in maintenance energy requirements (NRC, 2012). Moreover, when SID Lys (first limiting AA used as a reference in the ideal protein concept) is formulated on a ratio with energy, pigs will have a similar SID Lys intake (Oresanya et al., 2007). Nevertheless, when a lower energy density impairs energy intake and diets are formulated based on a ratio between SID Lys and energy, then pigs in the low energy diets also have a lower SID Lys intake (Hinson et al., 2011; Marçal et al., 2019). Therefore, sometimes it is difficult to discern whether the effects of reducing NE on ADG are due to energy or to lysine being limiting.

The SID Lys levels used in the experiments were chosen based on previous trials (Aymerich et al., 2020b) and on published nutrient requirements (NRC, 2012). As Pietrain sire line was expected to have a lower ADFI than a Duroc sire line, the differences in dietary SID Lys were greater in Exp. 1 than in Exp. 2, in order to achieve a similar effect on daily SID Lys intake. In Exp. 1 NE densities were chosen based on the available literature, reporting no effect of reducing NE concentration from 2.51 to 2.34 Mcal/kg on ADG or NE intake (Cámara et al., 2016a). By contrast, in Exp. 2 we wanted to determine the implications of reducing NE density in levels previously reported to impair ADG and increase fat deposition (2.29 Mcal/kg) in a Synthetic line (Cámara et al., 2014) . However, the low NE density in Exp. 2 was chosen to be even lower because of the high ADFI of the Duroc sire line. In this work, NE density of the diet was reduced by partly removing added fat (animal fat or palm oil, exchanged just for logistic reasons) and increasing the inclusion of high fibrous ingredients (wheat middlings), which could physically limit

NE intake at high inclusions (Stewart et al., 2013). Adding fat is the most common method used to increase energy density (Apple et al., 2004; De La Llata et al., 2007; Hinson et al., 2011; Quiniou and Noblet, 2012), as its value is around 2.5-3 times the one of cereal grains (Sauvant et al., 2004; NRC, 2012).

The results presented showed that in both experiments the calculated NE intake was limited when pigs were offered a low NE diet. In Exp. 1, although NE density was reduced by 7.5 %, pigs could only increase ADFI by 4.5 % (0.05 kg) and therefore the calculated NE intake was 3.2 % lower in the low NE diet. Similar results were observed in the *Growing phase* in Exp. 2. A 10.2 % reduction in NE resulted in ADFI increasing by 3.5 % (0.07 kg) and a 7.1 % lower NE intake. In contrast, in the *Finishing phase*, reducing NE by 9.0 % resulted in a 6.9 % increase in ADFI and only a 3.1 % reduction in NE intake. Therefore, reducing dietary NE results in an increased ADFI (Weatherup et al., 2002) but it negatively affects daily NE intake (Quiniou and Noblet, 2012; Marçal et al., 2019); however, the effect is less severe in heavier/older pigs (Li and Patience, 2017). Similarly to Exp. 2, De La Llata et al. (2007) only reported an effect of increasing energy density in the first growing phase (25-45 and 34-60 kg BW, for gilts and barrows, respectively), but it was not significant for later phases up to 120 kg BW. Other authors did not report an effect of reducing dietary NE on daily NE intake (Ettle et al., 2003; Cámara et al., 2016a; Ferreira et al., 2019); however, Beaulieu et al. (2009) reported effects when research was carried out in research facilities but not in commercial farms. It is possible, as suggested by Nitikanchana et al. (2015), that there is an extra value of adding fat to a diet in addition to its high energy content.

Another disagreement in studies is whether reducing NE density affects caloric efficiency for growth, measured either as digestible, metabolizable or net energy. Quiniou and Noblet (2012) showed that although NE intake was impaired when NE concentration was reduced in a wider range of NE (1.94-2.65 Mcal NE/kg), NEE was not affected. In contrast, in this study both experiments showed an improved NEE in the low NE diets, as less calories were needed per kg gain.

These results were explained based on no evidence (Exp. 1) or little effect (Exp. 2, -1.4%) of dietary NE on ADG, but a rather significant effect on NE intake. Other studies have also reported improvements in caloric efficiency when dietary NE is reduced (Yi et al., 2010; Fracaroli et al., 2017; Marçal et al., 2019). The unexpected effect on NEE might be attributed to an additional effect of fibrous ingredients, such as wheat middlings, by limiting physical satiety (Gondret et al., 2014; Li and Patience, 2017) or to an underestimation or overestimation of the NE value of some ingredients (Stewart et al., 2013; Marçal et al., 2019). For instance, Kil et al. (2011) reported low NE values for animal fat (5.90 Mcal/kg) compared to this study (7.56 Mcal/kg). Our value was closer to those provided in different ingredient composition tables (Sauvant et al., 2004; FEDNA, 2010; NRC, 2012). In addition, as indicated in the NRC (2012), part of the discrepancies in the NE value of feed ingredients might be related to using prediction equations that were developed using complete diets.

This study did not report any relevant interaction between dietary NE and SID Lys levels used in the two factorial arrangements. Interactions could be expected in Exp. 1, in which 1.00 % SID Lys limited growth performance. Thus, the results indicate that the difference in NE intake was not sufficient to limit available NE for protein deposition, or that pigs were still in the lysine dependent phase (Möhn et al., 2000). For instance, taking the low SID Lys and high NE diet in Exp. 1 as a reference, increasing SID Lys had a greater impact on the SID Lys:NE ratio than reducing NE (0.79 vs. 0.34 g/Mcal). On the contrary, Marçal et al. (2019) showed no effect of NE on ADG when diets were formulated with the same SID Lys and not based on SID Lys:NE. However, as in the present study SID Lys was formulated for the high NE diet, SID Lys intake was even higher in the low NE diets. Therefore, it was ensured that SID Lys was not limiting when NE was reduced. It is possible that if SID Lys:NE had been kept constant, reducing NE would have represented a greater negative effect on ADG because of the lower NE intake (Hinson et al., 2011). In addition, increasing SID Lys did not improve growth performance in Exp. 2 as SID Lys daily intake in the low level was greater than recommended, especially in the *Finishing phase* (NRC, 2012), because of a higher ADFI than expected in the experimental design phase. Main et al. (2008) suggested that around 20 g SID Lys/kg gain already maximized growth performance. In Exp. 2 this ratio was ≥ 19.4 g/kg and consequently it did not limit growth performance.

