Identifying and investigating factors which affect sow productivity in UK and Irish pig herds

Anna Mary Lavery

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds
School of Biology

Agri-Food and Bioscience Institute (AFBI), Hillsborough

Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark

October 2018

Declaration of Authorship

The candidate confirms that the work submitted is her own, except where the work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Chapter 2 is based on a jointly authored publication: Lavery, A., Lawlor, P.G., Magowan, E., Miller, H.M., O'Driscoll, K. & Berry, D.P (2018). An association analysis of sow parity, live-weight and back-fat depth as indicators of sow productivity, *Animal*. Available online. doi: 10.1017/S1751731118001799

AL conducted the research, collated and analysed the data and wrote the manuscript. Co-authors assisted in designing the experiment and revising the submitted manuscript.

Publications

Research papers

Chapter 2

Lavery, A., Lawlor, P.G., Magowan, E., Miller, H.M., O'Driscoll, K. & Berry and D.P. (2018) An association analysis of sow parity, live-weight and back-fat depth as indicators of sow productivity, *Animal*. Available online. doi: 10.1017/S1751731118001799

Published abstracts

Chapter 2

Lavery, A., Lawlor, P.G., Magowan, E., Miller, H.M, O'Driscoll, K and Berry, D.P. An association analysis of sow live-weight and back-fat depth as indicators of reproductive performance. In: Advances in Animal Bioscience, Proceedings of the British Society of Animal Sciences; 2016: 7(1) page 109.

Lavery, A., Magowan, E., Miller, H.M., Berry, D.P and Lawlor, P.G. Reproductive benefits and trade-offs with increasing sow live-weight and back-fat depth in late gestation. In: Advances in Animal Bioscience, Proceedings of the British Society of Animal Sciences; 2017: 8 (1) page 49.

Chapter 3

Lavery, A., Lawlor, P.G., Miller, H.M., O'Driscoll, K., Berry, D.P and Magowan, E. Digestible energy intake during gestation and associated sow reproductive performance. In: Book of Abstracts of the 67th Annual Meeting of the European Federations of Animal Science; 2016: page 446.

Chapter 4

Lavery, A., Lawlor, P.G., Miller, H.M and Magowan, E. The effect of litter birth order on piglet birth weight and vitality measures. In: Advances in Animal Bioscience, Proceedings of the British Society of Animal Sciences; 2018: 9 (1) page 214.

Lavery A., Miller, H.M., Lawlor. P.G and Magowan, E. Effect of dietary oil type and vitamin D_3 level during gestation on sow and litter performance. In: Advances in Animal Bioscience, Proceedings of the British Society of Animal Sciences; 2018: 9 (1) page 191.

Acknowledgements

I would like to thank both the University of Leeds and the Department of Agriculture, Food and Marine (Ireland) for their generous studentships and funding. I would also like to thank Teagasc Moorepark and the Agri-Food and Bioscience Institute (AFBI), Hillsborough for hosting me and facilitating the experimental work.

To my supervisors, Dr Elizabeth Magowan (AFBI), Dr Peadar Lawlor (Teagasc) and Prof Helen Miller (University of Leeds), thank you for your guidance, and support provided throughout my studies. I have enjoyed working with you all and I have no doubt that the knowledge and skills gained through this experience will support me in my professional life. Thanks to Dr Donagh Berry for sharing his enthusiasm and knowledge of statistical testing and for his patience and advice when completing the meta-analysis.

Thanks to the laboratory staff at AFBI Newforge for assisting with the sample analysis and to Mr. Alan Gordon for his advice regarding statistical analysis. To the Pig Unit staff at AFBI Hillsborough, thank you for your help with trial work. It has been a pleasure to work with you all.

Finally, I would like to dedicate this work to my family, without their continued support and encouragement this PhD would have been impossible. Thank you to my mum and dad for their continued patience and wonderful advice. To my husband Ryan, thank you for believing in me while I took this journey in life. You helped me keep things in perspective and ensured I escaped from my studies and enjoyed life together- Thank you.

Abstract

Increasing litter size in sows is accompanied by a rise in the number of unviable piglets at birth which limits the potential output of modern sows. Understanding sow and dietary characteristics that influence reproductive performance and developing nutritional strategies to improve piglet survival and growth to weaning will abate the negative impacts of high litter sizes. Therefore, this study took two approaches: 1. Use of historical data from two research sites to quantify the association between sow or dietary characteristics during gestation and resulting reproductive performance and 2. Two separate feeding trials to determine the effect of salmon oil, vitamin D_3 inclusion level in gestation diets and salmon oil and dietary energy regimen in lactation on piglet viability and growth to weaning. Sow live-weight and back-fat depth in late gestation were found to be important for subsequent reproductive performance. Current recommended digestible energy intakes during gestation were found to be appropriate for the modern genotype, however, current amino acid requirements should be increased for gestating sows. Salmon oil inclusion in gestation and lactation diets increased the proportion of omega-3 (n-3) fatty acids in samples while increased dietary vitamin D_3 level during gestation improved sow and piglet vitamin D_3 status, but the growth performance of piglets was not improved as a result. From this thesis it can be concluded that the transfer of n-3 fatty acids and vitamin D_3 from sow feed to the offspring is effective via placental transfer and milk secretions, but this did not improve performance. This conflicts with other work and further research is needed to clarify the associated biological pathways and mechanisms to explain these inconsistencies.

Table of Contents

List of Tables

List of Figures

List of Fatty acids

Lipid number	Abbreviation	Systematic name	Common name	Type of fat	Omega
C4:0	-	Methyl butyrate	Butyric acid	Saturated	-
C6:0	-	Methyl hexanoate	Caproic acid	Saturated	-
C8:0	-	Methyl octanoate	Caprylic acid	Saturated	-
C10:0	-	Methyl decanoate	Capric acid	Saturated	-
C11:0	-	Methyl undecanoate	Undecylic acid	Saturated	-
C12:0	-	Methyl laurate	Lauric acid	Saturated	-
C13:0	-	Methyl tridecanoate	Tridecylic acid	Saturated	-
C14:0	-	Methyl myristate	Myristic acid	Saturated	-
C14:1c9	C14:1c	Myristoleic acid methyl ester	Myristoleic acid	MUFA	n-5
C15:0	-	Methyl pentadecanoate	Pentadecylic acid	Saturated	-
C15:1c10	C15:1c	Cis-10-pentadecenoic acid methyl ester	Ginkgolic acid	MUFA	n-7
C16:0	-	Methyl palmitate	Palmitic acid	Saturated	-
C16:1c9	C16:1c	Methyl palmitoleate	Palmitoleic acid	MUFA	n-7
C17:0	-	Methyl heptadecanoate	Margaric acid	Saturated	-
C17:1c10	C17:1c	Cis-10-heptadecenoic acid methyl ester	Heptadecenoic acid	MUFA	n-7
C18:0	-	Methyl stearate	Steric acid	Saturated	-
C18:1t9	C18:1t	Trans-9-elaidic acid methyl ester	Elaidic acid	MUFA	n-9
C18:1c9	-	Cis-9-oleic acid methyl ester	Oleic acid	MUFA	n-9
C18:1c11	-	Octade-11-enoic acid methyl ester	Vaccenic acid	MUFA	n-7
C18:2t9,12	C18:2t	Linolelaidic acid methyl ester	Linoleaidic acid	PUFA	n-6
C18:2c9,12	C18:2c	Methyl linoleate	Linoleic acid (LA)	PUFA	n-6
C20:0	-	Methyl arachidate	Arachidic acid	Saturated	-

List of Fatty acids

Lipid number	Abbreviation	Systematic name	Common name	Type of fat	Omega
C18:3c6,9,12	C18:3cn6	Cis-6,9,12-octadectrienoic acid	Gamma-linolenic acid	PUFA	n-6
C20:1c11	C20:1c	Methyl eicosenoate	Eicosenoic acid	MUFA	n-9
C18:3c9,12,15	C18:3cn3	Methyl linolenate	Alpha-linolenic acid (ALA)	PUFA	n-3
C21:0	-	Methyl heneicosanoate	Heneicosylic acid	Saturated	-
C20:2c11,14	C20:2c	cis-11,14-eicosadienoic acid methyl ester	Eicosadienoic acid	PUFA	n-6
C22:0	-	Methyl behenate	Behenic acid	Saturated	-
C20:3c8,11,14	C20:3c8	Cis-8,11,14-eicosatrienoic acid methyl ester	Dihomo-γ-linoleic acid	PUFA	n-6
C22:1c13	C22:1c	Methyl erucate	Erucic acid	MUFA	n-9
C20:3c11,14,17	C20:3c11	Cis-11,14,17-eicosatrienoic acid methyl ester	Eiscosatrienoic acid	PUFA	n-3
C20:4c5,8,11,14	C20:4c5	Cis-5,8,11,14-eicosatetraenoic acid methyl ester	Arachidonic acid (ARA)	PUFA	n-6
C23:0	-	Methyl tricosanoate	Tricosylic acid	Saturated	-
C22:2c13,16	C22:2c	Cis-13,16-docosadienoic acid methyl ester	Docosadienoic acid	PUFA	n-6
C24:0	-	Methyl lignocerate	Lignoceric acid	Saturated	-
C20:5c5,8,11,14, 17	C20:5c	Cis-5,8,11,14,17-eicosapentaenoate methyl ester	Eicosapentaenoic acid (EPA)	PUFA	n-3
C24:1c15	C24:1c	Methyl nervonate	Nervonic acid	MUFA	n-9
C22:5cn3 7,10,13,16,19	C22:5cn3	Cis-7,10,13,16,19-dososapentaenoic aid methyl ester	Docosapentaenoic acid (DPA)	PUFA	n-3
C22:6c4,7,10,13, 16,19	C22:6c	Cis-4,7,10,13,16,19-docosahexaenoic acid methyl ester	Docosahexaenoic acid (DHA)	PUFA	n-3

Abbreviations

°C	Degrees Celsius
AA	Amino acid
ADFI	Average daily feed intake
ADG	Average daily gain
AFBI	Agri-food and Bioscience Institute
AHDB	Agriculture and Horticulture Development Board
BCS	Body condition score
BSAS	British Society of Animal Science
CLA	Conjugated linoleic acid
CF	Crude Fibre
CP	Crude Protein
CV	Coefficient of variation
d	Day (s)
DE	Digestible energy
ELISA	Enzyme-linked immunosorbent assay
EU	European Union
FCR	Feed conversion ratio
g	Gram (s)
GC-FID	Gas chromatography-flame ionisation detector
GLM	General linear model
IGF	Insulin-like growth factor
IgG	Immunoglobulin G
IU	International units
Kg	Kilogram (s)
KJ	Kilojoules
LCMS	Liquid chromatography-mass spectrometry
LYS	Lysine
ME	Metabolisable energy
mEq/kg	Milliequivalent/kilogram
mg	Milligram (s)
mins	Minutes
MJ	Megajoules
ml	Millilitre (s)
mm	Millimetres
MUFA	Monounsaturated fatty acids
NRC	National Research Council
ng	Nanogram (s)
n-3	Omega-3 fatty acids
n-6	Omega-6 fatty acids
n-6:n-3	Omega-6 fatty acid: Omega-3 fatty acid ratio
PROC MIXED	Mixed model
PUFA	Polyunsaturated fatty acids
REML	Linear mixed model
Saturated	Saturated fatty acids
SD	Standard deviation
SE	Standard error
SEM	Standard error of mean
UK	United Kingdom

Chapter 1

General Introduction

1.1 The Pig industry today

Pig meat is the most popular protein source consumed globally with 120,480,000 tonnes expected to be consumed in 2018 and this is predicted to reach 128,600,000 tonnes in 2025 (Statista, 2018). Both the UK and Ireland are key pork producing countries. In the UK, 635,000 tonnes of the pork reared is consumed locally and over 264,000 tonnes of pig meat per year is exported to the EU and the global market (AHDB, 2018). In Ireland, 147,000 tonnes of pig meat are consumed per year and over 240,000 tonnes are exported to the global market (Bord Bia, 2016). Therefore, with the increasing global demand for pork, the pig industry in the UK and Ireland must seize opportunities to increase production with minimal increases in costs.

Increasing sow output in terms of number of pigs weaned at a good weaning weight represents a key driver for increased sow productivity. The overall lifetime performance of a sow is also important and can be measured as the number of piglets born alive (Lucia et al., 1999). Improving sow longevity increases the opportunity to maximise numbers born, decrease culling rates and costs associated with replacement gilts, and therefore is crucial to the profitability of the commercial farm (Koketsu, 2007). As a result of pressures to develop traits associated with the total number of piglets born alive per litter, genetic selection within the pig industry (Bichard and David, 1984, Johnson et al., 1984, Legault, 1984, Knap and Rauw, 2008) has resulted in the modern hyperprolific sow being able to produce more than 30 plus pigs per/sow annually (AHDB, 2016). However, sow output in the UK and Ireland

(24.8 and 27.9 pigs weaned/sow/year, respectively) (AHDB, 2017) is still below the EU and improving this is now priority. Larger litter sizes are accompanied by an increase in the number of low-birth weight unviable piglets born and pre-weaning mortality (Wolf et al., 2008). As global demand for pig meat continues to increase attention continues to focus on important production traits such as numbers of pigs born alive, piglet survival, average daily gain and feed conversion ratio to increase profitability at farm level. However, many factors affect the ability of sows to rear and wean large litters over a number of parities. Sow characteristics such as back-fat depth and live-weight are associated with improved reproductive performance and can be practically managed through on-farm nutrition. Additionally, improving piglet survival at birth and growth to weaning are key to increasing overall sow output, mitigating welfare concerns and increasing farm profitability. More tailored nutrition can be used to achieve these goals. Maternal nutrition has been shown to influence placental growth and foetal development (Gao et al., 2012), muscle fibre type and distribution (Bee, 2004) farrowing rate, pigs born alive per litter (Allan and Bilkei, 2005) and piglet growth through improved milk quality (Ramanau et al., 2004). For this reason, significant priority has been given to determining new nutritional requirements and possible supplements that can be used to more closely meet the needs of the modern hyperprolific sow and her progeny (Moehn and Ball, 2013).

1.2 Key areas for improvement in sow output in the UK and Ireland

Based on current performance, key goals for the UK and Irish pig industry relating to large litters are to:

1. Increase the number of piglets reared by improving piglet vitality and survivability at birth.
2. Increase the number of piglets weaned by reducing pre-weaning piglet mortality during the suckling period.
3. Increase the weight of piglets weaning by increasing piglet growth during the suckling period.

The above are still major challenges for producers but can significantly contribute to increased sow output and kg of pig meat produced/sow/year, which can increase unit profitability.

1.2.1 Litter size and born alive

Litter size is dependent on successful follicular development and embryo survival and this is controlled by reproductive hormone levels in the sow. During lactation, follicular growth is restricted as suckling stimulation results in opioid release and the inhibition of gonadotrophins that stimulate follicular growth. At weaning, gonadotrophin concentration increases and Luteinizing hormone (LH) concentration increases in frequency and magnitude initiating ovulation (Kemp, 1998). However, the reproductive process can be affected by many factors such as sow body condition and nutrition. Schenkel et al. (2010) observed that gilts with >10 % weight and body protein loss > 20 % body fat loss and a body condition score loss of more the one point at first weaning had a significantly smaller litter in their second parity. Similarly, Thaker and Bilkei (2005) found that subsequent litter size was reduced when sows had >10 % weight loss in the previous lactation. Furthermore, calculated body protein loss between 9-12 % can result in decreased litter growth and ovarian function (Clowes et al., 2003a). Body protein mass can be estimated with sow live-weight and back-fat depth measures using the equations of Whittemore and Yang (1989): Body protein (kg)= -2.3 + (0.19 × live-weight, kg) – [0.22 × back-fat (P_2; mm)]. Low sow feed intake, creating negative energy balance during lactation, can reduce LH pulsatility resulting in a greater proportion of small follicles (up to 1mm) at weaning (Quesnel, 2011). Indeed, many metabolites and hormones such as insulin and insulin-like growth factor-1 (IGF-1) have been investigated to establish the connection between nutrient intake and reproduction. Van den Brand et al. (2006), investigated dextrose supplementation during the weaning to service interval (WSI) and found no effect on pregnancy rate, farrowing rate, litter size or birth weight but supplemented sows were found to have more uniform piglets with respect to birth weight. As follicle and oocyte quality and diversity are influenced by plasma insulin, IGF-1 levels and LH pulsatility, this may have reduced within litter variation.

Numbers of piglets total born and born alive varies with sow parity. Parity 3 to 8 sows have larger litters compared to gilts and second parity sows, although the percentage of pigs born dead is greater for parity 6 to 8 sows. Therefore, number born alive peaks for parity 3 to 5 (Milligan et al., 2002). Indeed, older sows tend to have an increased ovulation rate and as a consequence increased embryo numbers (Foxcroft et al., 2006). A solution to increase the litter size of parity 1 and 2 sows after weaning may be to skip the first oestrus, as sows bred on the second rather than first oestrus had significantly more total born (12.8 vs. 10.4 piglets total born), which may be attributed to increased embryo survival (Clowes et al., 1994). Cottney et al.

(2012) found that gilts served on their third oestrus produced more piglets over their lifetime. However, missing an oestrus will increase non-productive days. Kemp and Soede (2012) evaluated techniques such as using a progesterone analogue to delay the onset of ovulation. The total number of piglets born was increased by 2.5 piglets when progesterone was administered for 14 days (1 day prior to weaning to day 13 post-weaning), but shorter treatment periods were found to decrease subsequent performance (Van Leeuwen et al., 2011). The authors later concluded that management techniques such as skip-a-heat and progesterone analogue treatments can improve the subsequent reproductive success of sows with an expected low fertility after weaning i.e. gilts and sows with excessive weight loss.

As litter size increases, the numbers of stillbirths and weak low-birth weight piglet’s increases. With high ovulation rates in the sow, uterine space is a limiting factor and embryos experience competition for space and placental attachment. This can result in small piglets for gestational age (SGA) being born and/or intra-uterine growth restriction (IUGR). The SGA piglets have good growth potential if properly managed while IUGR piglets do not and often have reduced viability (Rutherford et al., 2013). Another consequence of larger litters is that duration of farrowing is prolonged, and piglets are at risk of hypoxia resulting in asphyxia both in utero and during birth leading to an increased prevalence of stillbirth and low viability piglets (Herpin et al., 1996). With genetic selection in the last decade concentrating on increasing total born, the focus is now on improving numbers weaned through selection against piglet mortality up to day 5 (Su et al., 2008). Selection for the number of live piglets at day 5 has resulted in a phenotypic improvement of 1.4 and

2.1 more piglets alive at day 5 per litter and a reduction in mortality to day 5 of 7.9 % and 7.6 % in Landrace and Yorkshire sows, respectively (Nielsen et al., 2013). However, the challenges arising from improved numbers born alive and alive at day 5 include maximising individual piglet and litter growth to weaning.