The results in Exp. 1 provided further evidence that growing pigs fed low NE diets will have a greater ADFI if fed a common diet in the finishing phase (Weatherup et al., 2002). Therefore, NE density in the growing phase could be adjusted to maximize feed intake in the finishing phase if necessary. Similarly, although it was not the aim of Exp. 1, the lower F/G in the *Finishing phase* observed in pigs fed the low SID Lys diet between 20-40 kg BW could be related to an effect similar to compensatory growth (Menegat et al., 2020a). However, it could be that if SID Lys in the common diets was not sufficiently high, only F/G would improve, but not ADG. Interestingly, in Exp. 2, the reduction in NE from 2,450 to 2,200-2,230 kcal/kg was sufficient to influence ADG. As different NE levels were applied in each experiment, it is not possible to compare the effects in each experiment. However, in different studies, Cámara et al. (2014; 2016a) also reported different results although working in rather similar NE ranges, which could be related to the different sire lines or sex in each experiment. For instance, in one study (Cámara et al., 2014) they observed a greater effect of NE on barrows ADG than boars or gilts, which we did not observe in our results.

The results on carcass composition from Exp 2. confirmed that the lower ADG observed when NE was reduced was the result of a lower fat deposition. Thus, when NE intake was limiting, the animals prioritized protein deposition above fat. Although carcass traits were only measured in the first marketed pigs, we hypothesize that a similar effect would be observed in last marketed pigs because no interaction between BW block and NE on ADG was observed for the *Overall* period. Similarly, other studies reporting a reduction in ADG when NE density was reduced also found an effect on BFT (Apple et al., 2004; Hinson et al., 2011; Cámara et al., 2014); however, others found significant effects on ADG but not on BFT (De La Llata et al., 2007). Therefore, considering that a minimum HFT for pigs in Exp. 2 is required for a correct dry-curing process (Čandek-Potokar and Škrlep, 2012; Masferrer et al., 2018), feeding low NE diets might not be a good alternative in this production system.

Finally, using low NE diets reduced feed cost per kg gain when pigs did not have a huge increase in ADFI. Otherwise, the high ADFI entails that the increase in cost for the greater amount of feed required for growth is higher than the reduction in cost associated with including lower amounts of fat. For instance, in Exp. 1 (20-40 kg BW) and in Exp. 2 (32-74 kg BW), reducing dietary NE reduced feed cost per kg gain. In contrast, in Exp. 2 (74-121 kg BW) it increased feed cost per kg gain because ADFI increased by 6.9 %. If the highest ADG is included by calculating the income over marginal feed costs, then the high NE density would probably result in an even better economical yield in Exp. 2 (De La Llata et al., 2001). Although these economical results are only valid in the price context when the experiments were carried out, they are useful for visualizing the economic consequences of modifying dietary NE.

7.6. Conclusions

The present work provides evidence that grow-finishing pigs can partly overcome a 190-250 kcal/kg reduced dietary NE by increasing ADFI, and therefore limit the negative impact on ADG. However, no significant interaction between NE and SID Lys was reported, and the latter only showed a positive effect in pigs with a low ADFI. Reducing NE concentration was only economically feasible when feed cost was substantially lowered, and pigs did not increase ADFI in the same proportion as NE was reduced. Furthermore, when low dietary NE density had a negative effect on ADG, this also had consequences on carcass quality by reducing fat deposition. Finally, an increased ADFI carry-over effect related to low NE diets was observed when pigs were fed a common NE die

CHAPTER 8

General discussion

The studies included in this PhD. dissertation have provided evidence that BW variability, sex, and genotype have a substantial effect on both growth and lean/fat tissue deposition. In addition, they report a different effect of increasing SID Lys:NE between pigs classified as small or large at the beginning of the grow-finishing phase, and boars and gilts in the finishing phase. As the underlying explanation of the effects has already been discussed in each Chapter, the present section will focus on a critical assessment of the experimental designs used in **Chapters 4** and **5**, a modelling of the economic implications and finally a general review of the practical applications and future perspectives.

8.1. Critical assessment of the experimental designs

In general, the methods used in the experimental designs have proven to be useful to answer the aims of the experiments. However, the results in **Chapters 4**, **5** and **6** showed the difficulties of determining whether groups of pigs have different requirements using BLL, BLQ or QP when modelling the effect of dietary SID Lys. Other authors have just compared the estimate between two models without considering the 95 % CI of those estimates (Moore et al., 2016; Schweer et al., 2019). However, considering the wide CI reported in this PhD. dissertation, it is necessary to provide them to understand how good the estimate provided is, and especially when the aim is to compare two different groups. Future works should include those CI at least for BLL and BLQ models, as it is easier to estimate it because the requirement is part of the estimates in the model.

In the studies presented in **Chapter 4** and **5**, the designs also aimed to minimize the differences in CP between the treatments to avoid that excess AA had to be deaminated (Bender, 2012). On the contrary, other authors have preferred strategies in which the SID Lys level is mainly the result of increasing AA rich ingredients such as soybean meal (Main et al., 2008). Those designs avoid differences in the absorption rate of AA related to the inclusions of crystalline AA (Yen et al., 2004). However, in the context of rearing pigs with less antibiotics, reducing CP has proven to be a good alternative to avoid digestive problems because of a lower protein fermentation in the distal large intestine and drier feces (Heo et al., 2009). Nowadays, the availability of crystalline AA enables reducing CP without impairing growth performance as long as SID Lys:NE and the ratios of essential AA to SID Lys are maintained (Molist et al., 2016). Therefore, considering the beneficial effects of lowering CP on gut health and to avoid excessive deamination, diets were formulated to have the closest CP between the extreme treatments.

8.2. Implications of feed ingredients cost variation

Formulating diets for monogastric animals such as swine, requires a balance between animal requirements and the specific context of feed ingredient prices. In the current feed formulation models based on linear programming to achieve the least cost while meeting a specific nutrient density (Castrodeza et al., 2005), energy and amino acids are usually the costliest constrains. In practice, when the prices vary, those constrains can be modified to achieve the maximum benefit per pig, which is not always at the same point as their maximum productive performance or the cheapest feed (De La Llata et al., 2001). For instance, grow-finishing pigs can increase their feed intake to compensate a low energy density diet (Li and Patience, 2017), but there is no certainty whether it implies a similar (Beaulieu et al., 2009; Cámara et al., 2016a) or a deficient energy intake (Hinson et al., 2011; Quiniou and Noblet, 2012).

8.2.1.Feed ingredient cost fluctuation

Some decades ago, the differential cost of feeding AA rich diets was associated to the price of soybean meal. Nowadays, other sources of AA are available in the market (sunflower meal, canola meal…), although they are not as rich in AA and usually soybean meal remains the major AA source in swine diets (Florou-Paneri et al., 2014; Ibáñez et al., 2020). Moreover, the constant reduction in dietary CP has resulted in an increased inclusion of crystalline AA in swine diets. Therefore, the cost of AA when formulating diets for grow-finishing pigs mainly depend on the cost of soybean meal and crystalline AA. **Figure 8.1** shows the price fluctuation of soybean meal and the most used crystalline AA from 2010 to 2019.

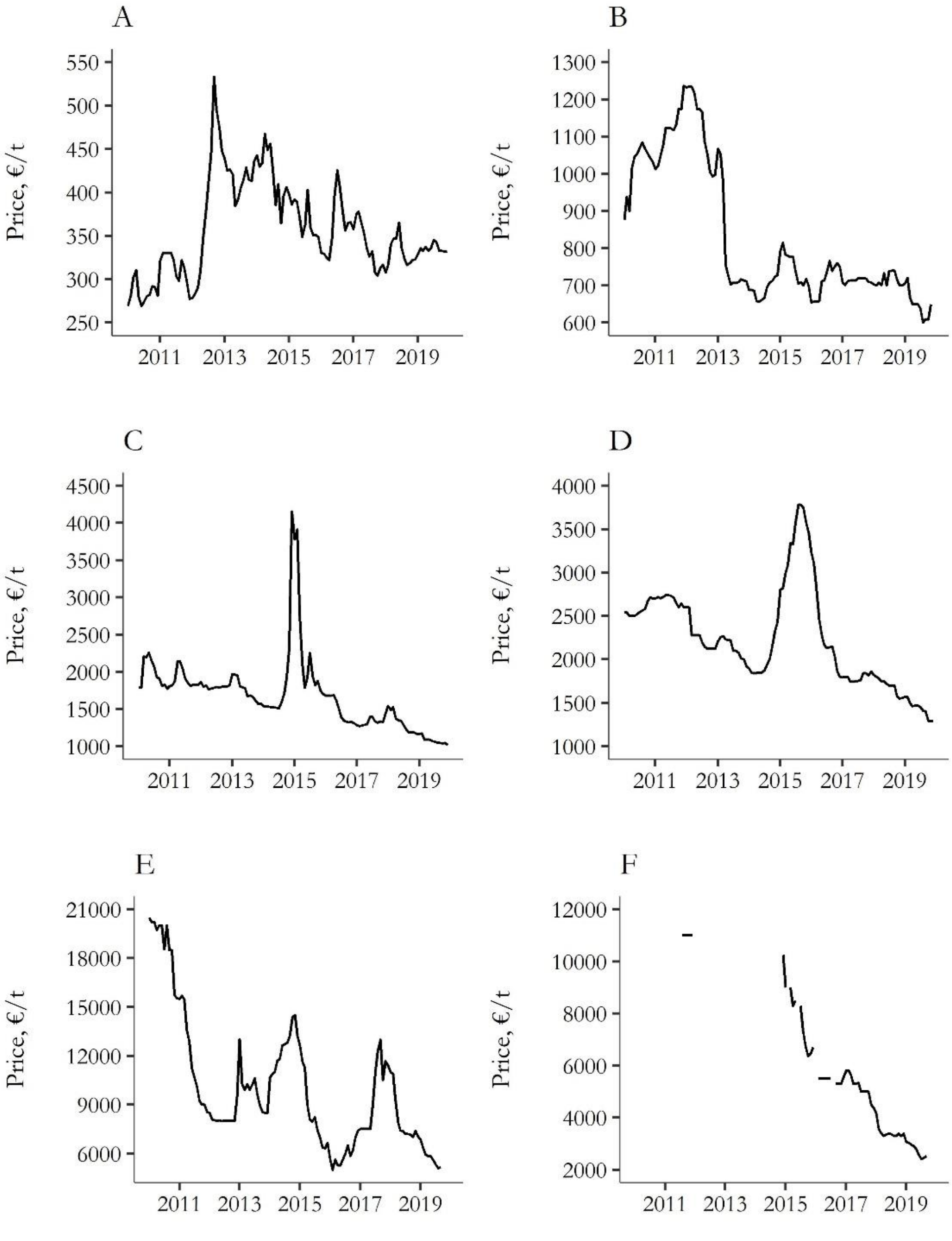

Figure 8.1. Price fluctuation of high amino acid and crude protein feed ingredients such as soybean meal (A), liquid Lysine 50% (B), L-Threonine (C), Methionine hydroxy analogue (D), L-Tryptophan (E), and L-Valine (F) from 2010 to 2019. Source: Vall Companys Group.

Fats and oils are the richer ingredients in NE, and therefore they are commonly the first ingredient inclusion that is modified to change dietary NE concentration. Cereals are also rich in NE, although around 3 times less than fats and oils, and maize is the one with highest NE concentration. Consequently, for the availability and price maize is one of the most common sources of energy in swine diets (NRC, 2012). **Figure 8.2** shows the price fluctuation of animal fat and maize in Spain during the last 10 years. Whereas animal fat price had an important variation, ranging from 500 to 800 €/t, maize price also varied significantly from 2010 to 2014, but the last six year it has remained quite constant.

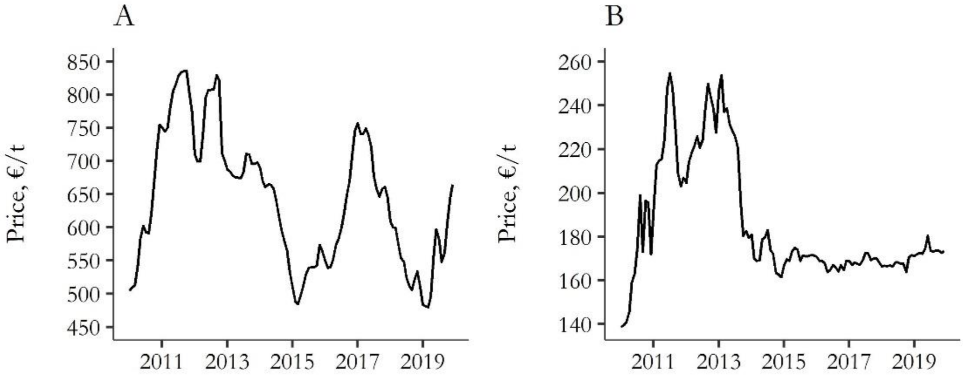

Figure 8.2. Price fluctuation of high energy density feed ingredients such as animal fat (A), and maize (B), from 2010 to 2019. Source: Vall Companys Group.