1.2.2 Weight gain of piglets

Piglet growth and weight gain during the suckling period is important to establish a good weaning weight as this is a major determinant for post-weaning growth (Klindt, 2003). Colostrum is essential in early life for newborn piglets, providing the energy, nutrients and immunoglobulins needed for survival. Quesnel et al. (2012), found that at least 200g of colostrum per piglet is needed to ensure piglet survival, however colostrum intake can vary greatly between and within litters (Declerck et al., 2017). Decaluwé et al. (2014), showed that piglet daily gain and survival was associated with both piglet birth weight and colostrum intake per kg/birth weight. Piglets with severe IUGR, which were lighter and tended to have a lower vitality score, ingested significantly less colostrum in the first 24 hours of life compared to normal piglets. Due to reduced energy reserves, these piglets may be too weak to survive (Amdi et al., 2013a).

Milk intake is the main driver of piglet growth pre-weaning but sow milk yield is influenced by many factors. Vadmand et al. (2015) found a positive linear relationship between litter size and lactation milk yield. However, Auldist et al. (1998) showed that the amount of milk ingested per piglet also decreases with increasing litter size as piglet average daily gain was reduced from 283 g/day to 202 g/day when litter size was increased from 6 to 14. Milk intake of piglets increases with increasing live-weight of piglets due to their higher energy requirements for maintenance rise. On average 317, 531 and 582 g/day of sows' milk is required to maintain piglet live-weight in weeks 1, 2 and 3, of lactation, respectively. Piglets with high milk intake retain more body fat (Theil et al., 2002).

As sow milk yield is a limiting factor for the growth of nursing piglets, the provision of supplementary milk and creep feed during lactation may provide additional nutrients and enhance piglet growth to weaning. Miller et al. (2012) found that piglets supplemented with milk replacer pre-weaning were significantly heavier at weaning than non-supplemented progeny. Similarly, Wolter et al. (2002) reported heavier pigs at weaning from litters fed supplemental milk replacer. Nonetheless, both trials found no effect of supplemental milk on subsequent growth performance between weaning and slaughter. Despite this, recent work using a nutrient dense complex milk replacer increased piglet weight but also increased small intestine weight and weight:length ratio as well as crypt depth and cell proliferation rates. It was thought that the latter should increase post-weaning growth as their capacity for nutrient uptake is increased (De Greeff et al., 2016).

Solid creep feed is often offered to piglets during the suckling period, to support piglet growth and prepare the digestive system for weaning onto solid feed. Sulabo et al. (2010) reported no difference in piglet total body weight gain, weight or coefficient of variation (CV) in litter weight at weaning in response to providing suckling litters with creep feed. However, piglets that consumed creep feed tended to be heavier at d21 post-weaning, had greater ADG and total BW gains post-weaning than non-creep eaters or pigs not provided with creep feed. Furthermore Bruininx et al. (2002) found that piglets that ate creep feed pre-weaning, ate more readily after weaning, had greater ADFI and ADG than non-creep feed eaters and pigs not provided with creep feed. These studies suggest that piglets that consume creep feed may adapt better to dietary changes after weaning through improved intestinal health (Jayaraman and Nyachoti, 2017). Conversely, Muns and Magowan (2018) found that although piglets that ate creep feed had increased feed intake the first week post weaning there was no effect of creep feed intake on piglet growth or gut structure during the post-weaning period. It is clear from the literature that supplementing piglets with milk replacer and creep feed prior to weaning has varying success. Investigating sow nutritional strategies to increase milk yield and piglet growth may replace the need for supplemental milk. As solid feed prior to weaning can improve feed intake post-weaning, future research should focus on the nutrient composition and palatability of creep feed to maximise the potential benefits for piglet growth and development post-weaning.

1.2.3 Number of piglets weaned/year and weaning weight

Pigs weaned/sow/year varies greatly between farms, regions and countries (Van Til et al., 1991). However, it is widely accepted as a measure for reproductive performance. The EU average in 2016 was 27.5 pigs weaned/sow/year, ranging from Italy achieving 24.3 to Denmark achieving 32.1 pigs weaned/sow/year (AHDB, 2017). Additional pigs weaned/sow/year are important as they allow farms to increase productivity without increasing herd size. However, pigs weaned/sow/year can be influenced by many factors; number of pigs born alive, pre-weaning mortality and litters/sow/year.

Lactation length differs greatly between countries and between producers. European Commission (2008) directive 2008/120/EC the *Minimum standards for the protection of pigs*, forbids weaning of piglets less than 28 days old, except when the welfare or health of the sow and piglet would otherwise be compromised. Earlier weaning can have an adverse effect on both growth and behaviour, thereby reducing the welfare of the piglets. Leliveld et al. (2013) found increased mortality rates and faecal *Escherichia coli* counts in pigs weaned at 3 weeks compare to pigs weaned at 4 weeks. Worobec et al. (1999) observed that piglets weaned at 7-14 days drank excessive amounts of water as they were unable to adjust to solid feed and this resulted in reduced weight gain compared to piglets weaned at 28 days old. They also spent less time interacting with enrichment objects and neighbouring pigs due to increased stress levels. However, Tang et al. (1999) found that segregated early weaned piglets, weaned at 15 days old, had accelerated gut maturation which resulted in improved growth and feed efficiency compared to those weaned at 34 days. The difference in findings of the fore mentioned studies may be a result of management techniques as segregated weaning moves piglet away from the farm it reduces pathogen exposure thus improving growth post-weaning. Another influencing factor on weaning age is the cost of production. Main et al. (2005) found that as weaning age was increased, the weight sold per pig weaned, the wean to finish cost per 100 kg sold, and the income over cost improved, whether or not finishing space was limiting. The economic benefit that arises from the increased growth rate and viability in response to increasing wean age was the impetus for increasing wean age in the US in recent years.

However maximising pigs weaned per litter continues to challenge the industry. Pre-weaning mortality is of major importance to the pig industry due to animal welfare concerns and the associated economic and production losses. The current average pre-weaning mortality rate is 11.5 % which accounts for approximately 75 % of deaths on a pig unit. Common causes of pre-weaning mortality being crushing by the sow; starvation; scour and respiratory problems (Kilbride et al., 2012). Crushing of the piglets by the sow can be influenced by maternal factors such as age, parity, breed and individual nature (Andersen et al., 2005). Pre-weaning mortality can be attributed to the responsiveness of the sow to the piglets' distress calls; those that respond more rapidly can release trapped piglets (Illmann et al., 2008). However, with sows penned closely together they can become un-responsive to distress calls as they are exposed to neighbouring litters calls thereby, increasing piglet mortality.

Weaning weight is often reported as predictor of subsequent growth to slaughter (Mahan and Lepine, 1991, Wolter and Ellis, 2001). Genetic selection for larger litters has increased the number of smaller piglets born as well as the within litter variation in birth-weight (Milligan et al., 2002). This results in reduced weaning weight. However, Quiniou et al. (2002) found that although low-birth weight induced a reduction in wean weight, it did not limit the growth potential of the lighter piglets. Indeed, piglets weighing 0.7 kg at birth had a sevenfold increase in body weight during the suckling period than their larger litter mates weighing 2.0 kg at birth which had a fourfold increase in body weight. This suggests that differences in weaning weight between litter mates may be reduced with the correct nutritional status and management practices during the lactation period. Indeed Magowan et al. (2011) found that light weight pigs at weaning (7.1kg) converted feed as efficiently during their lifetime as heavy weight pigs at weaning (10.4kg) and their lifetime growth rate and feed intake per kg of body weight was higher than that of heavy pigs. The current recommended weaning age of 28 days old is optimal for both sow and piglet health and welfare. As a number of factors can affect the number of piglets weaned and piglet weaning weight, a multifactor approach is needed to improve sow and piglet nutrition, increasing the growth of low-birth weight piglets to weaning, and to assess on farm management strategies to reduce pre-weaning mortality rates.

1.2.4 Slaughter weight and kg produced/sow/year

Ensuring pigs reach a good slaughter weight in the least amount of days is a major challenge for the industry particularly where speed of throughput is important (housing is limited). Previous studies have highlighted the reduced lifetime growth performance, increased days to market as well as the fatter carcasses of low birth weight piglets at commercial slaughter age (Rehfeldt et al., 2008). Indeed Williams et al. (2009) found that small piglets had more adipocytes at 7 days old, than normal and large siblings which may indicate a greater capacity to store lipids. However, correct nutritional management may mitigate against some of these negative traits. Madsen and Bee (2015) found that to overcome excessive adipose deposition, dietary energy intake of low-birth weight piglets should be restricted during the finishing period, although their growth rate was compromised which resulted in low-birth weight pigs being on average 13 days older at slaughter than high birth weight pigs. As previously noted, ensuring a good weaning weight is also an important factor influencing lifetime growth. Cabrera et al. (2010) found that heavier pigs at weaning had greater average daily gain (ADG), average daily feed intake (ADFI) and took less days to reach market weight. The latter found that pigs with a weaning weight of between 5.0 and 5.9 kg at 20 days old, reached 125 kg 8 days earlier than pigs weaned between 4.1 and 5.0kg. In addition, Collins et al. (2017) recorded that heavier pigs at weaning (>8.5 kg at 27 ± 3d) had higher ADFI and ADG compared with medium (6.5-8.0 kg) and light pigs (<6.5 kg) during the grower period (d 39 to d 88 post weaning). Despite this feed conversion ratio (FCR) during the grower and finisher stages (d 39 to d123 post weaning) was not influenced by weaning weight. Genetic selection has improved the feed efficiency of pigs but this must be complimented with the correct nutrition to growing pigs to maximise the FCR. King et al. (2000) demonstrated that increasing lysine levels from 4.8 to 6.7 g total lysine/kg, increased growth rate and improved FCR thereby maximising the protein deposition of pigs between 80 to 120 kg live-weight. FCR can also be greatly affected by both management practices and farm facilities such as split sex batches and feeder and drinker design (Agostini et al., 2014).

Maximising the kg of meat produced/sow/year is also an important matrix. Reducing sow non-productive days (NPD) will maximise productivity. The wean to service interval (WSI) is a major component of NPD and can be influenced by lactation length, nutrition, parity, seasonal changes and litter size (Prunier et al., 1996, Knox and Zas, 2001). Reducing lactation length allows pig producers to maximise litters/sow/year, as once weaned a sow will typically return to oestrus within 1 week. However, Smith et al. (2008) found no effect of early weaning on subsequent reproductive performance. Reducing suckling stimulus to induce oestrus (Gerritsen et al., 2008), could increase sow productivity where weaning age is high. Indeed Soede et al. (2012), reported neither litter size nor farrowing rate were negatively impacted by lactational insemination more than 3 weeks after farrowing and when intermittent suckling stopped between 2 to 9 days after ovulation. Piglet feed intake, growth between day 2 to 7 and gut characteristics post-weaning were improved for piglets with 1 week of intermittent suckling prior to weaning (26 days) compared to control piglets weaned at day 29, although they still experienced a post-weaning growth check (Berkeveld et al., 2009). Split weaning piglets can also reduce the WSI through reduced suckling stimulating follicle development (Soede and Kemp, 2015). Both management practises offer an opportunity to reduce NPD and increase sow output.

1.3 Sow productivity

Aforementioned sow reproductive performance is often quantified as the number of pigs weaned/sow/year, which is ultimately influenced by both pigs/weaned/sow and litters/sow/year. Pigs weaned/sow/year is a result of the number of piglets born alive and pre-weaning mortality rate, while litters/sow/year is determined by non-productive days, lactation and gestation length. Therefore, sow reproductive performance accounts for both sow fertility and prolificacy (Koketsu et al., 2017). In the present body of work, sow reproductive performance also encompassed these measures. Sow reproductive performance can be influenced by many factors such as breed, nutritional management during gestation and lactation as well as the environment but it is also important to investigate sow characteristics i.e. parity, back-fat depth and live-weight, that are associated with improved reproductive performance as potential practical on-farm performance monitoring tools. Indeed, sow live-weight and back-fat depth have been highlighted as important to optimise the number of piglets born alive and ensure the subsequent reproductive success of the modern prolific sow (Maes et al., 2004).

1.3.1 Parity

To be profitable a sow must remain in the herd for more than 3 parities (Lucia et al., 2000, Stalder et al., 2003). Sows can be culled involuntarily through breeding failure or death, or voluntarily to improve herd performance. The most common causes of sow removal are udder problems, low productivity and old age (Engblom et al., 2007). Litter size and numbers born alive varies across parities, with gilts and second parity sows having smaller litters compared to middle aged (3-5) and older sows (6-8). Number born alive was greatest for middle-aged sows as numbers born dead increases for older sows, although variation in birth weight was lowest in litters born to gilts, most likely due to the lower litter size, which increased with increasing parity (Milligan et al., 2002). Older sows have an increased ovulation rate. The increased embryo numbers can exceed the uterine capacity resulting in ‘uterine crowding’ and as a consequence variation in placental development, affecting piglet development. As a result, there is increased variation in piglet birth weight, and this affects subsequent piglet performance (Foxcroft et al., 2006). Older sows often experience increased farrowing duration due to greater body fat and/or reduced uterine muscle tone, which can increase the probability of piglets suffering hypoxia during the farrowing process, causing stillbirths or piglets with reduced vitality at birth (Zaleski and Hacker, 1993). Milligan et al. (2002) found that second and third parity sows experienced reduced pre-weaning mortality, weaned more piglets per litter than older sows. Wientjes et al. (2012) reported that piglets <1-week-old were at increased risk of death when reared by older sows, which could be related to a greater proportion of low birth weight piglets, prolonged farrowing or reduced teat functionality and accessibility. As sows age there is also a greater probability of crushing of newborn piglets (Weary et al., 1998). However, the suggestion that older heavier sows are less agile and responsive to piglet distress calls is not conclusive and regardless of parity, several factors can contribute to pre-weaning mortality by crushing such as large litter, low piglet birth weight and the sows' individual nature (Andersen et al., 2005).

Maximising sow feed intake is essential to ensure both sow and litter nutritional requirements for maintenance and growth are met. Feed intake varies greatly with parity, with gilts having significantly lower lactation feed intake than multiparous sows (Koketsu et al., 1996). Noblet et al. (1990) suggested that the voluntary feed intake of gilts during lactation frequently does not meet the demands for maintenance, growth and milk yield. Similarly, Pluske et al. (1998) found that gilts partition more energy to growth than milk production compared to higher parities, which would be expected as they are still growing, while increased lactation feed intake in older sows contributes to increased milk production throughout lactation (Eissen et al., 2000).

It has been reported that parity 4 to 7 sows produce less colostrum than parity 1 to 3 sows (Decaluwé et al., 2013). Lactogenesis is initiated with a drop in progesterone levels and an increase in prolactin. Primiparous sows with a low colostrum yield (0.9 to 4.8 kg of colostrum) were found to have increased progesterone concentrations on day 4 and 3 pre-partum, at 20 and 10 hours before farrowing, but decreased prolactin concentrations 40 and 30 hours prior to farrowing, compared to sows that produced a high yield of colostrum (2.8 to 4.6 kg of colostrum) (Foisnet et al., 2010). Similarly, after farrowing, piglet growth and survival were reduced when sows had greater circulating progesterone levels, with gilts having reduced prolactin levels in the peripartum period (day before to the day after farrowing) compared to older sows (Quesnel et al., 2013). Contrary to this, Quesnel (2011) found no effect of parity on colostrum IgG concentration or yield at farrowing but 24 hours after the onset of parturition, IgG concentration in colostrum was greater in older sows than primiparous sows (10.2 vs. 20.5 mg/ml for parity 1vs. >5, respectively). This is most likely explained by the increased antigenic exposure experienced by older sows. Milk yield is greater in multiparous sows rather than primiparous sows and is greatest for parity 2 to 4 sows (Dourmad et al., 2012), as litter size and number born alive are greater. Indeed, a major determinant of milk yield is suckling stimulus. Farmer et al. (2012) demonstrated that non-suckling of a mammary gland in the first parity, impaired gland development and milk yield in the next parity, although whether this effect is seen in subsequent parities is yet unknown. Vasdal and Andersen (2012) observed that during the first 24 hours post-partum, only 41 % of functional teats were suckled in older sows (parity 3 to 5) and fewer piglets suckled lower teats as parity increased. For larger litters born to older sows, this could result in increased time to suckle and reduced weight gain of piglets.

1.3.2 Sow live-weight

With regards to multiparous sows, recommendations suggest sows should gain between 25-30 kg during gestation, allowing for maternal gain and conceptus growth (Yang et al., 1989, Williams et al., 1993). Although with increased litter size these values underestimate gestation gain. Maternal weight gain in gestation (excluding the litter) can be estimated with the following equation: maternal weight gain in gestation (kg) = maternal weight pre-farrowing (kg) – (total born × 2.28). The value of 2.28, estimates the weight gain of the products of conception including the average weight of each piglet, placenta and placental fluids during the entire gestation period (NRC, 1998). Therefore, a sow with 16 pigs total born needs to gain 36.5 kg for the pigs and associated pregnancy tissue and fluids. Guidelines for gilt and sow management during gestation and lactation are available from many breeding companies and suggest target live-weights but as expected these differ between companies and breed. The average recommended weight of gilts at first service is 140-160kg with a body weight of 180-200kg at farrowing, while the recommended live-weight of parity 2+ sows at service is 180-220 kg and 220-290kg at farrowing (Topigs Norsvin, 2016, PIC, 2017).

During early gestation, there is little energy demand for foetal growth; therefore, this may be an opportune time for sows to recover from lactation weight loss (Dourmad et al., 1996). Sow gestation feed allowance is often determined by visual body condition scoring (1= very thin, 5= obese), however a restricted feeding strategy is commonly implemented in early gestation of gilts to reduce embryonic mortality. Almeida et al. (2000) found that gilts restricted from day 1 to 7 of oestrus had greater embryonic survival at day 28 of gestation than gilts restricted from day 8 to 15 of oestrus, potentially due to differences in progesterone concentrations in early gestation. Hoving et al. (2011), found that a 30 % increase in feed intake compared to the control (3.25 kg/d vs. 2.5 kg/d) from day 3 to 32 of gestation, increased sow body weight gain by 10 kg during the experimental period and increased litter size (15.2 vs. 13.2, respectively), for first and second parity sows in their subsequent parities, through increased embryonic and foetal survival.

As a result of lactation weight loss, many sows enter pregnancy in a state of negative energy balance. A lactation body weight loss of between 10 to 12 % can result in reduced reproduction in the subsequent parity (Thaker and Bilkei, 2005). Contrary to this, Wientjes et al. (2013) reported sow body weight loss of more than 28 kg in the previous lactation increased subsequent litter birth weight, but the standard deviation of piglet birth weight and the proportion of piglets in the litter >1.8 kg at birth also increased. Increased sow lactational weight loss may result in variation in follicular development, compromising the development of the resulting embryos and as a consequence decrease litter uniformity. Therefore, it is important to minimise sow weight loss during lactation for subsequent litter development. Monitoring sow live-weight during lactation can be difficult and labour intensive as sows are housed in farrowing crates but a flank-to-flank measurement has been proposed as a practical tool to indirectly estimate sows' weight while in the farrowing crate (Young and Aherne, 2005).