8.2.2. Effect of SID Lys:NE on feed cost

The variation in prices of AA rich ingredients such as soybean meal and crystalline AA was used to predict the effect of increasing dietary SID Lys:NE in two price contexts. On the one hand, a scenario in which the cost AA was rather low, taking the lowest raw material cost from the previous figure. On the other hand, a scenario in which the cost of AA was high, considering the highest cost of AA from 2010 to 2019. **Table 8.1** reports the feed ingredient prices used in each context. Other raw materials like cereals, minerals, vitamins, and additives were constant in each price context. These prices were used to simulate 9 feeds in each price context using a least cost formulation (Brill Formulation Version 2.08.002, Format Solutions, Hopkins, MN, USA). Only SID Lys:NE was modified throughout formulations, ranging from 2.56 to 4.13 g SID Lys/Mcal NE, or from 0.65 to 1.05 % SID Lys in a 2,450 kcal NE/kg diet. Most relevant constrains that were constant throughout all simulations were NE at 2,450 Kcal NE/kg, STTD P at 0.23% and

Ca at 0.54%. Minimum ratios between essential AA and Lys expressed in SID values were 0.60, 0.65, 0.18, 0.65 and 0.55 for Met+Cys, Thr, Trp, Val and Ile, respectively. Besides, the inclusion of each cereal ingredient was limited to 45% of the feed and at least 1 % animal fat was included in all diets for technological reasons.

Table 8.1. Price of ingredients in the two simulated amino acid (AA) price contexts, one of low costs of AA rich feed ingredients, and a low cost one

	AA context price	
Prices, €/t	Low	High
Maize	180	180
Wheat	190	190
Barley	175	175
Soybean meal	275	500
Animal fat	620	620
Calcium carbonate	27	27
Monocalcium phosphate	430	430
Salt	46	46
Phytase	5700	5700
Premix	875	875
Liquid lysine	600	1200
Methionine hydroxy analogue	1500	3500
L-Threonine	1000	4000
L-Tryptophan	5000	10000
L-Valine	4500	10000

The effect of increasing SID Lys:NE on feed cost in a low and a high AA price context is reported in **Figure 8.3** . As expected, increasing SID Lys:NE was more expensive in the high cost context than in the low one. Whereas in the low-cost scenario increasing the ratio 1 unit represented 13.9 €/t, in the high-price scenario it represented 37.9 €/t. Therefore, increasing SID Lys:NE was almost three times more expensive in the high- than in the low-cost scenario. In **Chapter 4** this increase was of 23.9 €/t/(g/Mcal) whereas in **Chapter 5** was 18.6 €/t/(g/Mcal). Moreover, **Figure 8.4** shows the effect of increasing SID Lys:NE on the inclusion of soybean meal in the diets. It shows that in the low-cost context, it was preferable to use soybean meal as a source of AA whereas in the high-cost the use of crystalline AA was preferred.

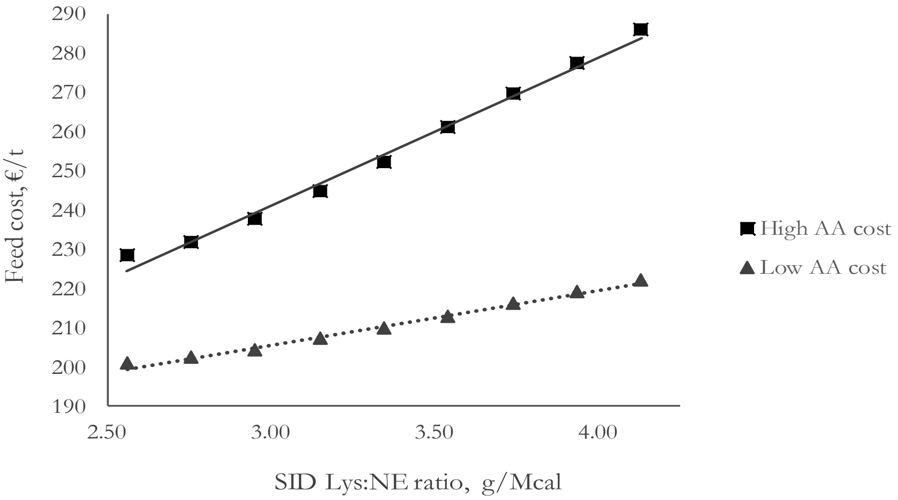

Figure 8.3. Minimum feed cost at different standardized ileal digestible lysine to net energy ratios (SID Lys:NE) in a context of high cost of feed ingredients rich in amino acids, and in a context of low cost (see Table 8.1) in isoenergetic diets.

8.2.3. Effect of net energy on feed cost

A similar approach as the one in the previous section was used to simulate two NE cost scenarios when the prices of animal fat and maize varied. In the high-cost context they were 800 and 220 €/t, whereas in the low-cost they were 500 and 150 €/t, animal fat and maize, respectively. **Table 8.2** shows the feed ingredient costs used in each scenario, with all other raw materials being constant. In the simulations NE was modified from 2,250 to 2,600 kcal/kg by changing the weight parameter, that concentrates or dilutes the whole nutrient concentration. This way, all other constrains were increased or decreased in the same proportion as the diet was concentrated or diluted. Consequently, as energy regulates pigs feed intake (Li and Patience, 2017), they also eat the same amount of nutrients such as AA or minerals. For instance, the ratio between SID Lys:NE was kept constant at 3.47 g/Mcal, and between STTD P and NE at 0.94 g/Mcal.

Table 8.2. Price of ingredients in the two simulated energy price contexts, one of low costs of high and the other low cost one

	Energy context price	
Prices, €/t	Low	High
Maize	150	220
Wheat	190	190
Barley	175	175
Soybean meal	330	330
Animal fat	500	800
Calcium carbonate	27	27
Monocalcium phosphate	430	430
Salt	46	46
Phytase	5700	5700
Premix	875	875
Liquid lysine	800	800
Methionine hydroxy analogue	1600	1600
L-Threonine	1160	1160
L-Tryptophan	7000	7000
L-Valine	5000	5000

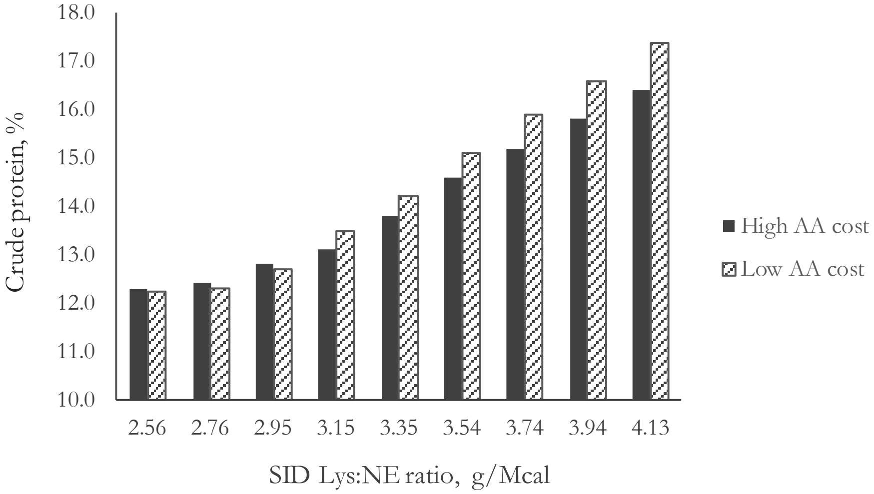

Figure 8.4. Feed crude protein at the different formulated standardized ileal digestible lysine to net energy ratios (SID Lys:NE) in a context of high cost of feed ingredients rich in amino acids, and in a context of low cost (see Table 8.1) in isoenergetic diets.