1.3.3 Back-fat depth

Back-fat depth can vary greatly dependent on sow parity, body size and sow condition as well as stage of gestation and lactation. Young et al. (2005) found that to increase maternal back-fat gain during gestation, target maternal weight gains must be greater than previously thought. Energy requirements for weight and back-fat gains of older sows (parity 3+) are greater than younger sows, as younger sows tend to have greater protein gain than older sows which has a lower ME energetic cost than fat (10.6 vs. 12.5 kcal/kg, respectively). Previous research on the body condition of replacement gilts, recommends a back-fat depth of between 18.0-23.0 mm for gilts at first service (Filha et al., 2010, Roongsitthichai and Tummaruk, 2014). However, Amdi et al. (2013b) found no significant difference in total born, number born alive or dead between gilts that were considered fat or thin at service (19 vs. 12mm back-fat depth, respectively). However, pigs born to fat gilts were heavier and fatter at slaughter (Amdi et al., 2014). Indeed management guideline for gilts, recommend a back-fat depth of 12-19 mm at service but this may differ between breeds (Topigs Norsvin, 2016, PIC, 2017).

Whittemore and Kyriazakis (2006) suggest optimal target back-fat depths for multiparous sows (parity 2 to 6), with a target of between 18.3 mm and 21.2 mm at farrowing and between 14.9 mm and 16.6 mm back-fat at weaning. Similarly sow management guidelines from breeding companies recommend between 15.0 to 22.0 mm back-fat depth or body condition score of 3.0-3.5 at farrowing and 15.0-20.0 mm back-fat depth at weaning or a body condition score of 2.5-3.0 (Topigs Norsvin, 2016, PIC, 2017). However, monitoring back-fat depth is important as excessive back-fat depth at parturition can increase the risk of stillbirth (Oliviero et al., 2010). Indeed, previous studies have reported increased back-fat depth gain during gestation can also negatively impact litter uniformity, but greater back-fat gain was observed in sows with greater reserve loss during lactation suggesting it was sows metabolic status during lactation that influences follicle quality and embryo development (Quesnel et al., 2008, Wientjes et al., 2013). Greater back-fat thickness has been linked to increased serum leptin levels as fat (>25 mm) sows had the highest circulating leptin level compared to medium (20-25 mm) and thin (<20 mm) sows at both farrowing at weaning (4.9, 3.7, 2.8 ng/ml and 3.1, 2.6, 2.7 ng/ml, respectively) (Estienne et al., 2000). Leptin which regulates appetite may also play an important role in regulating reproduction as its release, stimulates the release of gonadotropin hormone and consequently LH, (Barb et al., 2005), which is important for ovulation and follicular development, but the literature is conflicting (De Rensis et al., 2005).

Maes et al. (2004) reported a lower back-fat depth at the end of lactation was associated with increased number weaned, which is likely explained by a greater contribution of body reserves being mobilised for increased milk production. Mullan and Williams (1989) found that during the first week of lactation sows rely on the mobilisation of body reserves to support milk production but by late lactation they rely more on feed intake. A back-fat loss of approximately 1 mm during late gestation has been found to increase colostrum yield by 113 g per sow (Decaluwé et al., 2013) and sows with less body fat tend to have lower fat content in colostrum and early milk samples than fat sows (Revell et al., 1998, Beyga and Rekiel, 2009). However, Revell et al. (1998) also reported a tendency for milk yield to be increased in lean sows, with lean sows producing about 15 % more milk than fat sows. The authors suggest that lean sows may have had a greater lean reserve to mobilise for milk production but also better mammary development, as (Head and Williams, 1995) observed increased DNA in mammary tissue of sows fed 269 g/day compared to 145 g/day protein.

Back-fat depth is commonly monitored using body condition score (1= very thin, 5= obese) which in turn is often used to determine feed allowance, however, visual condition score and back-fat depth are only moderately related (Maes et al., 2004), with repeatability of the condition scoring technique largely based upon experience of the assessor. Accurately measuring back-fat depth is now relatively easy with modern handheld ultrasound technology. However, considering both sow back-fat depth and live-weight in tandem may allow for more accurate monitoring of sow body composition. Further investigation to identify optimal live-weight to fat ratios or target sow body compositions at different stages of production that could be calculated on farm with both weight and back-fat depth measures would be valuable practical tools to improve productivity in modern pig herds.

1.4 The piglet

To maximise piglet growth potential, it is important to understand factors affecting lifetime performance. Within large litters, low-birth weight piglets compete with littermates for colostrum and milk and consequently become immuno-compromised and nutritionally deprived (Le Dividich et al., 2005). Starvation and hypothermia follow, as piglets readily utilise glycogen stores to thermo-regulate in the extra-uterine environment (Le Dividich and Noblet, 1983). With increasing welfare concerns due to increasing piglet mortality associated with larger litter sizes, improving piglet survival at birth and growth to weaning have become very important goals.

1.4.1 Piglet vitality and survivability at birth

Despite advances in farm technology and management techniques, piglet mortality is still a major concern as a number of factors can influence it. Herpin et al. (2002) found that stillbirths account for 5-7 % of total pigs born, a common cause of which is anoxia during farrowing (Gugjoo et al., 2012). Although it has been suggested that it is not the duration of the farrowing but the number of piglets in the litter that influences number stillborn (Zaleski and Hacker, 1993). Ponderal index and body mass index use both piglet weight and length to characterise piglet shape and size. Baxter et al. (2008) observed that all stillborn piglets were in the lower quartiles of both body mass index (≤ 16.37) and Ponderal index (≤ 57.45) and therefore were longer and thinner than surviving piglets. Post farrowing, the majority of piglets that died during lactation were found to be shorter with a low body mass index.

Birth order can also influence piglet survival. As farrowing duration increases piglets born later in the farrowing process are more likely to experience asphyxia as successive contractions reduce oxygenation due to damage and/or rupture of the umbilical cord (Alonso-Spilsbury et al., 2005). Oxytocin is commonly administered to reduce farrowing time by stimulating uterine contractions and although treatment with oxytocin can reduce farrowing time, it has been shown to increase the incidence of intra-partum stillbirth with ruptured umbilical cords, the degree of meconium staining and the frequency of sows requiring assistance due to dystocia (Alonso-Spilsbury et al., 2004, Mota-Rojas et al., 2005). Asphyxia can be detected due to increased blood pCO_2 and lactate levels, while blood pH and pO_2 is reduced. Piglets that survive intra-partum asphyxia are likely to suffer reduced vitality (Herpin et al., 1996). Reduced piglet vitality score at birth can increase time to first suckle and reduce colostrum intake as piglets born later in the farrowing process compete with more litter mates for access to teats and colostrum. Therefore, piglet behaviour and vitality are also predictors of piglet survival. Indeed, Baxter et al. (2008), found that surviving piglets (piglets that survived the neonatal period and were weaned at 28 days) had a more vigorous rooting response at birth, which correlated positively with vitality score and reduced time to the udder and teat. It is important to be able to estimate or predict colostrum intake as a vitality measure.

Colostrum intake is critical for the survival and development of the piglet, providing both immune protection and energy for thermoregulation and growth. Devillers et al. (2004) and Theil et al. (2014a) propose simple weigh–suckle–weigh methods, with minimal impact on piglet behaviour, to be used to predict piglet colostrum intake. However, this assumes normal suckling activity of piglets. This is not the case with intrauterine growth restricted piglets (IUGR) piglets. IUGR can be visually scored as normal, mild or severe (Hales et al., 2013). Amdi et al. (2013a) found that ‘normal’ piglets had a greater colostrum intake between 0 to 24h than severe piglets, while mild piglets were intermediate (268 vs. 97 vs. 163g, respectively). Nevertheless, assessing piglet vitality at birth and predicting survival is difficult as Panzardi et al. (2013) identified multiple factors such as cyanotic skin, low rectal temperature at 24 hours old and both high and low glucose concentration as indicators of reduced ability of piglets to survive the first week after birth. Although birth weight is a good predictor of piglet survival it is clear from the literature that it cannot be considered exclusively.

1.4.2 Piglet survival and growth to weaning

Reports show an average pre-weaning mortality rate in the EU of 13.4 %, although this varies greatly across pig producing countries (AHDB, 2017). Edwards (2002) reviewed historical data from commercial herds in the UK and suggests that improvements in numbers weaned per sow are largely due to increased numbers of total born piglets per sow rather than a reduction in pre-weaning mortality *per-se*. This is despite large litters which have greater variation in, within litter piglet birth weight suffering increased pre-weaning mortality (Milligan et al., 2002). Tuchscherer et al. (2000) identified that surviving piglets were significantly heavier at birth (1368 g vs. 1063 g). However, in an earlier study, Milligan et al. (2001), found that cross fostering piglets to create a more uniform litter and reduce birth weight variation did not improve pre-weaning survival. Nonetheless, the literature is conflicting, and although birth weight is important, it alone is not sufficient to determine survival.

Greater within litter birth-weight variation is correlated with greater variation in weaning weight which subsequently leads to increase in the range of days taken to reach market weight (Quiniou et al., 2002). Alvarenga et al. (2013) found that high birth weight piglets (1.8-2.2 kg) not only have heavier and better developed organs than light weight piglets (0.8-1.2 kg) but have greater body weights at weaning and slaughter (7.63 and 106.94 vs. 4.97 and 99.19 kg, respectively). Heavier piglets at birth were found to have larger Longissimus muscles at 173 days old compared to low birth weight pigs (Fix et al., 2010). However, Rehfeldt et al. (2008) found that longissimus muscle of middle (1.23-1.53 kg) weight piglets had better meat quality traits compared to low (≤1.22 kg) and heavy weight (≥1.54 kg) piglets. Increasing piglet survival and growth to weaning will increase farm productivity but it is clear from the literature it is not without its challenges. Therefore, it is important to understand nutritional strategies to improve sow productivity and piglet growth.

1.5 Sow Nutrition

The nutritional requirement of a sow not only changes through gestation and lactation but is also influenced by age, health status and environmental conditions. As sow productivity has increased these factors are now more important than ever. To achieve optimal sow productivity, a comprehensive understanding of the modern sows’ nutritional requirements throughout her lifetime is essential. It is critical to make accurate estimates for energy and amino acid requirements for sows during both gestation and lactation to optimise their lifetime performance. Recent research has focused on sow nutrition as a tool to improve piglet development and growth both in utero and postnatally.

1.5.1 Gestation nutrition

Diet composition and feed allowance during gestation should aim to provide the sow with adequate energy and nutrients to produce a large uniform litter of healthy piglets with a good mean birth weight. It should also allow for maximum development of the mammary glands, ensuring optimum colostrum quality and efficient milk production for the new litter, as well as establishing the overall body condition of the sow before entering the farrowing house.

Low feed intake during gestation is associated with reduced sow body weight gain and back-fat depth at farrowing and sub-sequentially at weaning. The latter results in delayed oestrus and reduced farrowing rate. However over feeding between day 50 and day 80 of gestation can result in an increased number of stillborn piglets per litter (Lawlor et al., 2007a), with additional energy intake being deposited for maternal gain rather than foetal growth (King et al., 2006). Restricted feeding during gestation is generally recommended to avoid depressed lactation feed intake as sow weight loss greater than 10 % during lactation can increase the WSI and reduce litter size in at the subsequent farrowing (Thaker and Bilkei, 2005).

Sows and Gilts are commonly feed lactation diet ad libitum until insemination (13.5 MJ DE/kg, 144 g/kg CP, 8.8 g/kg total lysine), after which feed allowance is restricted to 2.0-2.2 kg/day for Gilts and 2.5 kg/day for mature sows (12.9 MJ DE/kg, 148 g/kg CP, 7.0 g/kg total lysine). Feed intake is increased to 3.0 kg/day in late gestation; to manage rapid foetal growth and avoid the utilization of sow body lipid stores resulting in negative energy balance. However nutritional requirements of the sow are dynamic, with variations in the nutrients required by the developing foetuses as such a constant feed allocation may not meet the nutritional demands of both sow and foetus (McPherson et al., 2004). A major challenge for modern pig farming is that current nutritional requirements for gestating sows are based on older research with less prolific sows (Ball et al., 2008). Consequentially, adhering to such recommendations, may contribute to decreased litter uniformity and piglet birth weight.

1.5.2 Foetal development

Prior to pregnancy, follicular development is important for embryo and resulting foetal growth. Supplementation of sows at weaning with dextrose can increase insulin levels and in turn IGF-1, which is critical during folliculogensis. Increased levels of insulin and IGF-1 at weaning are associated with peaks of LH (Van den Brand et al., 2001) stimulating the formation of larger follicles, creating a more uniform oocyte and embryo population. Van den Brand et al. (2006) observed a significant reduction in within-litter birth-weight variation, when sows were supplemented with 150 g/day dextrose during the WSI. Related to this, Quesnel et al. (2000) found that feed restricted gilts (from day 14 to 18 post oestrus) injected with insulin (daily from day 14 to 18 post oestrus; 0.6IU live weight/kg) had fewer large follicles than well fed gilts and so insulin supplementation may not alleviate the negative impact of inadequate nutrition.

Within the first month of gestation, litter size is determined by embryo survival. The majority of losses occur during the first 25 to 30 days of gestation (Ford et al., 2002). Foetal losses after day 30 of gestation are often due to insufficient uterine capacity, therefore sows with large litters experience greater foetal mortality rates (Town et al., 2005). As blood and nutrient flow vary along the uterus, foetal growth can be restricted and result in IUGR piglets. Dietary proteins play a crucial role in foetal survival and development as well as placental growth and vascularisation. Wu et al. (1998) fed gilts 13 % or 0.5 % crude protein during the first 60 days of gestation and found that sows on the protein deficient diet, 0.5 %, had reduced placental and foetal growth. Mateo et al. (2007) supplemented gilts with 1 % L-arginine hydrochloride (HCL) from day 30 to 114 of gestation and observed an increase in number of piglets born alive (+22 %) and live litter birth weight (+24 %) and a decrease in piglet pre-weaning mortality (-65 %). The authors suggest the arginine increased placental blood flow, improving nutrient transfer from mother to foetus, thereby improving foetal survival and development. Primary muscle fibres are formed between day 25 and 50 of gestation while secondary fibres develop between day 50 and 90 of gestation (Handel and Stickland, 1987) and the number of primary muscle fibres is predetermined at birth, secondary fibres can be affected by uterine environment (Dwyer et al., 1994). Indeed Town et al. (2004) reported that modest uterine crowding negatively affects placental and foetal development, with muscle weight, cross-sectional area and the total number of secondary fibres reduced.

From day 50-114, the foetus gradually acquires maturity. Muscle development and metabolism around day 90 of gestation is crucial for organs and tissues to be functional at birth and for energy storage and function (Voillet et al., 2014). Gastrointestinal tract (GIT) development, liver and muscle glycogen deposition as well as blood characteristics are important determinants for early survival. Leenhouwers et al. (2002) investigated foetal development in late gestation with regards to genetic merit for piglet survival. They reported that at day 111 of gestation foetuses that have high genetic merit for survival have higher serum cortisol, indicating a higher degree of development and maturity at birth. Increased serum cortisol was also linked to higher muscle and liver glycogen levels, which are important for foetal thermoregulation. Cortisol has also been shown to prepare the GIT for nutrition by improving nutrient digestion and increasing antibody uptake from colostrum (Sangild et al., 2000). Therefore, selection for piglets with improved maturity may improve piglet survival.

1.5.3 Lactation nutrition

Early lactation feed allowance is commonly restricted to allow for adaption to a new diet and avoid the sow becoming ‘sickened’ with excessive feed. Often late gestation feed allowance (~3.0kg) is continued albeit with a lactation diet, with an increase of 0.3-0.5kg/day to appetite post-farrowing. Many interacting factors can affect feed intake in lactation; sow parity, breed, body condition, litter size, environment temperature and diet (Eissen et al., 2000). By far the greatest proportion of the sows energy requirement during lactation is for milk production (NRC, 2012). With 70 % of the sow’s lactation energy requirement destined to support lactation, it is important to maximise sow feed intake. Alternatively, if feed intake has peaked, increasing the energy content of the lactation diet may better support the demands of the suckling litter whilst minimising catabolism of maternal body reserves.

Craig et al. (2017) reported that although sows fed a high specification diet (15.8 MJ/kg DE; 1.3 % total lysine) lost 6.4 kg more body weight during lactation and litter weaning weights were similar, their litter ADG was increased by 190 g/day between birth and weaning than the sows fed the normal specification diets (15.2 MJ/kg DE; 1.28 % total lysine). Contrary to this, Smits et al. (2013), reported that while sow lactation feed intake was not affected by dietary energy concentration (15.3 vs. 13.0 MJ DE/kg), daily energy intake increased with increasing dietary energy concentration. However, no improvement in litter gain or piglet growth was observed with the increased energy intake deposited as maternal gain as evidenced by increased sow weaning weight and back-fat depth.

As sow feed intake commonly plateaus in late lactation due to limited intestinal capacity, it was thought that a phase feeding approach in late lactation might improve energy intake. On the contrary, Craig et al. (2016) observed no improvement in sow or litter performance through phase feeding and a single diet containing 14.4 MJ/kg DE for the duration of lactation, with an average intake of 7.7 kg/d enabled sows to wean 13 pigs at an average weight of 8.6 kg at 28 days old. In the study of Craig et al. (2016), although sow feed intake during the phased period is not reported it is likely that as the energy level between the flat and phased regimen only differed by 0.5 MJ DE/kg, this possibly wasn’t enough of a divergence to see an effect on sow feed intake or piglet performance, as it only equates to approximately 4 % of difference in total energy intake over a 28 day lactation, when sow feed intake was already high. Another area to improve sow lactation performance may be to introduce lactation efficiency as part of the genetic selection process. Bergsma et al. (2009) showed that higher lactation efficiency was associated with lower feed intake and fat losses, while piglet mortality was reduced, and piglet growth rate was higher. Lactation efficiency has a relatively low heritability, but over time if combined with selection for unchanged feed intake it could improve sow productivity (Bergsma et al., 2008).

1.5.4 Colostrum and milk production

Colostrum is defined as the mammary secretion ingested by piglets up to 24 hours after the birth of the first piglet. Transient milk is produced from 34h post-partum until day 4 of lactation and is rich in fat from day 2 to 4, while mature milk is produced from day 10 to end of lactation and its composition remains fairly constant (Theil et al., 2014b). Colostrum production can vary greatly between sows, ranging between 1.9 kg to 5.3 kg (Le Dividich et al., 2005), with older sows (parity 4>) tending to produce less colostrum than younger sows (Quesnel et al., 2015). Theil et al. (2014a) recently developed a mechanistic model to predict piglet colostrum intake and sow colostrum yield. The authors concluded that colostrum yield of sows is on average 29 % greater when estimated with the mechanistic model, than previously believed when derived using an empirical predictive model (Devillers et al., 2004). Therefore, maternal investment in colostrum production is greater than previously thought.

With colostrum and liquid droplets detectable in the mammary tissues of swine from day 105 of gestation (Farmer et al., 2006), maternal nutrition during gestation also may be important for colostrum yield. Theil et al. (2014a) found that high fibre diets containing pectin residue and sugar beet pulp fed to sows from mating to d108 of gestation, increased colostrum production as predicted thorough colostrum intake of piglets. Loisel et al. (2013) increased sow dietary fibre (23.4 vs. 13.3 % total dietary fibre) by partly replacing wheat and barley with a mixture of soybean hulls, wheat bran, sunflower meal and sugar beet pulp, which increased the insoluble and soluble fibre content of the high fibre diet compared to low fibre diet (20.6 and 2.8 vs. 11.4 and 1.9 %, respectively). The authors reported that increasing dietary fibre during late gestation (day 91 to parturition) did not increase colostrum yield but high fibre sows; produced colostrum with 23 % more lipid content, colostrum intake of low birth weight piglets (<900 g) was greater and pre-weaning mortality was lower (6.2 vs. 14.7 %). The authors concluded that the increase in lipid content of colostrum could have been the result of either the catabolism of maternal adipose tissue or increased lipid synthesis in mammary glands. Sow nutrition in late gestation also influences colostrum composition. Krogh et al. (2012) supplemented sows with 1.3 % CLA (conjugated linoleic acid) from d108 gestation to weaning. CLA fed sows produced less colostrum but had higher fat levels. Similarly, Corino et al. (2009) found that supplementing sows with 0.5 % CLA from 7 days before parturition until 7 days post-partum, improved piglet growth and immune capacity as supplemented sows produced colostrum with increased IgG, IgA and IgM levels and piglets nursing CLA fed sows were heavier with significantly more circulating IgG at weaning. It is clear from the literature that sow nutrition is important for both colostrum yield and composition, but the optimal timing of nutritional intervention is not yet clear.

Maternal supplementation during lactation can improve milk yield. Ramanau et al. (2004) found that supplementation with L-carnitine (250 mg/day) increased sow milk yield, milk carnitine levels, piglet growth and weaning weight. The authors suggested that increased milk carnitine may have improved energy utilisation in the piglets. Similarly, Mateo et al. (2008) supplemented sows with arginine during lactation and reported increased piglet weight gain and amino acid concentrations in milk, without any changes in sow body weight as well as reduced plasma urea levels, indicating sows enhanced dietary protein utilisation for milk synthesis. Milk production also varies greatly between sows, but typically, it follows an ascending and plateau pattern, with sows being weaned before milk production decreases (Quesnel et al., 2015). However, the literature regarding when sow milk yield peaks is conflicting as it has been shown to plateau at ~day 14 (Craig et al., 2016), ~ day 17-19 (Hansen et al., 2012) and ~day 21 post-partum (Vadmand et al., 2015) and appears to depend greatly on litter size and litter weight gain. Indeed, accurately measuring milk yield is difficult. Hansen et al. (2012) carried out a meta-analysis of published data since 1980 of experiments that recorded milk yield at least twice from day 3 to 30 of lactation and developed a prediction model to calculate sow lactation curves. The model uses the production parameters litter size and litter gain (kg/d) to predict sow milk production and the model equations are freely available online.

It is clear from the literature that the litter plays a crucial role in determining milk production. The size of piglets is important as older and heavier piglets can strip more milk from mammary glands, suggesting larger piglets may drain milk glands better, or have greater suckling and massaging activity to stimulate more milk production (King et al., 1997). Špinka et al. (1997) found that milk glands are refilled approximately 35 mins after a suckling bout, therefore prolonging suckling intervals would not increase the milk available at the next nursing. Auldist et al. (2000) demonstrated that increasing the suckling frequency (30 min intervals) increased mammary gland weight and tended to increase milk production in early lactation. On the contrary, Thodberg and Sørensen (2006) found no effect of nursing frequency or udder massage on d11 and d18 on milk production. Nevertheless, the nursing litter has a direct effect on both colostrum and milk production and with larger litters, ensuring optimal body condition and nutrition for sows is important to support lactation.

1.6 Dietary energy

Supplying sufficient dietary energy to the sow is critical in ensuring her reproductive success. Energy requirements during gestation are determined by sow growth, body maintenance functions and restoring lost body condition, growth of the foetus and development of the uterus and mammary glands. The energy availability for these processes is influenced by parity, sow body weight, productivity and environmental condition (NRC, 2012). Excess energy intake during gestation results in fat deposition, which can be mobilized for foetal growth and sow maintenance during times of reduced energy intake. Energy intake of sows during gestation is sufficient support both maternal and foetal growth. However, energy intake of the modern prolific during lactation is rarely sufficient to support both sow body maintenance and piglet growth. Digestible energy (DE) is the energy from feed minus the energy lost in faeces while metabolisable energy (ME) is the energy remaining from feed intake after faecal and urinary losses. Cereals are lower in ME and DE compared to animal fat, vegetable oil or sugar-based diets. Quiniou et al. (2008) compared the use of corn starch and soybean oil during gestation and/or in lactation. Survival rate and litter growth rate to weaning was significantly greater for sows fed soybean oil throughout gestation and lactation; however, these sows suffered higher back fat loss. Therefore, when increasing the dietary energy content, it is also important to consider the energy source.

1.6.1 Digestible Energy

Restricted energy intake in gestation is common practise to minimise surplus energy being deposited as maternal gain. The *Nutrient Requirements of Swine* (NRC, 2012) recommends between 29.1 and 37.0 MJ DE/day for multiparous sows during gestation (Table 1.1).

Table 1. 1. National Research Council (NRC) energy and lysine requirements for gestating sows

Parity	1		2-3		4+	
Body weight at breeding (kg)	140		165-185		205	
Gestation weight gain (kg)	65		52.5-60		40-45	
Litter size[a]	12.5		13.5		13.5	
Days of gestation	<90	>90	<90	>90	<90	>90
Feed intake (kg/day)[b]	2.1	2.5	2.21	2.61	2.1-2.2	2.4-2.6
DE intake (MJ/day)	30.2	35.9	31.3	37.0	29.1-31.2	34.7-36.9
Total lysine (g/day)	12.4	19.3	9.4-11.0	15.4-17.5	7.7-8.2	13.1-14.0

[a] *Estimates mean piglet birth weight 1.4kg*
[b] *Assumes feed wastage is 5 % and DE content of diet is 14.2 MJ DE/kg*
Source: (NRC, 2012)

As expected severely restricted energy intake has detrimental effects on piglet growth as demonstrated by Buitrago et al. (1974) who found that a low energy intake in gestation (9.2 MJ DE/day) decreased individual piglet birth weight and total litter weight as well as muscle fibre numbers. Heyer et al. (2004) investigated energy intake over two consecutive parities and found that sows receiving 40.7, 51.1 and 60.4 MJ DE/day, between day 25 to 85 of gestation, tended to give birth to an additional 3 piglets per litter compared to the control group (30.2 MJ DE/day). On the contrary Bee (2004) reduced the energy intake of sows during the first 50 days of gestation from 42.8 to 18.5 MJ DE/day and found no effect on reproductive performance i.e. litter size, piglet birth weight. it is unlikely reduced energy intake in early gestation would affect total number of piglets born as follicular development and embryo survival are significantly influenced by changes in lactation weight and body condition. A review by Kongsted (2005) concluded that the association between energy intake and reproductive performance is not clear due to conflicting results in the literature.

Feed intake and therefore digestible energy intake is often increased in late gestation to meet the increasing demands of the developing litter and to establish lactation intake. Similarly, Cromwell et al. (1989) observed an increase of 0.35 total born and 0.34 born alive as well as improved piglet birth and weaning weight, when digestible energy intake from day 90 to farrowing was increased from 44.4 to 50.6 MJ DE/day. Although the authors later concluded the increase in total born and born alive was likely a result of treated sows being in better condition at the end of lactation. Gonçalves et al. (2016) reported that increased energy intake in later gestation (26.5 to 39.7 MJ DE/day) increased birth weight of piglets born alive to sows and gilts, sows with the high energy intake also had an increased probability of stillbirths compared to those with the low energy intake.

Ensuring adequate energy intake in lactation is important to minimise sow body reserve mobilisation and to support milk production. Current recommendations suggest an average daily energy intake of 84.5 to 93.9 MJ DE/day for lactating sows dependent on parity, litter size and litter average daily gain (Table 1.2).

Table 1. 2. National Research Council (NRC) energy and lysine requirements for lactating sows

Parity	1			2+		
Pre-farrowing weight (kg)	175			210		
Litter size	11			11.5		
Lactation length	21			21		
Daily weight gain of piglets (g)	190	230	270	190	230	270
Feed intake (kg/day)[a]	5.95			6.61		
DE intake (MJ/day)	84.5			93.9		
Total lysine (g/day)	48.7	52.6	56.5	52.4	56.4	60.5

[a] *Assumes feed wastage is 5 % and DE content of diet is 14.2 MJ DE/kg*
Source: (NRC, 2012)

Park et al. (2008) found high energy intake in lactation reduced sow body weight and back-fat loss and increased piglet growth. Similarly, Craig et al. (2016) found that dietary energy density above 13.8 MJ DE/kg enabled the sow to raise a large litter (12.8 pigs) to a good weaning weight (average. Piglet weight 8.63kg) without compromising sow body condition. On the contrary, Strathe et al. (2017) found that the ADG of the litter was positively related to the sows' ADFI and body weight loss as well as litter size. These studies indicate that both a high feed intake and high level of body reserve mobilisation are needed to support high milk production, but these are dependent again on sow intake and energy density of the diet. Therefore, establishing optimal DE and feed intakes for sows in both gestation and lactation is important to support maternal and litter growth, avoiding detrimental effects on sow body condition and litter performance.

1.6.2. Oils

Fats and oils are essential in swine diets as mammals are unable to naturally synthesise adequate amounts of fatty acids. There are currently no recommended inclusion rates of omega-3 fatty acids (n-3) in pig diets but the requirement for the omega-6 fatty acid (n-6) Linoleic acid is 2.1 and 6.0 g/day for gestating and lactating sows, respectively (NRC, 2012). Additional fats are often added to increase energy density in swine diets due to their high available energy content compared to that of cereals (2.25 times greater).

Linoleic acid (LA) (C18:2) is commonly found in plant oils such as soya oil and is important for the biosynthesis of prostaglandins and cell membranes. Conjugated linoleic acid (CLA) is a mixture of isomers of linoleic acid and is found naturally in some plant oils such as sunflower and safflower oil but also in meat and dairy products. In ruminants, CLA is modified by enzymes such as lipase and further converted by bacteria and hydrogenation in the rumen. However, feeding purified CLA oil to pigs is more effective due to the limited hydrogenation of fats in the monogastric digestive tract (Dugan et al., 1997). Supplementing sows with 1 % CLA, reduced sow body weight loss during lactation and increased sow milk yield and piglet body weight gain during the suckling period as well as the immune capacity of piglets (Lee et al., 2014). Many studies emphasise the fatty acid composition of the maternal diet and the impact on nursing piglets through the sow's milk (Pettigrew, 1981, Lauridsen and Danielsen, 2004). In order to influence colostrum and milk lipid quality Pettigrew (1981) suggested that additional fat should be fed to the sow at least 5 days before farrowing. This allows the fatty acids to be metabolised and transferred to the mammary gland. Supplementing sows with 10 g/kg CLA from day 107 of gestation until weaning increased daily weight gain and final weaning weight of piglets and altered the fatty acid composition of both colostrum and milk (Cordero et al., 2011). Similarly, Corino et al. (2009) found piglets were heavier at weaning and colostrum IgG, IgA and IgM concentrations and piglet serum IgG at weaning were also greater for sows supplemented with 0.5 % CLA.

Docosahexaenoic Acid (DHA) is an n-3 fatty acid (C22:6) commonly found in fish oils, but in commercial pig diets which are primarily cereal based it is found as its precursor Alpha-Linolenic Acid (ALA), Figure 1.2. De novo synthesis of DHA from ALA is less than 1 % efficient in swine; therefore, dietary inclusion of DHA is more beneficial. DHA is an essential component in the phospholipid membrane of cells, making it crucial for rapid tissue formation as seen during gestation and foetal growth. It is also critical in the development and myelination of the central nervous system and acts as a precursor in cell signalling (Li et al., 2009). Leroy et al. (2008) reported that n-3 fatty acids in the diet of dairy cows reduced prostaglandin secretion, extending the lifespan of the corpus luteum and embryo survival. As follicle development begins during lactation, n-3 fatty acid supplementation may have greater effect in the subsequent litter. Mateo et al. (2009) found that supplementing sows with 0.2 % n-3 fatty acid from day 60 of gestation to day 21 of lactation increased piglet birth weight and DHA concentration in colostrum and mature milk, improving the growth of nursing piglets regardless of sow parity. It was also noted that treated sows tended to have more total born alive and larger piglets in the subsequent farrowing than the control group. The literature shows promise for the use of fatty acids to improve performance but a better understanding of how maternal supplementation with oils can influence reproductive performance is still required.

1.6.2.1 Plant oils

Soya oil is an n-6 rich oil readily used in pig diets as an energy source due to its relatively low cost compared to other plant oils e.g. palm and coconut oil. Although research is focused on investigating alternative plants oils to improve sow and piglet performance, e.g. linseed also known as flaxseed oil is a source of alpha linoleic acid (ALA) an n-3 fatty acid. Supplementing sows with flaxseed oil can improve sow, milk and piglet n-3 fatty acid levels, reduce saturated fatty acids and decrease the n-6:n-3 fatty acid ratio (Farmer and Petit, 2009). Tanghe et al. (2014) found that sows supplemented with linseed oil from day 45 of gestation and during lactation had significantly more piglets born alive and weaned in the current parity; and significantly more piglets born alive in the subsequent litter, than sows fed fish oil. This suggests that feeding linseed oil during gestation improved embryo survival, increasing subsequent litter size. Piglets from sows fed linseed oil were also heavier at 5 days old compared to those fed palm oil. The authors conclude that a lack of decrease in ARA in the liver of piglet from sows offered linseed oil had a positive effect on piglet growth. However, Corson et al. (2008) reported sows fed palm oil during the first half of gestation (first 60 days of gestation) had larger litters that were heavier at birth than sows fed sunflower oil. The shorter chain length of medium chain fatty acids (MCFA) means they are more soluble in water so are rapidly broken down. MCFA present in palm oil are therefore readily available energy source that could better support foetal growth.

Maternal supplementation with coconut oil, a rich source of MCFA from day 84 of gestation to farrowing, increased the liver and muscle glycogen and plasma albumin of piglets (measured approximately 4 hours after birth), improving piglet maturity and survival of low birth weight piglets (Jean and Chiang, 1999). Similarly, Casellas et al. (2005) improved the survivability of piglets weighing under 1.25 kg at birth with an oral supplementation of coconut and soya oil emulsion (3 ml/day) during the first 3 days of life. However, the dose of MCFA is important as although energetically optimal, 6 ml/kg BW $^{0.75}$ every 12 hours had a narcotic effect, increasing blood ketone bodies, reducing piglet activity and increasing mortality (Lin et al., 1995). Therefore, the optimal MUFA oral supplement dose for piglets may be 3 ml/day but further investigation is needed. Indeed, it is also important to consider the ratio of n-6: n-3 fatty acids in diets. Papadopoulos et al. (2008) reported a lactation diet with high n-6:n3 ratio (10:1), reduced sow feed intake on the two days post-farrowing and was associated with increased leptin levels and short-term insulin resistance compared to sows offered a low n-6:n-3 diet (2:1). Increasing the proportion of n-6 fatty acids in the diet may have initially increased leptin released from fat to suppress sow appetite. However, increased Arachidonic acid (n-6 fatty acid) has been shown to induce leptin resistance in mice, suppressing the effect of leptin on feed intake (Cheng et al., 2015). This may explain why sow lactation feed intake from day 2 to weaning was unaffected by dietary treatment. Increasing dietary n-6 fatty acids has also been shown to decrease glucose tolerance and insulin sensitivity in rats (Liu et al., 2013), which may explain the short-term insulin resistance in sows offered the high n-6:n-3 ratio diet. Feeding sows plant oil-based diets can improve piglet growth. Eastwood et al. (2014) reported increased piglet ADG from birth to weaning and piglet weaning weight when sows were offered diets with n-6: n-3 ratios of 9:1 and 5:1 from day 80 of gestation to weaning. Similarly Yao et al. (2012), observed increased litter daily gain from day 0 to 14 when sows were fed diets with plant oil based n-6:n-3 ratio of 9:1. Moreover the n-6:n-3 ratio in the sow diet was also shown to influence cytokine levels in piglet plasma, with reduced interleukin-1β on day 14 of lactation and a tendency for less tumour necrosis factor-α on day 21 of lactation in the plasma of piglets born to 9:1 fed sows. This suggest a dietary ratio of n-6: n-3 of 9:1 improved inflammation prevention capacity and immune status of piglets compared to a n-6: n-3 of 3:1. The literature shows that the use of plant oils in both sow diets and as a supplement for piglets can improve piglet survival and growth to weaning, although the ratio of n-6:n-3 and dose needs to be optimised. Many plant oils are now available for commercial use and provide a more sustainable source of n-6 and n-3 fatty acids than animal fats.