The results of the modifying dietary NE concentration in two price context of animal fat and maize on the cost of each megacalorie are reported in **Figure 8.5**. In the high energy cost scenario, increasing NE from 2,250 to 2,660 resulted in an increased cost, mainly from 2,400 kcal/kg onwards. By contrast, increasing NE density in the low energy cost reduced the cost of each megacalorie down to 2,450 kcal/kg. Then, it remained constant or tended to slightly increase. The results presented in **Chapter 7** showed that pigs can partially compensate a reduction in NE density by increasing ADFI, however they could not reach the same NE intake. If pigs can reach the same NE intake, therefore the same amount of megacalories, then the cost per megacalorie can be directly used to decide the most feasible energy level. However, when their energy intake is limited in low NE densities, then it might be more feasible to fed them at intermediate levels.

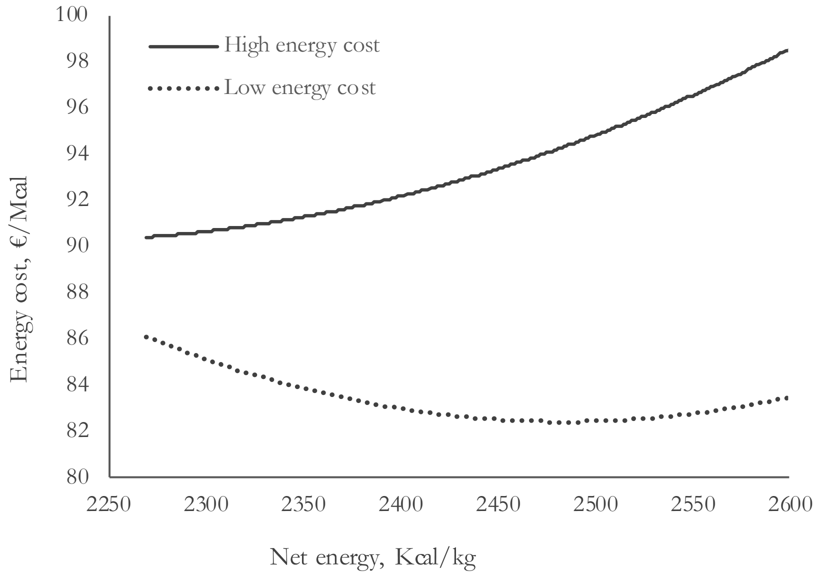

Figure 8.5. Mega calorie cost depending on the net energy (NE) density of the diet when diluting or concentrating the density of all other constrains in feed formulation in a context of high cost of energy rich ingredients (maize and animal fat) and in a low cost context. Diets were formulated at a ratio of 3.47 g standardized ileal digestible lysine per Mcal NE. Feed ingredients costs is reported in Table 8.2.

In Exp. 1 in **Chapter 7**, reducing NE concentration increased the cost of each megacalorie around 2.6-3.0 €, but as they did not reach the same energy intake, the feed cost per kg gain was lower in the low NE diets. In Exp. 2 in **Chapter 7**, reducing NE increased the cost of each megacalorie around 5.0-3.4 € in the growing phase and around 4.7-5.3 € in the finishing phase. They had a 7.1 and 3.1 % lower NE intake in the low NE diets, for the growing and finishing phase, respectively. Although the megacalorie cost was higher, when the relative reduction in NE intake was greater than the relative increase in feed cost, this resulted in a better feed cost per kg gain. However, in the finishing phase, the cost per megacalorie increased around 5.4-5.7 % whereas NE intake was only reduced a 3.1 %. Consequently, feed cost per kg gain was higher in the low NE diet. In addition, it should be considered when lowering NE results in an impaired ADG because this will result in producing less kg of meat (De La Llata et al., 2001).

8.3. Implications of semi-precision feeding

This PhD. dissertation has focused on studying whether groups of pigs that have different protein deposition potential or feed intake should be differentially fed. The results have been mainly focused on the implications on growth performance and carcass composition. Therefore, this section will focus in the economic and environmental implications of semi-precision feeding.

8.3.1. Semi-precision feeding by initial body weight

The results presented in **Chapter 4** provided evidence of the different effect of dietary lysine on growth performance of pigs sorted by their initial BW in the grow-finishing phase. A different effect on feed cost per kg gain was already reported, but it might be even better to determine the income over feed and facility cost (IOFFC) considering the differential effect on ADG. According to Menegat et al. (2019) this approach is specifically interesting in systems that are managed in a fixed-time basis. **Figure 8.6** shows the effect of SID Lys:NE on relative ADG compared to the maximum performance reached using results from 28 to 46 kg BW in **Chapter 4**. Only small pigs (Sp) did not show a quadratic response, and because the effect of SID Lys:NE was significantly linear, they were modelled using BLL. The other categories, medium (Mp) and large (Lp), were modelled using quadratic models. The figure clearly shows that Sp required more SID Lys:NE to reach their maximum performance.

Furthermore, the results from **Chapter 4** were used to model the IOFFC depending on SID Lys:NE by considering pork price at 1.3 €/kg liveweight and facility cost at 0.12 €/pig and day (**Figure 8.7**). Increasing SID Lys:NE more than 4.00-4.25 g/Mcal did not improve the economics of Mp and Lp. Contrarily, Sp IOFFC increased up to the highest level included in the experiment. In addition, IOFFC of Mp and Lp was slightly impaired when fed the highest SID Lys:NE. Similarly, **Table 8.3** shows the implications of feeding a common diet, considering three different SID Lys:NE levels, and two different semi-precision feeding strategies. Whereas a low SID Lys:NE common diet would impair severely IOFFC of Sp, the impact on Mp and Sp would be rather moderate. By contrast, a high SID Lys:NE common diet would improve the IOFFC of Sp but reduce Mp and Lp IOFFC. Therefore, the semi-precision feeding 1 seems a reasonable option to reach Sp maximum IOFFC without increasing production costs of Mp and Lp.