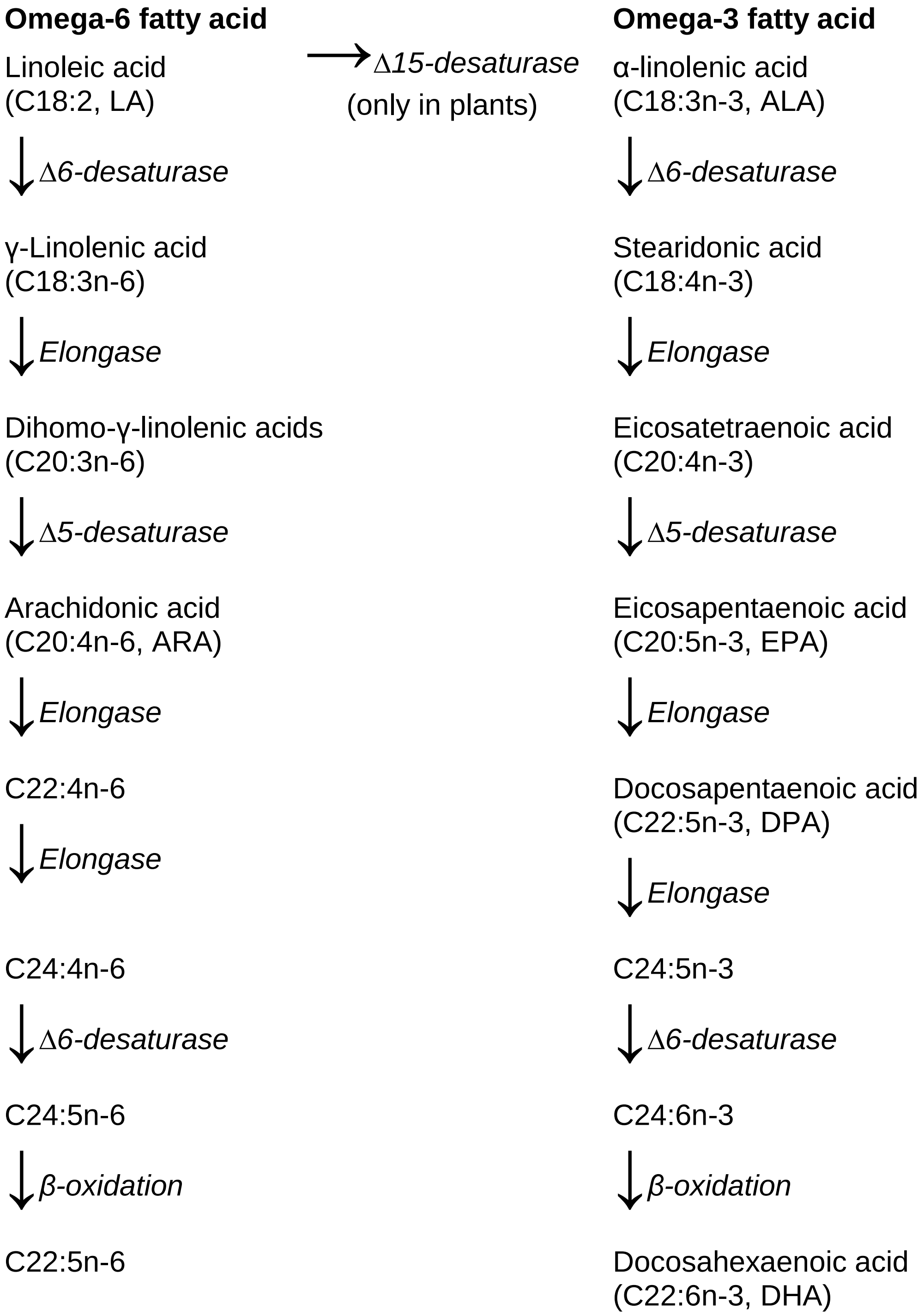

Figure 1. 1. Synthesis of omega-6 and omega-3 fatty acids from their precursor fatty acids linoleic acid (n-6) and α-linolenic acid (n-3), adapted from Tanghe et al. (2013)

1.6.2.2 Fish oils

Rooke et al. (1999) noted an increase in plasma DHA in the umbilical cord of sows treated with tuna oil in the last 21 days of gestation, suggesting the PUFA’s can pass into the foetus via the placenta. Increasing the proportion of n-3 fatty acids with the addition of tuna oil in the maternal diet (25.8 vs. 7.8 g/100g total n-3) prolonged gestation and delayed the onset of parturition (Rooke et al., 1998). Although the exact mechanism is not clear research in both cattle and sheep has shown that increasing dietary n-3 fatty acids affects prostaglandin production which is important for the onset of parturition (Gulliver et al., 2012).

N-3 fatty acids are found in high concentrations in the brain, which undergoes rapid development during late gestation and therefore n-3 fatty acid inclusion in the maternal diet is essential for the cognitive and visual development of the foetus. Rooke et al. (2001b) found that piglets from sows supplemented with tuna oil from day 92 to parturition, had increased vitality, reaching the udder and suckling sooner than piglets from control sows. This improved piglet growth throughout the lactation period. Contrary to this, Rooke et al. (1998) observed that piglets from sows fed tuna oil during late gestation (last 21 days of gestation and first week of lactation) had a lower viability score at birth (based on heart rate and standing time) even though DHA was increased in the piglet brain. This finding is supported by Gunnarsson et al. (2009) who investigated the effect of maternal PUFA’s on cognitive development by behavioural testing. Although progeny from sows offered diets high in n-3 fatty acid had increased brain DHA compared to progeny from sows offered diets high in n-6 fatty acids, it did not improve piglet behaviour. Laws et al. (2007a) found piglets had an increased pre-weaning weight gain from birth to day 21 (weaning), when sows were supplemented with fish oil from day 1 to 60 of gestation. However, when supplemented with fish oil from day 60 to parturition no effect was found (Laws et al., 2007b). Similarly, Laws et al. (2009) found that low birth weight piglets had growth rates akin to larger piglets when sows were supplemented with PUFA oils in the first 60 days of gestation; possibly linked to placental growth, which occurs during this period.

Fritsche et al. (1993) examined the efficiency of fatty acid transfer to piglets from sows supplemented with lard or menhaden fish oil during late gestation and lactation. They observed a significant increase in sow n-3 fatty acid serum concentration and a 10-fold increase in piglet n-3 fatty acid serum concentration in immune cells within 24 hours of birth, from sows fed 3.5 % and 7 % fish oil. However, using a marine oil to supply DHA, decreases the concentration of Arachidonic Acid (ARA) an n-6 fatty acid (C20:4). ARA is an intracellular messenger important in the regulation of enzymes and inflammatory responses. Rooke et al. (2001b) found that piglets from tuna oil treated sows grew quicker in the first 35 days post-weaning than control piglets. The authors also observed that DHA concentration in piglet tissues (brain, liver, retina and remaining carcass) were greater at birth from sows supplemented with tuna oil from day 92 to parturition. However, when sows were supplemented with tuna oil between day 63 and 91 of gestation, piglet brain and retina ARA was lower than when sows were supplemented between day 92 to farrowing. This suggests that decreases in piglet ARA in the brain and retina during this stage of gestation are not reversible as later nutrition did not reverse decreased ARA or increased DHA levels.

It is clear that piglet development can be improved by feeding n-3 fatty acids in the maternal diet. The ideal timing for supplementation to sows may be in late gestation (day 90 onwards) to influence piglet brain development and piglet survivability and throughout lactation to influence subsequent litter growth. However early application (before day 60 of gestation) could also influence piglet growth and in particular the growth of low birth-weight piglets. Supplementation of n-3 fatty acids is normally in the form of fish oils, due to high concentrations of DHA, allowing for maximum availability. However, there is controversy regarding the sustainability of fish oil and its supply and in the future alternative sources such as algae are likely to be considered.

1.7 Amino acids

Amino acids (AA) are the building blocks for the synthesis of protein. Essential AA need to be supplied through the diet as pigs cannot synthesise them themselves (*de novo*) or synthesise enough to meet their metabolic requirements. Lysine is an essential AA and is considered the first limiting AA in pigs diets as they are primarily based on cereal grain which are deficient in lysine. As modern genetics have focused on increasing the efficiency of lean pork production, AA and in particular lysine requirements for modern pigs are important. Current AA recommendations for gestation sows suggest increasing AA after day 90 of gestation as lysine requirements increase. Indeed, foetal and mammary growth increase as pregnancy progresses (Kim et al., 1999, McPherson et al., 2004). As previously discussed, lactation weight loss and consequently protein loss during lactation influence subsequent reproduction (Clowes et al., 2003a). However, increasing ileal digestible AA supply alone by 30 %, during the first month of gestation (day 3 to 32) did not improve the recovery of sow body weight lost during lactation and consequentially did not affect subsequent reproductive performance (Hoving et al., 2011). As might be expected the sows in this case could not benefit from the extra protein provided, as it was not accompanied by an associated energy supply (Campbell et al., 1985).

1.7.1 Lysine

In typical grain-based diets, lysine is considered the first limiting amino acid; therefore, other amino acid requirements are often expressed relative to lysine. Lysine is important for both metabolic and physiological function in pigs such as the biosynthesis of proteins and peptides, non-peptide molecules i.e. urea as well as hormone production and gene expression (Liao et al., 2015). Current recommendations suggest that between 8.2 and 19.3 g/day total lysine is required by gestating sows but is dependent on parity, body weight at breeding, anticipated litter size, pregnancy weight gain and stage of gestation (Table 2.1) (NRC, 2012). Samuel et al. (2012) investigated lysine requirements in early (day 24 to 45) and late gestation (day 86 to 110) and found that lysine requirements increase from 9.4 g/day in early to 17.4 g/day in late gestation. This is not surprising since the recovery of body tissues of sows following lactation is the principle sink for the AAs in early gestation whereas foetal growth becomes an important AA sink in late gestation (McPherson et al., 2004). Similarly, Kim et al. (2009) calculated the lysine requirement for gestating sows to be 5.57 g/day in early gestation (d0 to 60) and 8.78 total lysine g/day in late gestation (d60 to 114). In addition, Zhang et al. (2011)

reported increased sow body weight, backfat depth, total litter weight, piglet birth weight, colostrum dry matter and protein content with dietary lysine levels between 0.56 to 0.74 % from day 30 of gestation until parturition compared to 0.46 % dietary lysine. Often a single diet is offered during gestation which may not meet the requirements of younger sows in both early and late gestation. Feed allowance is frequently increased in late gestation to meet the demands for mammary and foetal growth, but increased energy may be deposited as back-fat gain. As AA requirements and the ideal protein ratio differ during early and late gestation (NRC, 2012), a phase feeding approach may be better to meet the nutritional demands of the sow during gestation (Goodband et al., 2013).

Recommended total lysine requirements for lactating sows are 48.7 to 60.5 g/day dependant on sow parity, pre-farrowing weight, litter size and average daily gain of the litter over a 21-day lactation (Table 2.2) (NRC, 2012). Most dietary lysine is used for milk production, although it is also needed for other metabolic process such as reproduction, mammary growth and colostrum production (Theil, 2015). Indeed, an additional 1.0 g of lysine per day is needed for mammary growth for each additional piglet in the litter (Kim et al., 1999). During the first week of lactation, 94 % of lysine requirement is for milk production and only 5 % for sow maintenance (Feyera and Theil, 2014). It is important to consider that the regressing uterus can provide approximately 13 % of total lysine requirement on d2 and 8 % on d7 of lactation (Theil, 2015). However, Vadmand et al. (2015) demonstrated that dietary protein and essential amino acids supplied may not be adequate for the high-yielding sows, as with increasing sow milk yield, milk protein concentration was found to reduce. Similarly (Jones and Stahly, 1999) found that sows offered a low lysine diet (0.34 %) had reduced milk protein concentration throughout lactation in comparison to sows offered a high lysine diet (1.2 %), although the amino acid requirement for milk production can be supplemented through mobilisation of sow body reserves (Strathe et al., 2017). Therefore, establishing optimal amino acid requirements for lactating sows and ensuring optimal levels are offered on farm could maximise milk yield and composition but also maintain sow body composition for subsequent reproduction.

1.8 Vitamins

Synthetic vitamins are added to the premix of pig diets as their content in other dietary ingredients is limiting. Lactating sows do have a greater vitamin requirement than gestating sows but as percentage or g/kg of diet, current dietary vitamin recommendations do not differ between gestating and lactating sows, with the exception of vitamin A and choline which are lower during lactation (Table 1.3).

Ensuring adequate vitamin supply is essential for both the sow and offspring to maintain metabolic functions, mediate biochemical pathways and for normal health and growth. Increasing maternal supplementation can increase vitamin status in the dam; however, the efficiency of vitamin transfer across the placenta is limited with the majority of vitamin supply to piglets being via colostrum and milk (Pinelli-Saavedra and Scaife, 2005). Literature regarding vitamins in pig diets is limited and with genetic selection for improved reproductive performance as well as feed efficiency, it is important to understand the vitamin requirements of modern pigs (Matte et al., 2006).

Table 1. 3. National Research Council (NRC) vitamin requirements for gestating and lactating sows

	Requirements	
Vitamins	Gestation	Lactation
Vitamin A (IU/kg)	4000	2000
Vitamin D_3 (IU/kg)	800	800
Vitamin E (IU/kg)	44	44
Vitamin K (IU/kg)	0.50	0.50
Biotin (mg/kg)	0.20	0.20
Choline (g/kg)	1.25	1.00
Folacin (mg/kg)	1.30	1.30
Niacin (mg/kg)	10	10
Pantothenic acid (mg/kg)	12	12
Riboflavin (mg/kg)	3.75	3.75
Thiamin (mg/kg)	1.00	1.00
Vitamin B_6 (mg/kg)	1.00	1.00
Vitamin B_{12} (µg/kg)	15	15

Source: (NRC, 2012)

1.8.2 Vitamin D_3

Vitamin D_3 is classified as a fat-soluble vitamin, indicating that it is absorbed similar to lipids. It is commonly associated with sunlight, exposure to which can reduce the dietary requirement for the vitamin. It is important for the promotion of calcium (Ca) homeostasis, bone health and of both innate and adaptive immunity (Aranow, 2011).

Synthesis of vitamin D_3 from its precursor contains a light dependent step, to facilitate the opening of an aromatic ring. However, Cholecalciferol is commonly used in pig diets and therefore does not depend on the light-dependant stage. In the liver, vitamin D_3 is hydroxylated to calcifediol (25-hydroxycholecalciferol (25(OH)D3); the major circulating form. It is then further hydroxylated in the kidneys to the hormonally active form, calatriol (1, 25-dihydroxycholecalciferol (1, 25$(OH)_2$D3)), Figure 1.3. Many studies not only evaluated the dose of vitamin D_3 but also the different forms. 25(OH)D3 is commercially available as a supplement and is widely used due to its active absorption in the intestine. Weber et al. (2014) found that the weight gain of sucking piglets was greatest when vitamin D_3 was provided in the gestation diet and lactation diets. However, in a separate study to total litter weight and birth weight of piglets was greatest in sows supplemented during gestation and lactation with the 25(OH)D3. Therefore, piglet weight and growth were influenced by maternal vitamin D status and by the 2 difference sources of vitamin D_3.

During gestation and lactation, the vitamin D_3 requirement of the sow increases with the demand for calcium that is needed for foetal growth and milk production. In mature swine, insufficient dietary calcium and/or vitamin D_3 can result in a reduction of bone mineral content and the disease Osteomalacia. More commonly vitamin D_3 deficiency will cause lameness or in severe cases bone fractures. This can result in welfare concerns and increased culling rates (Kirk et al., 2005). In young growing pigs, low vitamin D_3 levels can result in Rickets; common symptoms include broken bones, swollen and stiff joints. Maternal vitamin D_3 status is closely linked to offspring levels. Rortvedt and Crenshaw (2012) reported a 20-30 % incidence of kyphosis, as well as decreased whole body and femur mineral content in young pigs from sows fed very low levels of vitamin D_3 (45 IU/kg) during gestation. Similarly, Witschi et al. (2011) found reduced bone strength, mineral content and density of tibia bones of pigs that were born to sows supplemented with 5 µg/kg (200 IU/kg) vitamin D_3 during gestation and lactation and were offered the same vitamin D_3 level as the dam in creep feed until approx. 20 kg (~35 days old).

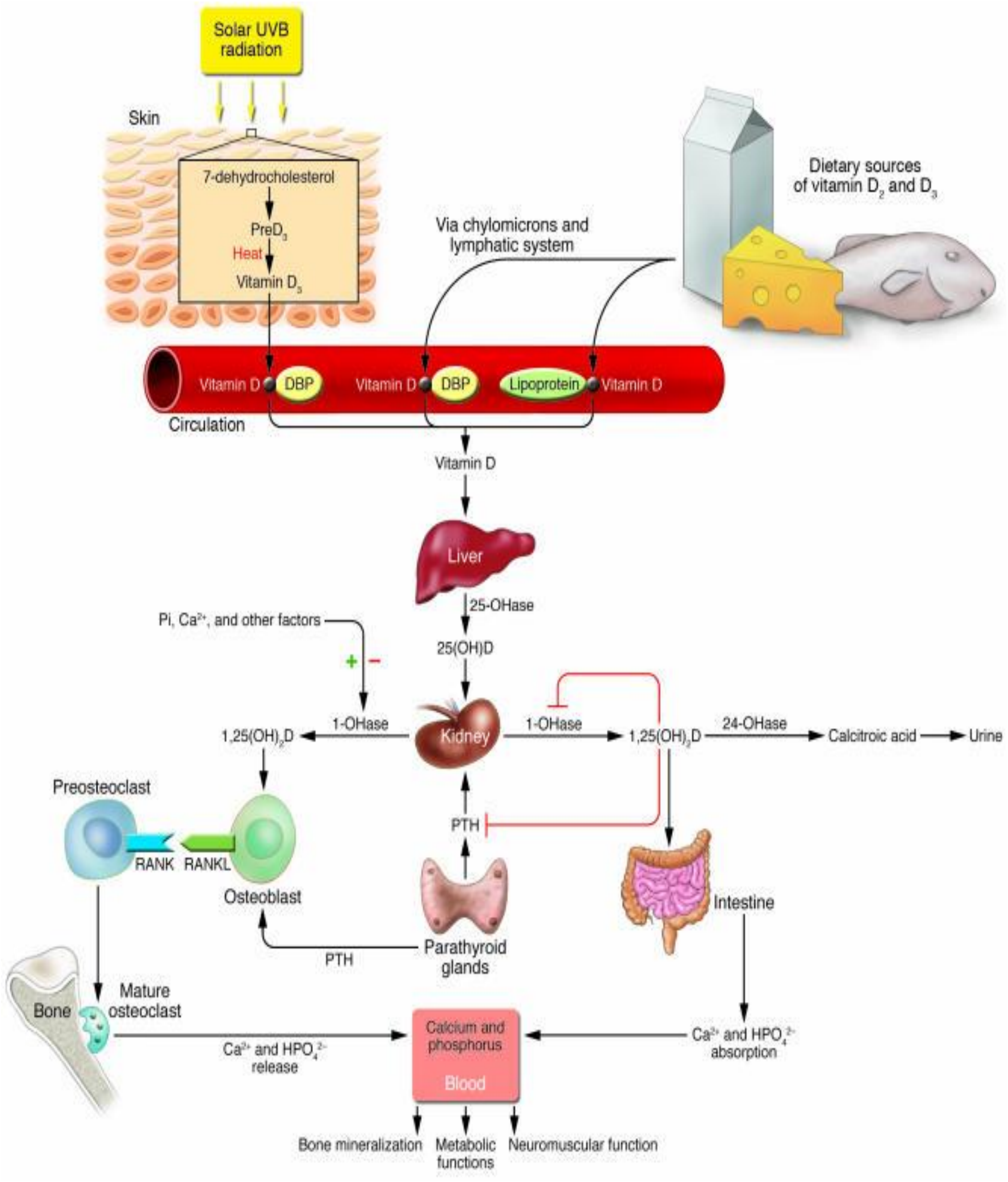

Figure 1. 2. Overview of vitamin D metabolism (Holick, 2006)

Flohr et al. (2014) observed sow 25(OH)D3, milk vitamin D_3 and piglet serum 25(OH)D3 increase with increasing maternal supplementation. The ultimate strength of bone and ash content was increased when gilts were supplemented with vitamin D_3 rather than 25(OH)D3. with regards to the Ca content in the bone an interaction was observed between the form and dose of vitamin D_3 with 2000 IU/kg supplied from the 25(OH)D3 supplement reducing Ca content by 0.9 % compared to 800 IU/kg vitamin D_3 (Lauridsen et al., 2010). Foetuses from gilts offered diets containing 500 IU/kg vitamin D_3, supplemented with 50 µg 25(OH)D3 /kg had significantly increased number of longissimus muscle fibres and numerically more Pax 7+ myoblast numbers, with extended proliferative phase compared to progeny from gilts offered diets containing 2500 IU/kg vitamin D_3. Potentially those foetuses would have had enhanced postnatal skeletal muscle growth (Hines et al., 2013).

It has been suggested that vitamin D_3 may play a role in maternal-conceptus cross talk, as decidual and placental tissues are key sites for 1,25$(OH)_2$D3 production. Vitamin D_3 may influence implantation or regulate specific target genes involved (Vigano et al., 2003). Indeed Coffey et al. (2012) reported that in addition to improved maternal and foetal 25(OH)D3 status, gilts supplemented with 25(OH)D3 before breeding had increased pregnancy rate and litter size but reduced mean foetal weight. Lauridsen et al. (2010) found that the number of stillborn piglets was decreased with increased doses of vitamin D_3 (1400 and 2000 IU/kg resulted in 1.17 and 1.13 stillborn piglets, respectively) compared to lower doses of vitamin D_3 (200 and 800 IU/kg resulted in 1.98 and 1.99 stillborn piglets, respectively). The current recommended inclusion rate is 800 IU/kg for both gestating and lactating sows (NRC, 2012). However, on commercial farms vitamin D_3 is commonly included at a rate of 2000 IU/kg as vitamin D_3 is relatively cheap. As current recommendations for vitamin D_3 in gestation and lactating sows are below those investigated in the current literature and what is used on farm, establishing optimal up to date vitamin D_3 inclusion level for sow diets could improve numbers of piglets born alive and the weight gain of piglets during lactation.

1.8 Rationale for research

The hyper-prolific sow has the potential to wean 32 plus pigs per year, however many EU countries still experience sup-optimal performance (e.g. UK 24.83 and Ireland 27.92 vs. Denmark 32.1 pigs weaned/sow/year respectively) (AHDB, 2017). The major reason for this lower productivity is the number of piglets born alive per litter (NBA). Attempts to increase the NBA, result in increased pre-weaning mortality, as the proportion of low-birth weight, unviable piglets in the litter increased within the litter. Recently research has begun to focus on maternal nutrition during gestation and lactation as a solution to improve piglet vitality at birth and viability to weaning. Research suggests that the use of salmon oil during gestation can improve piglet vitality at birth and improve piglet growth to weaning. Increasing vitamin D_3 level above the current recommendation of 800 IU/kg during gestation can improve both sow and progeny vitamin D_3 status, increase bone strength and mineral content as well as reduce stillbirths and increases piglet and growth to weaning. Nevertheless, the use of both a fish oil and increased vitamin D_3 supplementation simultaneously in sow gestation diets has not been investigated. Similarly, research has found that the use of fish oil in lactation diets can influence the n-3 fatty acid profile of milk and improve piglet growth to weaning. Increasing the energy density of lactation diets can help increase energy intake in lactating sows thereby minimising the mobilisation of the sows’ body reserves while more closely matching the increased energy demand for milk production. However, the use of salmon oil to increase the energy density of lactation diets has not previously been investigated.

When available, it is important to harness the power of multiple research datasets to consider how sow and dietary characteristics can influence sow and litter performance, since individual studies have limitations. With regards to sow characteristics, sow back-fat depth and live-weight are important to optimise the number of piglets born alive and ensure the subsequent reproductive success of the prolific sow. Current recommendations are based on older data using less prolific sows (litter size approximately 11.5 piglets) and may no longer be applicable for the modern sow who is capable of litter sizes in excess of 14 piglets. Furthermore, evaluating both digestible energy and lysine intakes during gestation may help identify optimal nutritional strategies to improve piglet birth and weaning weight as well as maintain sow body condition.

Therefore, the overall hypotheses of this research are:

- Salmon oil inclusion in the gestation diet or lactation diet of sows will improve piglet vitality at birth i.e. lessen time to first suckle and increase colostrum intake of piglets as well as improve piglet growth to weaning. A phased dietary regimen for sows during lactation will increase sow dietary energy intake in late lactation, improving sow milk yield, increasing piglet weight at weaning.
- Sow reproductive performance will be optimal for parity 3 animals. Sow live-weight and back-fat depth measures in early gestation will be associated with reproductive performance, with heavier sows with a greater back-fat depth having more piglets total born, that are heavier at birth and weaning.

- Increased digestible energy and lysine intake of sows' during gestation and in particular late gestation will be associated with improved sow reproductive performance i.e. heavier piglets at birth and weaning.

The aims of this research were to investigate nutritional strategies during gestation and lactation aimed at improving piglet vitality at birth as well as survivability and growth performance to weaning. In addition, this work aims to determine the association of sow parity, live-weight and back-fat depth as well as dietary digestible energy and lysine intake with subsequent reproductive performance through meta-analysis of research data sets. Specific objectives include:

1. To complete an association analysis of data collected at two pig research farms (Teagasc Moorepark and AFBI Hillsborough) to determine the association of sow characteristics such as parity, live weight and back-fat depth with reproductive performance, demonstrating that sow measures can be used as indicators of sow productivity.
2. To carry out an association analysis of data collected at two research farms to identify aspects of sow nutrition i.e. digestible energy and lysine intakes that optimise sow and piglet productivity and to use these findings to provide guidelines for future research to update feeding recommendations.
3. To investigate the effect of salmon oil and vitamin D_3 inclusion in sow gestation diets on piglet vitality at birth and survivability and growth to weaning.

4. To investigate the effect of replacing soya oil with salmon oil in sow lactation diets as well as increasing the energy level from day 15 of lactation by offering either a flat or phased feeding regimen on colostrum and milk composition, sow condition and litter growth performance to weaning.

Chapter 2

An association analysis of sow parity, live-weight and back-fat depth during gestation as indicators of sow reproductive performance

2.1 Abstract

Understanding the influence of sow live-weight and back-fat depth during gestation on sow reproductive performance is important to ensure optimum productivity. Therefore, the objective of this study was to quantify the association between sow parity, live-weight and back-fat depth during gestation with sow reproductive performance. Information from 10 experimental studies, carried out on two research farms between the years 2005 and 2015 were available for analysis. This resulted in 1 058 sows and 13 827 piglet records available for analysis. Sows ranged from parity 1-6 with the number of sows per parity distributed as follows 232, 277, 180, 131, 132, and 106, respectively. Variables analysed included total number of piglets born (TB), number of piglets born alive (BA), piglet birth weight (BtWT), pre-weaning mortality (PWM), piglet wean weight (WnWT), number of piglets weaned (Wn), wean to service interval (WSI), piglets born alive in subsequent farrowing and sow lactation feed intake. Variables that were calculated from the information available included the within-litter coefficient of variation in birth weight (LtV), pre-weaning growth rate per litter (PWG), total litter gain (TLG), lactation efficiency and litter size reared after cross fostering. Data were analysed using linear mixed models, accounting for covariance among records. Third and fourth parity sows had more ($P<0.05$) piglets TB, BA and heavier piglets at birth compared with gilts and parity 6 sows. Parity 2 and 3 sows weaned more (P<0.05) piglets than older sows, and piglets from parity 2 and 3 sows were heavier (P<0.05) at birth compared to piglets from gilt litters. LtV and PWM were greater (P<0.01) in litters born to parity 5 sows than those born to younger sows. Sow live-weight and back-fat depth at service, day 25 and 50 of gestation were not associated with TB, BA, BtWT, LtV, PWG, WnWT or lactation efficiency (P>0.05). Heavier sow live-weight throughout gestation was associated with an increase in PWM (P<0.01) and Wn and lactation feed intake (P<0.05). Greater back-fat in late gestation was associated with fewer piglets (P<0.05) BA but they were heavier (P<0.05) at birth, while deeper back-fat depth throughout gestation was associated with reduced sow lactation feed intake (P<0.01). Sow back-fat depth during gestation was not associated with LtV, PWG, TLG, WSI or piglets born alive in subsequent farrowing (P>0.05). In conclusion, this study demonstrated that sow parity, live-weight and back-fat depth can be used as indicators of reproductive performance of sows during gestation. This study also provides validation for future development of a benchmarking tool using both sow live-weight and back-fat measures to monitor and improve the productivity of modern sow herds.

2.2 Introduction

Genetic selection within the pig industry has focused on increasing litter size to achieve greater production with the aim to provide consumers with lower cost pork meat products. This has resulted in the modern hyper-prolific sow being able to wean up to 32.1 pigs per year. However, pigs weaned/sow/year still varies greatly across the EU, with many EU countries having sub-optimal performance (e.g. UK 24.8, Ireland 27.9 vs. Denmark 32.1 pigs weaned/sow/year respectively) (AHDB, 2017). Many factors can influence sow reproductive performance, such as breed, parity, semen quality, nutrition management and environment. In particular, sow back-fat depth and body condition have been identified as crucial to optimise numbers of piglets born alive and subsequent reproductive success in prolific sows (Maes et al., 2004). Published research on the body condition of replacement gilts, recommended back-fat depths of between 18.0-23.0 mm for gilts at first service (Filha et al., 2010, Roongsitthichai and Tummaruk, 2014). However, Amdi et al. (2013b) reported no significant difference in total born, born alive, or born dead between gilts considered fat or thin (19.0 versus 12.0 mm back-fat depth, respectively) at service.

Current recommendations for optimal sow live-weight and back-fat depth during gestation are based on historic data from less prolific sows, and therefore they may no longer be appropriate for modern multiparous sows. It is generally recommended that sows should gain between 25.0 and 30.0 kg during gestation to allow for maternal and conceptus growth (Yang et al., 1989 Williams et al., 1993), although with increasing litter size these values likely underestimate gestation gain. Optimal target back-fat depths for multiparous sows (parity 2 to 6) at farrowing are between 18.3 mm and 21.2 mm (Whittemore and Kyriazakis, 2006). Although sow live-weight and back-fat depth are indicative of metabolic state, more subtle measures such as body protein mobilisation and energy balance may be more closely associated with subsequent sow fertility (Clowes et al., 2003b, Willis et al., 2003). However, these measures are currently not convenient for on farm use. As visual body scoring is commonly used on farm to determine feeding level during gestation, it is also important to identify optimal sow live-weight and back-fat depths during gestation to more appropriately meet the nutritional demands of the sow and foetal growth. Therefore, as sow live-weight and back-fat depth are easily obtained direct measures they can potentially be used as a practical on-farm tool to optimise sow productivity.

Association analyses of data accumulated from multiple studies offers the opportunity to increase the statistical power of comparisons as well as the detection of possible interactions. This allows for a more comprehensive understanding of optimal management procedures and animal characteristics as well as their possible interactive effects on reproductive performance. In a meta-analysis of 23 studies and 5 production data sets, Douglas et al. (2014), quantified the association between multiple factors and their interactions on the performance of gestating sows. The number of piglets born alive per litter was associated with initial and final sow live-weight during gestation, with a positive linear relationship between sow live-weight at the end of gestation and number born alive. Piglet birth weight was also associated with sow live-weight at the end of gestation. Piglet wean weight was associated with sow parity as well as both initial and final sow live-weight during gestation.

While previous studies have highlighted the importance of sow parity and live-weight for subsequent reproductive performance, back-fat depth should also be taken into consideration as it gives a representation of lean body mass. Therefore, quantifying parity, live-weight and back-fat depth associations in tandem could help identify new approaches to sow herd management which would improve sow productivity and piglet performance. The objective of the present study was to quantify the association of sow parity, live-weight and back-fat depth with sow reproductive performance and litter characteristics at birth and weaning by using individual sow information from 10 different studies.

2.2.1 Hypotheses

- Sow reproductive performance is optimised between parity 3-5.
- Sow live-weight and back-fat depth in early gestation will be associated with subsequent reproductive performance, with heavier sows with greater back-fat depth in early gestation having improved subsequent reproductive performance.
- Sow live-weight and back-fat depth in late gestation will be associated with sow lactation performance and litter growth performance to weaning, with heavier and fatter sows having a heavier litter at weaning.
- Using sow-live weight and back-fat in tandem (LW/BF) will better assess the association between sow body condition during gestation and subsequent reproductive success.

2.3 Materials and methods

2.3.1 Data

Data were obtained from the research farms at both the Agri-Food and Bioscience Institute (AFBI), Hillsborough, Co. Down, Northern Ireland (54°0N; 6°1W) and the Teagasc Pig Development Department, Moorepark, Co. Cork, Ireland (52°7N; 8°16W) from the years 2005 to 2015 inclusive, with the majority of the data originating from the Teagasc Moorepark research centre (>70 %). Data were collated from original trial data sheets (electronic and paper documents) into an electronic masterfile and the distribution of data was assessed. Any data outliers were re-checked against original trial data in case of a typing error. If data point(s) fell outside the normal distribution of the data set, they were removed from the masterfile for analysis. Information regarding the sows and piglets originated from 10 different experimental trials which aimed to evaluate gestation and lactation diet composition, feed allowance and timing of feed increments (Lawlor and Lynch, 2005, Lawlor and Lynch, 2007, Lawlor et al., 2007a, Markham et al., 2009, Ryan et al., 2009, McNamara et al., 2011, Buzoianu et al., 2012, Cottney, 2012, Lawlor et al., 2012, Walsh et al., 2012, Amdi et al., 2013b, Craig et al., 2016). A total of 13 827 piglet records and 1 058 sow records from 24 different treatments were available for use in the analysis. Sows ranged from parity 1-6, with the number of sows per parity distributed as follows 232, 277, 180, 131, 132 and 106, respectively. In the Moorepark data, sows in two gestation and two lactation trials were liquid fed, which used the Big Dutchman feed systems (*Vechta, Germany*) while sows in one gestation and one lactation trial were dry fed using hoppers. Also, in the Moorepark data, sows in one trial used both liquid and dry feeding during the lactation period. In the AFBI data, all sows used in trials were dry feeding during gestation using a Nedap electronic sow feeder (*Groenlo, Netherlands*) and during lactation all sows were fed using wet and dry hoppers. Individual sow feed intake during gestation and lactation was recorded daily in all trials either electronically or manually. In all trials, each piglet was weighed at birth and given an identification marking, either an ear notch or ear tattoo, which was subsequently replaced with a corresponding ear tag at approximately 2 weeks of age. In all trials, each piglet was then weighed again at weaning, at approximately 28 days old. At both research farms, cross fostering was carried out within 24 hours of birth. Gestation trials standardised litters between animals within treatment groups, while lactation trials standardised litters across all animals. In the Moorepark data, three trials standardised litters to a minimum of 9 pigs/sow while one trial ensured 10 pigs/sow. In the AFBI data, one trial standardised litters to 14 pigs/sow. The cause of pre-weaning mortality could not be analysed in this study as it was not recorded in every trial but when recorded the most the common causes of pre-weaning mortality were stillbirths, lain on by sow and weakened by starvation.

Information was available on the number of piglets born (TB), born alive (BA), piglet birth weight (BtWT), pre-weaning mortality per litter (PWM), piglet wean weight (WnWT), number of piglets weaned (Wn), wean to service interval (WSI), piglets born alive in subsequent farrowing and sow lactation feed intake. Variables calculated from the available information included the within-litter coefficient of variation in birth weight (LtV), pre-weaning growth rate per litter (PWG), total litter gain (TLG), lactation efficiency and litter size reared (Table 2.1). Litter size reared was an additional fixed effect for use in the statistical model and was calculated by subtracting the piglets fostered out of the litter from total born alive and adding any piglets fostered in. BtWT, WnWT and PWG were analysed on a mean per litter basis. Information was available for each sow regarding parity, live-weight and back-fat depth, which was recorded using a back-fat scanner (*Renco Lean-Meater and Pig Scan-A-Mode backfat scanner*) at the P_2 site (65 mm from the midline at the level of the last rib). Sow live-weight and back-fat depth were recorded at service, day 25, 50, 80, 110 and at weaning.

Table 2. 1. Variables of interest in the analysis, their corresponding abbreviation and descriptive information

Variable	Abbreviation	Description
Total number of piglets born	TB	Total number of piglets born includes piglets born alive, stillbirths and mummified piglets in the litter
Number of piglets born alive	BA	Number of piglets born alive includes piglets alive at birth and also piglets that died shortly after birth (i.e. crushed by sow, weak at birth) before experimental recording
Piglet Birth weight (kg)	BtWT	Average body weight of piglets at birth
Pre-weaning mortality (%)	PWM	Number of piglet deaths in a litter prior to weaning, expressed as a percentage
Piglet wean weight (kg)	WnWT	Average body weight of a piglet at weaning
Number of piglets weaned	Wn	Number of piglets in a litter at weaning
Wean to service interval (days)	WSI	Number of days between a sow is weaned and insemination
Piglets born alive in subsequent farrowing	BASF	Number of piglets born alive (as per above) at farrowing after the consecutive gestation i.e. parity 1 sows in 2nd parity, parity 2 sows in 3rd parity etc.
Lactation feed intake (kg)	-	Total feed intake of sows during the lactation period
Within-litter co-efficient of varaition in piglet birth weight (%)	LtV	Measure of the variation in birth weight of piglets in the litter. Calculated as: within litter standard deviation in BtWT/ mean piglet birth weight within the litter
Pre-weaning growth rate (g/day)	PWG	Average growth of the litter between birth and weaning per day. Calculated as: ((mean litter birth weight-mean litter wean weight)/age at weaning)

Total litter gain (kg)	TLG	Total weight gain of the litter between birth and weaning. Calculated as: Total litter wean weight- total litter birth weight
Lactation efficiency	-	Quantify how efficiently sows use energy intake in lactation (from feed and/or mobilsation of body reserves) for weight gain of the litter during the suckling period. Calculated as: sow net energy input during lactation (MJ DE)/total litter gain (kg). Where net energy input was calculated as: sow net energy input= total energy gained from feed during lactation (MJ DE) + energy gained from weight lost during lactation (assuming every 1 kg loss = 12.5 MJ DE) and energy from creep feed (every 1 kg = 1.1 MJ DE × lactation days) (Close et al., 2000)

The Moorepark and AFBI data sets analysed complemented each other as each trial collected similar baseline data, which enabled the information to be easily merged before analysis. However, although all sows in the data were either Landrace and/or Large white based, sow genetic merit at each site differed and therefore a genetic effect on sow reproductive performance could not be analysed.

2.3.2 Statistical analyses

The association of each dependent variable (i.e., TB, BA, BtWT, PWM, WnWT, Wn, WSI, piglets born alive in subsequent farrowing, lactation feed intake, LtV, PWG, TLG and lactation efficiency) with sow parity, live-weight and back-fat depth (independent variables) was determined separately using multiple regression mixed models in the (PROC MIXED) procedure of SAS statistics (*version 9.3, SAS Institute Inc., Cary NC, US*). Fixed effects included in the model were sow parity (1, 2, 3, 4, 5, 6), month and year of farrowing, while sow was included as a repeated effect, with the appropriate covariance structure among records within sow. To analyse sow live-weight and back-fat depth in tandem, sow live-weight adjusted for back-fat depth (LW/BF), a separate analysis was carried out, with the association of each dependent variable and sow live-weight quantified with back-fat depth also included as a covariate in the model. Whether the associations detected differed between gilts and sows (i.e., parity >1) was also investigated.