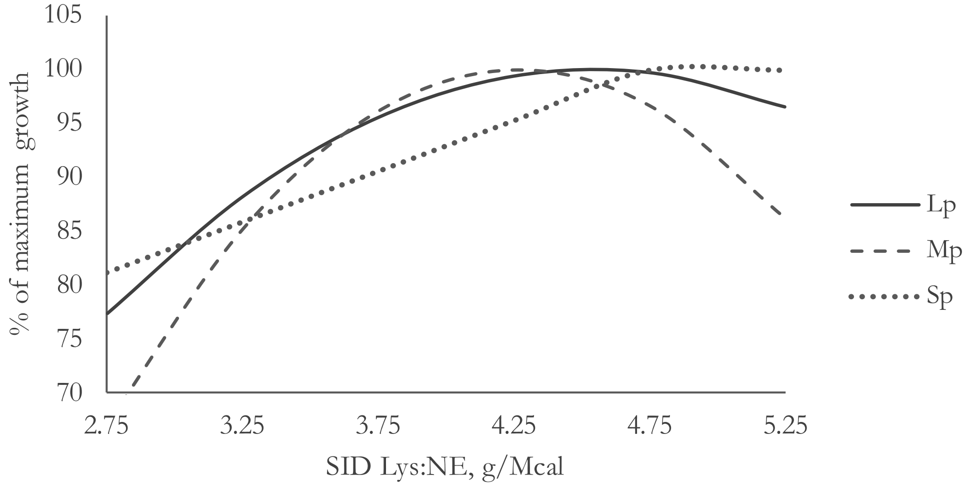

Figure 8.6. Relative growth of growing pigs initially classified as large (Lp), medium (Mp) or small (Sp) at different standardized ileal digestible lysine to net energy ratios (SID Lys:NE) in comparison to their maximum performance in Chapter 3 from 0 to 26 days. Average initial and final body weight were 28 and 46 kg, respectively.

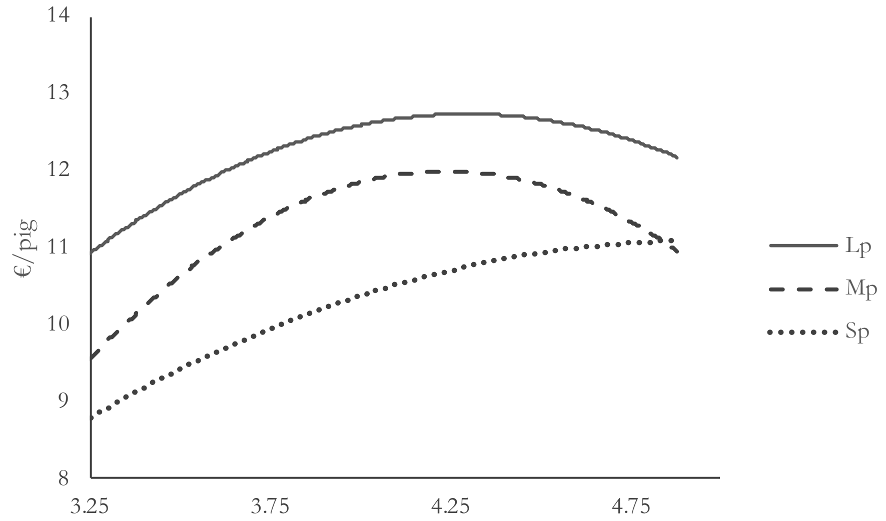

Figure 8.7. Income over feed and facility cost of growing pigs initially classified as large (Lp), medium (Mp) or small (Sp) at different standardized ileal digestible lysine to net energy ratios (SID Lys:NE) in a fixed-time calculation (26 days) using data from *Phase 1* in Chapter 3. Average initial and final body weight were 28 and 46 kg, respectively.

Table 8.3. Economic implications of a semi-precision feeding strategy consisting in split-feeding depending on initial body weight (BW) category[1]

	Initial BW category[1]			
	Lp	Mp	Sp	Average
IOFFC, €/pig[1]				
Common diet 3.88 g SID Lys/Mcal	12.5	11.7	10.2	11.4
Common diet 4.28 g SID Lys/Mcal	12.7	12.0	10.7	11.8
Common diet 4.88 g SID Lys/Mcal	12.2	11.0	11.1	11.4
Semi-precision feeding 1				
SID Lys:NE, g/Mcal	4.28	4.28	4.88	
IOFFC, €/pig	12.7	12.0	11.1	11.9
Semi-precision feeding 2				
SID Lys:NE, g/Mcal	3.88	3.88	4.88	
IOFFC, €/pig	12.5	11.7	11.1	11.7

[1] From 28 to 46 kg BW, modelling results presented in Chapter 4.

[1] Lp: large; Mp: medium; Sp: small.

[1] IOFFC: income over feed and facility cost.

8.3.2. Semi-precision feeding by sex

The results presented in Chapters 5 and 6 confirmed a different response of finishing boars and gilts from 70 to 105 kg BW to increasing dietary lysine levels. Both chapters reported a greater benefit on boars growth performance than in gilts.

8.3.2.1. Economic implications

The QP equations presented in Chapter 6 were used to model the IOFFC depending on SID Lys:NE in the two AA price scenarios presented earlier in this Chapter. For the models, gilts maximum ADG was assumed at 0.820 kg with a 2.0 kg ADFI, whereas boars were assumed to grow a 0.944 kg/d. The economic simulation was carried out in two systems, one in a fixed-weight while the other in a fixed-time basis. Initial BW was considered at 70 whereas final at 100 kg, and for the fixed time the duration of the simulation was of 35 days, starting at the same initial BW. Pork price was 1.30 €/kg live weight whereas facility daily cost was 0.12€/pig. The results are shown in **Figure 8.8**. In the low AA context, the differences in IOFFC between boars and gilts were greater, especially at high SID Lys:NE levels. In all scenarios, boars reached maximum IOFFC at higher SID Lys:NE than gilts. As expected, in the high AA cost context, the SID Lys:NE at which IOFFC was maximized was lower than in the low AA cost context.

The economic implications of semi-precision feeding strategies considering the two AA price contexts and in a fixed-weight and fixed-time basis are reported in **Table 8.4**. Those implications depended a lot on the context and the assumptions. For instance, in a low AA cost, there was only a benefit of feeding boars higher SID Lys:NE when the system run in a fixed-time bases. This way, in the same 35 days, boars gained 1 kg BW more that resulted in a +0.7 € per boar. However, in the high AA context, the benefits of feeding boars and gilts separately were related to feeding gilts lower SID Lys:NE than the reference diet. This was especially a realistic option in systems that run on a fixed-weight basis.

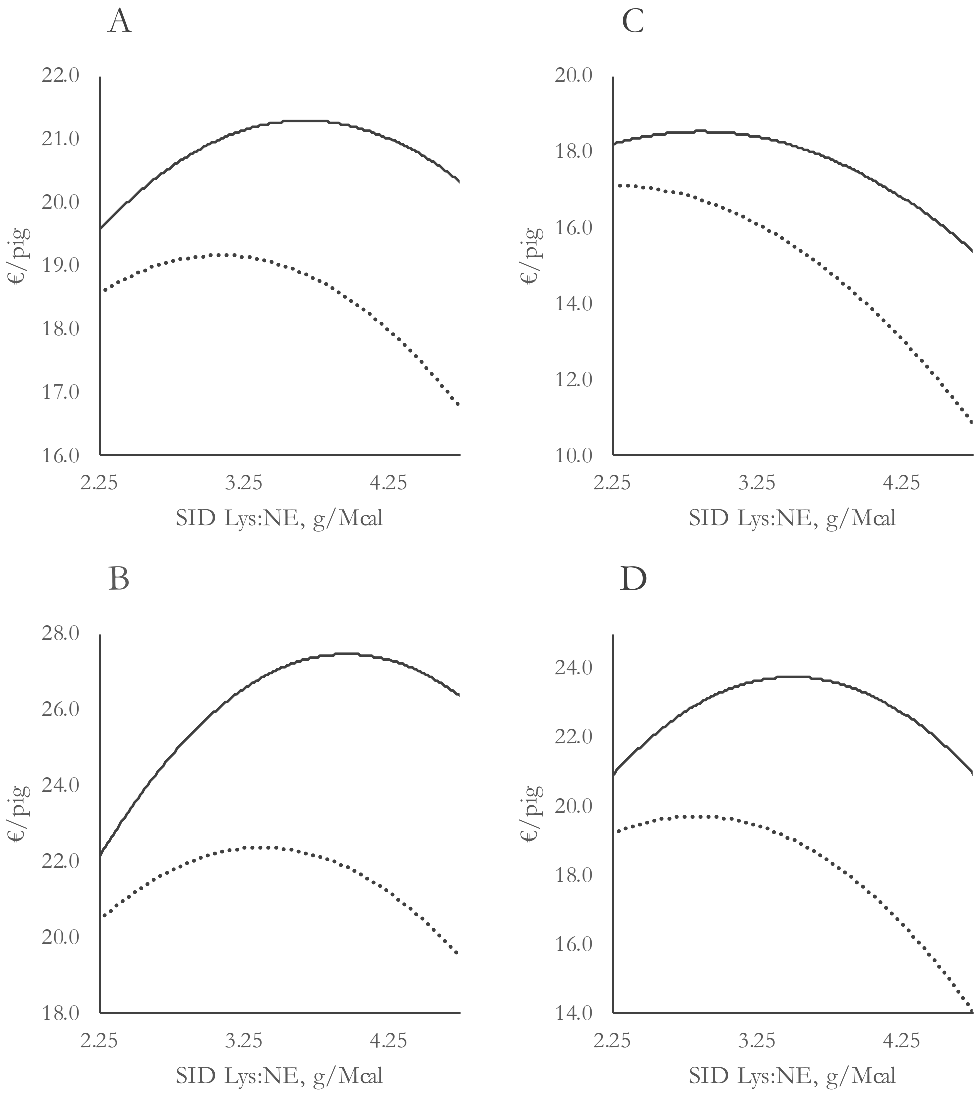

Figure 8.8. Income over feed and facility cost for boars (solid line) and gilts (dotted line) in a context of low cost of amino acid rich feed ingredients in a fixed weight (A) or fixed-time (B) calculation, or in a context of high AA cost in a fixed weight (C) or fixed-time (D) assumption.

8.3.2.2. Environmental implications

Among others, emissions of nitrous oxide and ammonia are a major concern in swine production for their environmental impact. The reduction of feed crude protein has resulted a feasible strategy to reduce them by the use of crystalline AA (Garcia-Launay et al., 2014). The results presented in Chapter 5 and 6 suggest that when boars and gilts are fed a common diet, it could be that gilts are overfed whereas boars underfed in terms of dietary lysine. These results were the basis to hypothesize that because gilts were overfed, it could be that by a semi-precision feeding, nitrogen excretion could be reduced without impairing growth performance. To predict nitrogen excretion from, the method reported by Garcia-Launay et al. (2014) was simplified to the available data in a fixed-weight approach. The methodology was based on determining N intake by considering ADFI and CP content in the feed at a specific SID Lys:NE. Nitrogen retained in the body was calculated by considering the BW gain and the N content in gain, which was estimated according to the carcass leanness at 100 kg using equations for Pietrain from **Chapter 3**.

Table 8.4. Productive and economic implications of a split-sex semi-precision feeding strategy compared to a common sex diet feeding strategy in two contexts of prices of amino acid (AA) rich feed ingredients[1]

	Fixed-weight[2]		Fixed-time[3]	
	Boars	Gilts	Boars	Gilts
Low AA cost context				
SID Lys:NE, g/Mcal	3.68	3.09	3.96	3.38
Change finishing days	-0.7	0.4	-	-
Change BW gain, kg/pig	-	-	+1.0	0.0
Change IOFFC, €/pig	+0.1	+0.1	+0.7	0.0
High AA cost context				
SID Lys:NE, g/Mcal	2.86	2.23	3.50	2.83
Change finishing days	+1.7	+3.3	-	-
Change BW gain, kg/pig	-	-	+0.3	-0.7
Change IOFFC, €/pig	+0.23	+1.29	+0.04	+0.42

[1] Assuming maximum ADG of gilts at 0.820 kg and boars 0.944 kg, both with an ADFI of 2.0 kg. Reference diet with 2,540 kcal net energy/kg and 0.85% standardized ileal digestible lysine (NRC, 2012). Initial body weight 70 kg.

[2] Final body weight 100 kg.

[3] 35 days simulation.

Table 8.5 presents the effects of three different feeding scenarios on nitrogen excretion from 70 to 100 kg BW. The first scenario is a conventional feeding system based on a common diet aiming to feed an intermediate level between the SID Lys:NE requirement of boars and gilts to reach 99 % of maximum ADG (**Chapter 6**). Although they eat the same feed, gilts need 4.1 days more to reach the target BW and eat 8.2 kg more feed, resulting in a greater N excretion because of a greater N intake. In the first semi-precision feeding scenario, the overall N excretion would not be significantly reduced (-1.6 %), but unlike the conventional feeding, boars and gilts would have a similar N excretion. The second semi-precision feeding scenario would target reducing N excretion with just slightly impairing growth performance. Thus, both boars and gilts would be fed different diets, aiming to reach 98 % of each sex maximum ADG. The modelling shows that this strategy would reduce ADG a 0.9% but N excretion a 11.6 %.