In a separate series of analyses, when the dependent variable was either BtWT or LtV, litter size was also included as a fixed effect in the model. In the analysis of Wn, WSI and BASF, litter size reared was included as a fixed effect in the model. Furthermore, when analysing PWM, PWG and TLG, litter size reared and the lactation diet (n=20) were also included as fixed effects in the multiple regression mixed model. When the dependent variable was WnWT, lactation feed intake or lactation efficiency; then litter size reared, lactation diet and lactation length were also included as fixed effects in the model, along with parity, month and year of farrowing.

2.4 Results

2.4.1 Descriptive statistics

Descriptive statistics for the dependent and independent variables analysed are summarised in Table 2.2. Across all data, sows gained on average 72.6

kg during gestation and lost on average 32.9 kg live-weight during lactation. The mean sow parity differed between each study and both research sites; but the modal parity number in the whole data set analysed was parity 3. Gestation length (mean=114.7 days) and lactation length (mean=27.7 days) did not differ between sites. On average 1.0 (SD=1.36) piglet was born dead per litter and average pre-weaning mortality was 11.2 % (SD=12.09 %). Piglets had an average weaning weight of 7.8 kg (SD=1.88 kg).

2.4.2 Sow parity associations

Gilts had less piglets TB and BA ($P<0.05$) than parity 3 and 4 sows (Figure 2.1a). Piglets born to gilts had the lowest BtWT ($P<0.05$), weighing 0.1 kg less than piglets born to parity 3 and 4 sows (1.5 kg vs.1.6 kg). Piglets born to gilts also weighed less at weaning (mean of 8.2 kg); 0.3 kg lighter ($P<0.05$) than piglets from parity 2, 3 and 6 sows (Figure 2.1b). The lactation feed intake of gilts was lower ($P<0.001$) compared to all older sows, with the feed intake of gilts being on average 156.8 kg (Figure 2.2b). Similarly, lactation efficiency was poorer ($P<0.05$) in younger sows compared to older sows (Figure 2.2b). Average piglet BtWT in parity 2 sows was not different ($P>0.05$) from parity 3, 4 or 5 sows. Parity 2 and 3 sows weaned more ($P<0.01$) piglets per litter than parity 5 and 6 sows (Figure 2.1a). TLG was greatest in litters from parity 2 sows compared to litters from gilts and parity 4 sows (Figure 2.2b). BASF was significantly higher ($P<0.05$) for gilts, parity 2 and 3 sows compared to parity 6 sows (Figure 2.2c). LtV was greater ($P<0.01$) in litters born to parity 5 sows than in those born to younger sows, with 21.0 % variation between litter mates born to parity 5 sows. Similarly, PWM was greater ($P<0.05$) for parity 5 and 6 sows, than for parity 2 and parity 3 sows (Figure 2.1c). Overall piglets from parity 6 sows had the greatest PWG which was on average 13.0 g/day greater ($P<0.05$) than piglets from gilts (Figure 2.2a). The WSI was shorter for older parity sows than for younger parity sows, and this was significant for parity 5 vs. gilts ($P<0.05$).

Table 2. 2. Number of observations (N), mean, range of data, standard deviation (SD) and coefficient of variation (CV [%]) of variables in the entire sow data set

Variable	N	Mean	Range	SD	CV
Sow					
Parity	1 058	3.0	1.0-6.0	1.6	54.9
Service weight, kg	513	174.4	112-270	30.9	17.7
Farrowing weight, kg	1 040	246.9	148-354	34.2	13.8
Weaning weight, kg	1 032	214.0	119-342	36.6	16.8
Service back-fat, mm	344	14.2	6.0-28.0	4.1	28.8
Farrowing back-fat, mm	870	15.8	6.0-29.0	4.4	29.2
Weaning back-fat, mm	741	13.1	6.0-25.0	3.5	26.5
Gestation days	1 055	114.7	107-120	1.5	1.3
Lactation days	1 058	27.7	18-35	2.8	5.1
Litter					
Total litter size	1 058	12.9	1-21	3.4	25.9
Litter live weight, kg	1 057	17.7	0-30.6	4.5	25.5
Number born alive	1 058	11.8	0-20	3.3	27.7
Number born dead	1 058	1.0	0-13	1.4	137.2
Pre- wean mortality, %	1 056	11.2	0-100	12.1	107.7
Number weaned	1 056	10.2	1-17	2.2	21.8
Piglet					
Birth weight, kg	13 228	1.5	0.1-3.9	0.4	25.1
Weaning weight, kg	10 685	7.8	1.0-16.0	1.9	24.0

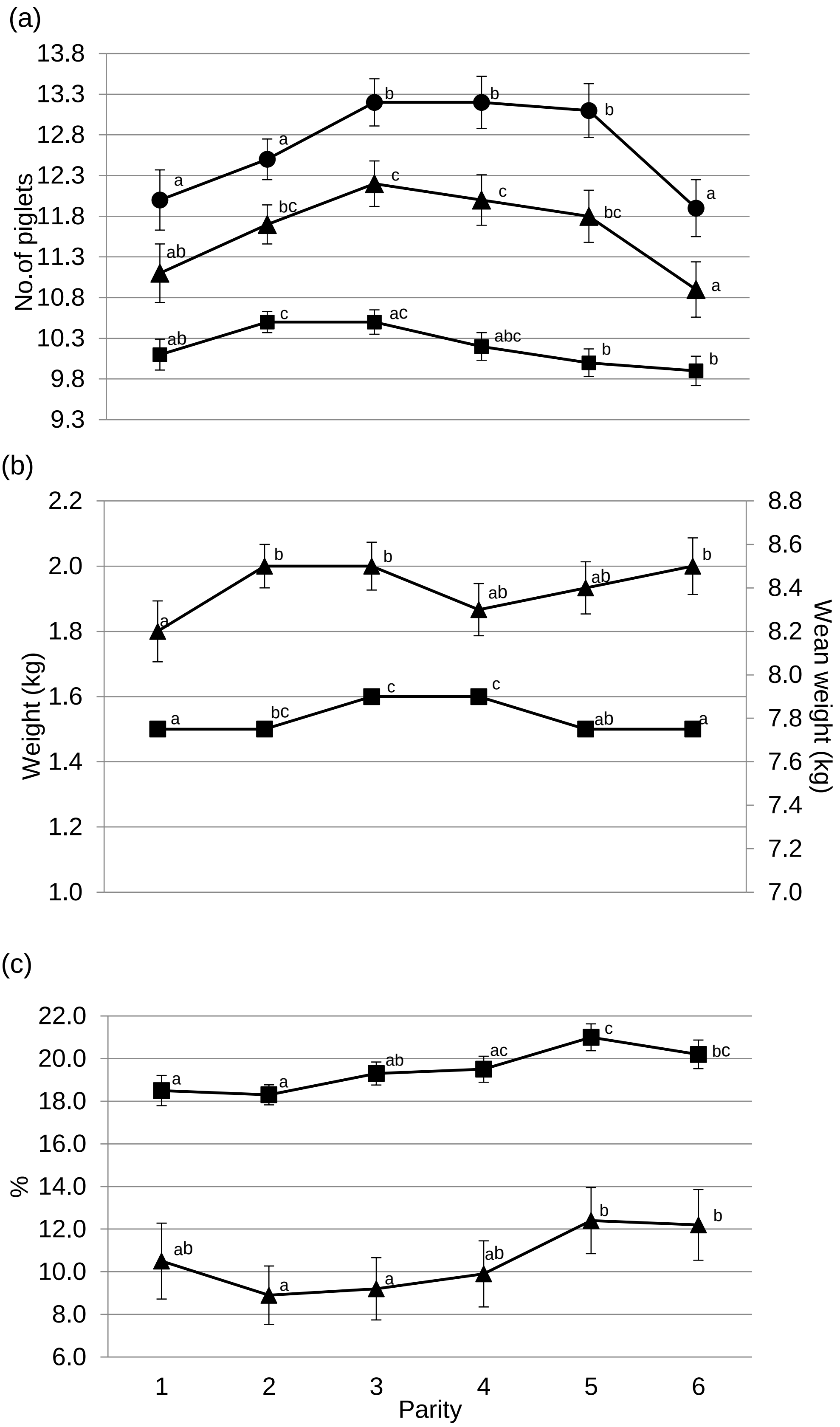

Figure 2. 1. Sow parity and associated (a) mean total born (●), born alive (▲) and number weaned (■), (b) mean piglet birth weight (■) and wean weight (▲), (c) within-litter variation in birth weight (■) and percentage pre-weaning mortality (▲)

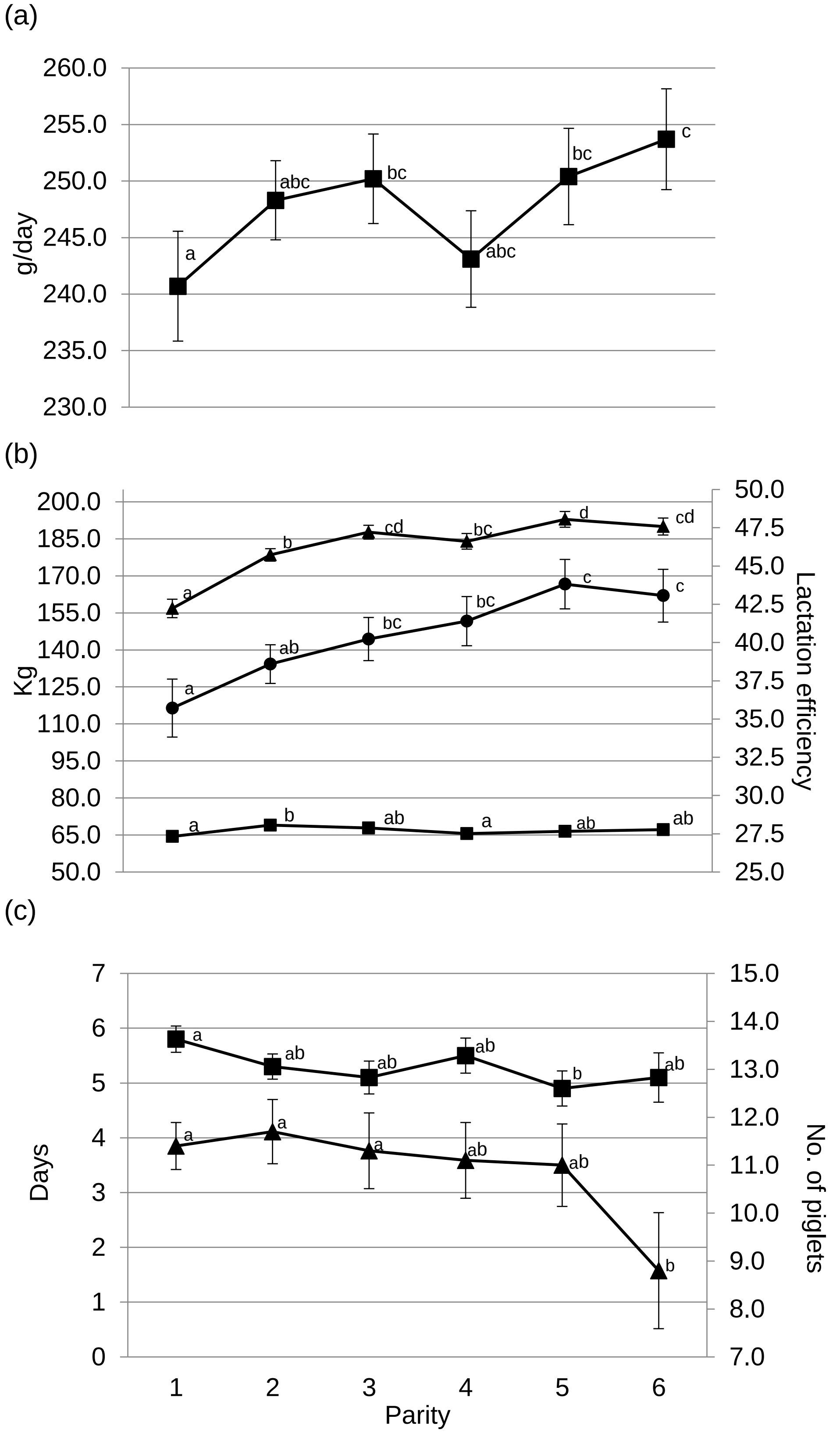

Figure 2. 2. Sow parity with associated (a) pre-weaning growth rate (■), (b) total litter gain (■), lactation intake (▲) and lactation efficiency (●), (c) wean to service interval (■) and number born alive in subsequent farrowing (▲)

2.4.3 Sow live-weight associations

Sow live-weight at service, day 25 and day 50 of gestation was not associated with TB, BA, BtWT and LtV (Table 2.3). Heavier sow-live-weight at day 110 was associated with an increase in piglets TB and BA. The association between sow live-weight at day 80 with BtWT was linear but the associations between sow live-weight at day 110 and BtWT was non-linear. At weaning, sow live-weight was positively associated with LtV. Heavier sow live-weight at service, day 25, 50, 80, 110 and at weaning was associated with an increase in PWM, with both linear and quadratic associations detected (Table 2.4). Sow live-weight at service, day 25, 50, 80, 110 and weaning were negatively non-linearly associated with Wn. Sow live-weight at both day 110 and weaning were positively associated with both PWG and WnWT.

At weaning, each 10 kg increase in sow live-weight was associated with a 0.4 kg reduction in TLG (P=0.043, Table 2.5). Heavier sow live-weight from service to day 110 was associated with a greater sow lactation feed intake. There was no association between sow live-weight and lactation efficiency. The WSI was reduced by 0.1 days for each 10 kg increase in sow live-weight at day 50 of gestation, while each 10 kg increase in sow live-weight at day 25, 50 and 80 of gestation was associated with 0.2 less piglets BASF.

2.4.4 Sow LW/BF associations

Sow LW/BF at service, day 25 and day 50 of gestation was not associated with TB, BA, BtWT and LtV (Table 2.3). When sow LW/BF, significant associations existed at day 80 (P=0.028) and 110 (P<0.001) with the number of piglets TB, and at day 110 and the number of piglets BA (P<0.001).

Regarding piglet BtWT, when sow LW/BF, independent of parity and litter size, each incremental 10 kg increase in sow live-weight at day 80 and 110 was linearly associated with an increase of 0.02 kg in individual piglet BtWT. At weaning, sow LW/BF was positively associated with LtV. When sow LW/BF, all previously observed non-linear associations between live-weight and PWM were linear (Table 2.4). Similarly, when sow LW/BF, the observed non-linear associations between sow live-weight and Wn were linear. At day 110 and weaning, sow LW/BF was positively associated with both PWG and WnWT.

When sow LW/BF, each 10 kg increase in sow live-weight at service, day 50, 80 and 110 was associated with a decrease in TLG of 1.3 kg, 1.2 kg, 1.1 kg, 0.5 kg, respectively (Table 2.5). Regarding sow lactation feed intake, when sow LW/BF, only associations at day 50, 110 and at weaning remained significant. There was no association between sow LW/BF and lactation efficiency. When sow LW/BF, each 10 kg increase in sow live-weight at service and day 50 reduced WSI by 0.13 days. The associations between sow live-weight at day 25, 50 and 80 of gestation and the number of piglets BASF were no longer significant when sow LW/BF.

2.4.5 Sow back-fat depth associations

Sow back-fat depth at service, day 25 and 50 were not associated with the number of piglets TB and BA, piglet BtWT or LtV (Table 2.3). Non-linear associations existed between sow back-fat depth at weaning and the number of piglets TB. Each 1 mm increase in sow back-fat depth at day 80 and 110 was associated with a decrease of 0.1 and 0.08 in piglet BA, respectively. Each incremental 1 mm increase in sow back-fat depth at day 80 of gestation was associated with a 0.007 kg increase in piglet BtWT. At day 110 of gestation, each 1 mm increase in sow back-fat depth was associated with a 0.09 decrease in the number of piglets TB but an increase ($P<0.01$) in piglet BtWT of 0.005 kg. No association existed between sow back-fat depth and LtV.

Sow back-fat depth at service, day 25, 50, 80 and 110 was not associated with PWM or Wn (Table 2.4). Each 1 mm increase in sow back-fat depth at weaning was associated with a 0.4 % increase in PWM and a 0.06 decrease in Wn. No association existed between sow back-fat depth and PWG, but there was a significant association between sow back-fat depth at day 110 and increased WnWT. Each 1 mm increase in sow back-fat depth at day 110 of gestation was associated with a 0.3 MJ/kg reduction in lactation efficiency (Table 2.5). An increase in sow back-fat depth at each time point between day 25 to weaning was associated with reduced sow lactation feed intake. Sow back-fat depth during gestation was not associated with either TLG, WSI or the number of piglets BASF.