Table 8.5. Effect of feeding a common diet (CD) or a different diet for each sex in a semi-precision feeding (SPF) approach on nitrogen excretions per pig[1]

	CD		SPF 1		SPF 2	
	Boars	Gilts	Boars	Gilts	Boars	Gilts
SID Lys:NE, g/Mcal	3.50	3.50	3.75	3.25	3.50	3.00
CP, %[2]	14.9	14.9	16.0	13.9	14.9	13.0
ADG, kg	0.923	0.819	0.935	0.814	0.923	0.804
N intake, kg[3]	1.56	1.75	1.65	1.64	1.56	1.55
N retained, kg[4]	0.79	0.79	0.79	0.79	0.79	0.79
N excreted, kg[5]	0.76	0.97	0.86	0.85	0.76	0.76
Average N excreted, kg	0.87		0.85		0.76	

[1]From 70 to 100 kg BW, with a 2.0 kg ADFI.

[2]Predicted from the simulations of the effect of increasing SID Lys:NE (X, g/Mcal) in feed cost in the low-cost AA context (Figure 8.1). The equation used was:

$$CP(\%) = -1.545 \times X^3 + 16.45 \times X^2 - 53.95 \times X + 68.5$$

[3]$N_{intake} = 2.0\ (ADFI) \times (30 \div ADG) \times (CP \div 100) \div 6.25$

[4]$N_{retained} = 30\ (kg\ gain) \times Body\ nitrogen\ (kg/kg)$

Body nitrogen was estimated as suggested by Rigolot et al. (2010).

[5]$N_{excreted} = N_{intake} - N_{retained}$

8.4. Future perspectives and practical application

This PhD. dissertation has provided evidence that there is a step in between conventional feeding practices and precision feeding for grow-finishing pigs. This system has been called semi-precision feeding and might be used with the aim of improving the productive and economic performance or reducing the environmental impact of grow-finishing pigs. Nevertheless, it is acknowledged that applying this system would require key management changes in commercial grow-finishing farms. For instance, barns should have at least 2 feeding lines that allow feeding different feeds simultaneously to pigs grouped by initial BW or sex. In addition, feeding pigs with different initial BW would require sorting pigs by initial BW, which is a time costly activity. However, the results in **Chapter 3** have provided evidence that conventional feeding systems limit growth performance of the lightest pigs.

The present thesis has not studied whether pigs with different initial BW show a different response to increasing dietary lysine levels in the finishing phase (e.g. 70-100 kg BW). However, the authors hypothesize that the effect would be null or small compared to the results in **Chapter 4** because finishing pigs have a similar ADG as shown previously in **Chapter 1**. Future studies might aim to test that in a similar design as used for growing pigs in **Chapter 4**. Moreover, the present thesis confirmed that boars and gilts are differently affected by increasing dietary lysine levels in terms of growth and efficiency. As hypothesized, this thesis confirmed that boars require more SID Lys:NE to reach their maximum performance. Generally, it can be considered that boars require around 0.5 g SID Lys/Mcal NE more than gilts to reach a similar relative performance to their maximum. Similar differences were estimated by modelling performance data using available software like InraPorc (van Milgen et al., 2008). For instance, in **Chapter 1** the SID Lys required for growth by grow-finishing boars and gilts after modelling the data from Quiniou et al. (2010) was presented. The results showed that on average, from 70 to 100 kg BW the SID Lys requirement was 19.9 and 17.1 g/d, for boars and gilts, respectively.

Therefore, boars required 16 % more SID Lys intake than gilts, like the results in **Chapter 5** and **Chapter 6** (15-17 %).

Feeding boars and gilts separately can be achieved by two systems: using two feeding lines in a single barn or placing each sex in a different barn. The latter would be the most feasible when the flow of pigs is sufficient to fill the barns in around one week. Otherwise, the difference in requirements for the variability in BW related to multiple fillings would exceed the benefits of single-sex housing (Tokach et al., 2007). Future studies might aim to test the effects of split-sex feeding and housing in large-scale trials to determine the effects of specific semi-precision strategies through the whole grow-finishing phase. Summarizing, the present thesis has confirmed the potential of semi-precision feeding strategies to feed pigs more precisely considering their potential protein deposition.

CHAPTER 9

Conclusions

In the commercial conditions in which the studies in **Chapters 3, 4, 5** and **7** and in the various conditions that studies in **Chapter 6** were carried, the following conclusions were drawn:

1) There are numerous factors in grow-finishing pigs that impact growth performance and carcass composition.
    a. Pietrain sired pigs have a lower feed intake and growth but leaner carcasses than a Synthetic line.
    b. Boars are leaner than gilts independently of their carcass weight.
    c. Increasing carcass weight increases carcass fatness in a different manner depending on the sire-line and sex.
    d. Last pigs marketed, used as a reference of body weight variability, have a reduced carcass fatness.
2) Increasing dietary lysine has a different effect in growing pigs (30-60 kg body weight) classified in categories according to their initial body weight.
    a. Growth performance of the lightest pigs improves linearly more than the largest ones in response to increasing dietary lysine.
    b. The lightest pigs have a greater gain to feed than their heavier counterparts when provided sufficient dietary lysine.
3) Increasing dietary lysine has a greater effect in growth performance and carcass composition of finishing boars than gilts (70-100 kg body weight).
    a. Greater growth of boars is related to a higher protein deposition potential, that results in leaner carcasses considering that there are no differences in feed intake compared to gilts.
    b. There is no evidence that the efficiency of using dietary lysine for growth differs between boars and gilts. Therefore, until future studies confirm it, the requirements can be assumed to be proportional to the potential growth performance. Boars growth potential can be assumed to be around 15-16 % than gilts one.

   c. On average, boars require around 0.5 more g SID Lys/Mcal NE than gilts to reach the same relative performance to the maximum.

4) Dietary net energy density can be reduced 190-250 kcal/kg compared to a reference diet of 2,450-2,550 kcal/kg without impairing growth performance when pigs can overcome the reduced concentration by increasing their feed intake. However, when pigs cannot overcome it and have a deficient energy intake this can reduce growth and fat deposition.

5) Semi-precision feeding is a feasible practice to improve the sustainability of swine production by:
   a. Improving growth performance and return on investment of the lightest pigs.
   b. Improving productive performance of boars when a common sex diet limits their potential growth.
   c. Reducing costs and environmental excretion when gilts are not overfed dietary lysine overfed.

CHAPTER 10

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