Table 2. 3. Linear and quadratic (where different from 0; P<0.05) regression coefficients (standard error in parenthesis) of the association of sow live-weight and back-fat depth on total born (TB), born alive (BA), average birth weight (BtWT [kg]) and within-litter coefficient of variation in birth weight (LtV [%])

Variable	Total born	Born alive	Average birth weight	Within-litter variation
Sow weight[1]				
Service	0.037(0.08)	-0.012(0.08)	-0.009(0.01)	-0.022(0.15)
d25	0.025(0.12)	-0.063(0.12)	0.0001(0.01)	-0.288(0.21)
d50	0.001(0.09)	-0.047(0.08)	0.002(0.01)	-0.097(0.15)
d80	0.071(0.08	-0.052(0.08)	0.018(0.01)***	-0.175(0.15)
d110	0.137(0.04)***	0.093(0.04)*	0.020(0.002)-0.0002(0.00004)***	-0.029(0.08)
Weaning	-0.057(0.04)	-0.079(0.04)	-0.003(0.003)	0.176(0.08)*
Sow LW/BF[1]				
Service	-0.009(0.13)	-0.085(0.12)	-0.014(0.01)	-0.307(0.23)
d25	0.055(0.14)	-0.039(0.14)	-0.001(0.01)	-0.315(0.26)
d50	0.005(0.11)	-0.055(0.10)	-0.001(0.01)	-0.104(0.19)
d80	0.230(0.10)*	0.109(0.10)	0.016(0.01)*	-0.149(0.19)
d110	0.298(0.05)***	0.220(0.05)***	0.022(0.003)***	0.005(10.10)
Weaning	0.008(0.06)	-0.029(0.06)	-0.005(0.004)	0.302(0.12)*
Sow back-fat[2]				
Service	-0.023(0.05)	-0.058(0.05)	0.002(0.003)	-0.085(0.09)
d25	-0.008(0.05)	-0.028(0.05)	0.0004(0.003)	-0.057(0.09)
d50	-0.014(0.05)	-0.034(0.04)	0.002(0.003)	-0.013(0.08)
d80	-0.060(0.04)	-0.101(0.04)*	0.007(0.003)*	-0.071(0.08)
d110	-0.086(0.03)**	-0.084(0.03)**	0.005(0.002)**	-0.035(0.05)
Weaning	-0.145(0.04)-0.016(0.01)***	-0.159(0.03)***	0.001(0.002)	-0.024(0.07)

[1] Coefficients expressed per 10 kg increase in sow live-weight i.e. at service a 10 kg increase in sow live-weight was associated with a 0.037 increase in total born (TB)

[2] Coefficients expressed per 1 mm increase in sow back-fat depth i.e. at service a 1 mm increase in sow back-fat depth was associated with a 0.023 decrease in total born (TB)

*P<0.05 **P<0.01 ***P<0.001

Table 2. 4. Linear and quadratic (where different from 0; P<0.05) regression coefficients (standard error in parenthesis) of the association of sow live-weight and back-fat depth on pre-weaning mortality (PWN [%]), number weaned (Wn), pre-weaning growth rate (PWG [g/day]) and average wean weight (WnWT [kg])

Variable	Pre-wean mortality	Number weaned	Pre-wean growth	Average wean weight
Sow weight[1]				
Service	1.081(0.30)+0.014(0.01)***	-0.116(0.05)-0.002(0.001)*	0.382(0.79)	-0.002(0.02)
d25	1.249(0.47)+0.018(0.01)**	-0.128(0.06)-0.002(0.001)*	1.103(1.08)	0.023(0.03)
d50	1.157(0.35)+0.022(0.01)***	-0.108(0.04)-0.002(0.001)**	0.034(0.87)	-0.003(0.03)
d80	1.029(0.32)+0.016(0.005)***	-0.106(0.04)-0.002(0.001)**	0.675(0.76)	0.029(0.02)
d110	0.415(0.13)+0.011(0.002)***	-0.055(0.02)-0.001(0.0004)***	1.688(0.46)***	0.056(0.01)***
Weaning	0.944(0.14)+0.005(0.002)***	-0.124(0.02)-0.001(0.0002)***	1.810(0.48)***	0.040(0.01)**
Sow LW/BF[1]				
Service	1.574(0.52)**	-0.173(0.07)**	-0.530(1.31)	-0.045(0.04)
d25	1.321(0.57)*	-0.146(0.07)*	0.016(1.32)	-0.020(0.04)
d50	1.274(0.44)**	-0.133(0.06)*	-0.536(1.08)	-0.027(0.03)
d80	1.123(0.42)**	-0.124(0.05)*	0.005(0.98)	0.007(0.03)
d110	0.613(0.19)**	0.135(0.16)	1.400(0.57)*	0.042(0.02)**
Weaning	1.092(0.22)***	-0.142(0.03)***	2.311(0.69)***	0.045(0.02)*
Sow back-fat[2]				
Service	0.304(0.21)	-0.016(0.03)	0.362(0.50)	0.021(0.01)
d25	0.276(0.20)	-0.023(0.03)	0.810(0.46)	0.027(0.01)
d50	0.305(0.19)	-0.027(0.02)	0.360(0.45)	0.011(0.01)
d80	0.295(0.18)	-0.026(0.02)	0.574(0.41)	0.021(0.01)
d110	0.043(0.10)	-0.003(0.01)	0.449(0.29)	0.018(0.01)*
Weaning	0.392(0.13)**	-0.058(0.02)***	0.463(0.40)	0.013(0.01)

[1] Coefficients expressed per 10 kg increase in sow live-weight i.e. at service a 10 kg increase in sow live-weight was associated with a 1.081 % increase in pre-weaning mortality

[2] Coefficients expressed per 1 mm increase in sow back-fat depth i.e. at service a 1 mm increase in sow back-fat depth was associated with a 0.304 % increase in pre-weaning mortality

*P<0.05 **P<0.01 ***P<0.001

Table 2. 5. Linear and quadratic (where different from 0; P<0.05) regression coefficients (standard error in parenthesis) of the association of sow live-weight and back-fat depth on total litter gain (TLG, [kg]), lactation intake (kg) lactation efficiency, wean to service interval (WSI, [days]) and number of piglets born alive in subsequent farrowing (BASF)

Variable	TLG	Lactation intake	Lactation efficiency	WSI	BASF
Sow weight[1]					
Service	-0.535(0.35)	-1.364(0.65)*	0.172(0.47)	-0.024(0.08)	-0.163(0.10)
d25	-0.551(0.54)	-2.050(0.94)*	0.469(0.76)	-0.033(0.06)	-0.294(0.13)*
d50	-0.725(0.40)	-3.750(0.70)***	-0.804(0.52)	-0.109(0.04)**	-0.224(0.10)*
d80	-0.577(0.38)	-2.604(0.65)***	-0.106(0.54)	-0.034(0.04)	-0.227(0.09)*
d110	-0.071(0.18)	-2.604(0.65)***	-0.350(0.18)	-0.010(0.04)	-0.153(0.08)
Weaning	-0.374(0.18)*	0.719(0.40)	0.345(0.19)	-0.085(0.04)	-0.080(0.09)
Sow LW/BF[1]					
Service	-1.329(0.61)*	-1.401(1.07)	-0.225(0.83)	-0.130(0.06)*	-0.271(0.14)
d25	-0.920(0.66)	-0.784(1.15)	0.407(0.94)	-0.014(0.07)	-0.292(0.16)
d50	-1.188(0.50)*	-3.249(0.87)***	-0.850(0.66)	-0.131(0.05)**	-0.201(0.12)
d80	-1.067(0.49)*	-1.124(0.82)	-0.210(0.69)	-0.027(0.05)	-0.220(0.12)
d110	-0.478(0.24)*	-1.692(0.52)**	-0.013(0.26)	0.012(0.05)	-0.139(0.10)
Weaning	-0.475(0.30)	2.276(0.65)***	-2.550(2.24)	-0.069(0.06)	0.005(0.11)
Sow back-fat[2]					
Service	0.117(0.23)	-0.770(0.42)	0.093(0.32)	-0.007(0.02)	-0.111(0.06)
d25	0.038(0.23)	-1.129(0.40)**	0.148(0.33)	-0.017(0.02)	-0.074(0.06)
d50	-0.009(0.21)	-1.585(0.37)***	0.009(0.28)	-0.023(0.02)	-0.098(0.05)
d80	0.063(0.20)	-1.652(0.34)***	0.018(0.29)	-0.015(0.02)	-0.077(0.05)
d110	0.235(0.13)	-2.155(0.27)***	-0.325(0.14)*	-0.018(0.02)	-0.052(0.05)
Weaning	-0.163(0.17)	-1.251(0.39)**	-0.014(0.19)	-0.064(0.03)	-0.078(0.06)

[1] Coefficients expressed per 10 kg increase in sow live-weight i.e. at service a 10 kg increase in sow live-weight was associated with a 0.535 kg decrease in total litter gain (TLG)

[2] Coefficients expressed per 1 mm increase in sow back-fat depth i.e. at service a 1 mm increase in sow back-fat depth was associated with a 0.117 kg increase in total litter gain (TLG)

*P<0.05 **P<0.01 ***P<0.001

2.5 Discussion

Providing practical information with regards to sow live-weight and back-fat depth as indicators of sow productivity within a commercial herd will benefit the pig industry through increased productivity and efficiency (Maes et al., 2004). As a result of genetic gains within the last decade there is little information available regarding the association of sow parity, live-weight and back-fat depth with reproductive performance in the modern hyper-prolific sow. The current study enabled a large number of variables in relation to sow output to be investigated and as a result demonstrates that sow parity, live-weight and back-fat depth are associated with sow reproductive performance.

2.5.1 Sow parity

The findings of this study agree with the hypothesis that sow reproductive performance would be optimised for parity 3 to 5 sows, as the current study found that gilts had significantly fewer total born than older sows, while the number of piglets born alive was maximised for parity 3-5 sows compared to older sows. This finding is supported by, Milligan et al. (2002) who reported that first and second parity sows (Yorkshire and Yorkshire X Landrace) also had fewer TB than middle-aged (parity 3-5) or older sows (parity 6-8) and numbers born alive was greatest for middle-aged sows because stillbirth rate increased with age. In the current study, first and second parity sows produced litters with less variation in piglet BtWT than older sows. It has been suggested that litters from younger sows are more uniform with regards to BtWT as a result of the associated lower litter size (Quesnel et al., 2008), which could explain why in the current study, first and second parity sows produced more uniform litters. In the present study, the greater variation in piglet birth weight was observed in litters born to older sows may be explained by increased ovulation rate. With high ovulation rates and increased embryo numbers, uterine space becomes limited, resulting in ‘uterine crowding’ and as a consequence there is variation in placental development which impacts piglet growth, development and subsequent performance (Foxcroft et al., 2006).

In the present study, gilts had lower lactation feed intake, TLG and PWG compared with litters and piglets born to older sows. Indeed, first parity sows with lower lactation feed intake, also experienced poorer lactation efficiency and a prolonged WSI. Voluntary feed intake of primiparous sows during lactation is often inadequate to meet the nutritional demands of maintenance and growth as well as supporting milk yield (Noblet et al., 1990). Pluske et al. (1998) suggested that primiparous sows may partition more energy to growth than milk production compared to higher parities. As a result of reduced lactation feed intake many gilts experience an increase in lactation weight loss that can cause delayed return to oestrus, reduced conception rate and embryonic survival (Eissen et al., 2000). Although the sows in this study are representative of a more modern sow than those reported in the research mentioned above, the findings in the current study do concur with the observation of others regarding primiparous sow productivity.

The current average piglet pre-weaning mortality rate in the EU is 13.4 % (AHDB, 2017), but mean piglet pre-weaning mortality can range between 10-20 % in commercial pig herds (Muns et al., 2016b). In the current study, average piglet pre-weaning mortality was 11.2 % and so is comparable to commercial herds. In agreement with the findings of Milligan et al. (2002), the current study found that second and third parity sows had reduced PWM, and consequently weaned more piglets per litter, than older sows. Unfortunately, in the present study, it was not possible to analyse the cause of piglet deaths. The majority of pre-weaning piglet deaths can be attributed to crushing of piglets by the sows (33.8 %) and low piglet viability (29.7 %) (Koketsu et al., 2006). It has been previously reported that piglets <1-week old are at increased risk of death when reared by older sows (Wientjes et al., 2012) and that there is a greater probability of crushing of newborn piglets as sows age (Weary et al., 1998). However, the suggestion that older sows are less agile and responsive to piglet distress calls is not conclusive. Indeed, independent of sow parity, several factors can influence the incidence of crushing of piglets such as, housing system, large litters, low piglet birth weight, sow breed and individual nature (Andersen et al., 2005). Also increased piglet deaths associated with older sows could be related to a greater variation in piglet birth weight, prolonged farrowing or reduced teat functionality and accessibility.

The current study found that parity 3 sows had more piglets TB and BA which were heavier at birth than piglets born to younger sows. Indeed, Sasaki and Koketsu (2008) reported both gilts and parity 2 sows had a lower number of piglets born alive compared to older sows. Therefore, removal of young sows for poor reproductive performance should be avoided. It is well documented that to be profitable a sow must persist in the herd for more than 3 parities (Lucia et al., 2000, Stalder et al., 2003). The average parity of sow removal in a commercial herd in the U.S ranges from 3.1 to 4.6, with the most common causes of removal of older parity sows being udder problems, low productivity and old age (Engblom et al., 2007). Koketsu et al. (1996) reported that gilts had significantly lower lactation feed intakes compared to multiparous sows. Similarly, the present study found that lactation feed intake increased with increasing parity, and lactation efficiency also increased. As a result, piglets born to parity 6 sows gained more during the suckling period than parity 1 to 5 sows. However, this could also be explained by the smaller total litter size of parity 6 sows, and as a result there may have been more milk available per piglet. It has also been reported that parity 4 to 7 sows produce less colostrum than younger sows (Decaluwé et al., 2013) and milk yield tends to be greater for parity 2 and 3 sows compared to gilts and older sows. Despite this, the greater lactation feed intake of older sows enables them to produce more milk throughout lactation (Eissen et al., 2000).

2.5.2 Sow live-weight and reproductive performance

With increasing parity, sows become heavier as they develop a greater proportion of lean mass (Whittemore and Kyriazakis, 2006). Therefore, in the present analysis, sow live-weight was adjusted for back-fat depth to more accurately reflect size, as a heavier sow does not necessarily have greater back-fat depth. In this study, heavier sow live-weight in late gestation was associated with an increase in the number of piglets TB and BA. This is in agreement with the findings of Douglas et al. (2014). With an average total born of 12.9, sows in the current study are comparable to their commercial counterparts, as between the years 2010 and 2016, the UK average total born was 13.2 (AHDB, 2016). In disagreement with the hypothesis, sow live-weight at service to day 50 of gestation, whether adjusted for sow back-fat depth or not, was not associated with sow reproductive performance in the present study. Sows in this study are representative of genetics between 2005 and 2015 and this finding suggests that sow live-weight and back-fat depth at service may not be as critical to the reproductive success of modern sows. On the contrary, previous research found that a weight loss of greater than 10.0 % before service reduced subsequent reproductive performance (Thaker and Bilkei, 2005), with the negative effect more pronounced in younger parity sows as they continue to deposit lean mass post weaning.

Nevertheless, sow body condition at service and during early gestation may be more influential during lactation with regards to weaning output since this study found that greater sow live-weight and back-fat depth during gestation was associated with reduced lactation intake but with no negative effect on piglet WnWT. One explanation may be that sows with greater body weight and back-fat depth can mobilise body reserves more readily to meet the demands of litter (Whittemore and Kyriazakis, 2006). However, maximising sow lactation feed intake is still important to limit the loss of sow body condition during lactation and reduce any detrimental effect on subsequent reproductive performance such as prolonged WSI (Thaker and Bilkei, 2005).

2.5.3 Sow back-fat depth and reproductive performance

As sow live-weight increases with parity it is not necessarily accompanied by an increase in back-fat depth (Whittemore and Kyriazakis, 2006). Indeed, the energy requirements for weight and back-fat gains of sows parity of 3+ are greater than younger sows, as younger sows tend to have greater protein gain which has a lower ME energetic cost than fat (10.6 vs. 12.5 kcal/kg, respectively) (Young et al., 2005). The current study found that greater back fat depth at day 80, 110 and weaning was associated with decreased BA whereas, Maes et al. (2004) reported decreased back-fat depth at the end of gestation increased number of piglets stillborn. It is well documented that sows that are too fat at parturition suffer longer farrowing duration and have a greater risk of stillbirths (Oliviero et al., 2010). However, it is also possible that a smaller litter size, required less energy to maintain during pregnancy, which enabled the sow to partition proportionately more energy towards the accumulation of back-fat.

In the present study, greater back-fat depth at weaning was associated with reduced number of piglets weaned. Conversely, Maes et al. (2004) found that a lower back-fat depth at the end of lactation was associated with more pigs weaned. A lower back-fat depth at the end of lactation is to be expected as sows often mobilise body reserves to better support milk production when lactation energy intake is deficient; but as previously mentioned, sows may deposit additional energy as maternal gain rather than milk production which could have affected number weaned if milk production was insufficient for piglet growth. The current study found that increasing back-fat depth was associated with reduced total sow lactation feed intake. Dourmad (1991) reported that increasing the body fatness of gilts at farrowing was associated with a reduction in sow lactation feed intake in the first 2 weeks after parturition, but total lactation intake was unaffected. In the present study, greater back-fat depth during late gestation was negatively associated with lactation efficiency, suggesting fatter sows at parturition did not mobilise reserves to meet the demands of the litter. However, a back-fat loss of 1 mm between day 85 and

109 of gestation has been found to increase colostrum yield by 113 g per sow in the first 24 hours post farrowing (Decaluwé et al., 2013).

2.5.4 Reproductive benefits and trade-offs associated with sow live-weight and back-fat depth

It is difficult to determine the effect of both sow live-weight and back-fat depth during gestation on reproductive performance as the latter can be influenced by many factors; nonetheless, the need to optimise both measures is apparent. For instance, heavier sow live-weight in late gestation was associated with improved reproductive performance (i.e. TB and BA), heavier sow live-weight was also accompanied by an increase in PWM and a reduction in the number of piglets weaned. This result is to be expected, as with increasing litter size the proportion of low-birth weight, unviable piglets' increases (Wolf et al., 2008); in turn increasing pre-weaning mortality and ultimately reducing number weaned. Indeed, welfare concerns have been raised, as although larger litter size incresases number weaned, piglet pre-weaning mortality rates have also increased. In this study, a disadvantage of greater sow back-fat depth during gestation was a reduction in sow lactation feed intake but this coincided with an increase in piglet weaning weight. This is in agreement with the hypotheses that sows with greater back-fat depth in late gestation would have heavier litters at weaing. Similarly, Amdi et al. (2013b) reported that gilts that were fat at service experienced increased back-fat loss during lactation and increased piglet growth during the suckling period, with no difference in lactation intake. These results suggest that sows with more back-fat may be able to mobilise body reserves to meet the demand of the suckling litter.

2.6 Conclusions

The current study quantified the association of sow parity, live-weight and back-fat depth with the subsequent reproductive performance of modern sows and highlights the importance of considering both sow live-weight and back-fat depth in tandem as indicators of farrowing and pre-weaning productivity. Sow live-weight and back-fat depth at service, or indeed during early gestation, appears not to be critical to reproductive success, but may be important later in gestation and during the lactation period. Greater sow live-weight and back-fat depth in late gestation was associated with increased litter size and numbers born alive. Sows that were heavier and fatter had heavier piglets at birth and at weaning and did so with less lactation intake indicating sows had improved ability to mobilise body reserves to meet the demands of the litter. This study demonstrates that sow parity, live weight and back-fat depth can be used as indicators of reproductive output and consequently these sow measures should be continually monitored within a commercial herd. Unfortunately, due to the data sets used, this study was unable to determine optimal target sow live-weights and back-fat depths during gestation or determine the effect of diet composition or feeding level during gestation on subsequent reproductive success. Therefore, these should be the focus of future analyses of experimental studies or data collected on farm. Sows used in this analysis are representative of a more prolific animal compared to sows 20 years ago, but with continued improvements in sow productivity, the association of sow parity, live-weight and back-fat depth and the use of these measures as indictors of reproductive performance should be re-assessed on a regular basis.

Chapter 3

Association analysis to identify aspects of sow nutrition that optimise sow and piglet productivity

3.1 Abstract

Ensuring that sow nutrition during gestation meets both maternal and foetal growth requirements is crucial to optimise sow reproductive performance. The objective of this study was to determine the association between sow gestation nutrition [digestible energy intake (DEI), lysine intake (LYS) and lysine intake to digestible energy intake ratio (LYSin:DEI)], of different stages of gestation and its association with subsequent reproductive performance. Records from 876 sows and 11,572 piglets originating from 8 experiments at 2 research farms between the years 2005 and 2015 were analysed. Performance measures of interest included total born (TB), born alive (BA), piglet birth weight (BtWT), piglet wean weight (WnWT) and sow lactation intake. Mean sow DEI (MJ/day), LYS (g/day) and LYSin:DEI (g: MJ DE) in early (day 0-24), mid (day 25-80) and late (day 81-114) gestation were available. Each intake variable was stratified within each stage into very high intake (VH), high intake (H), medium intake (M), low intake (L) and very low intake (VL) dependent on the distribution of the data. The data were analysed using linear mixed models accounting for repeated records within sow. In early gestation, sows with medium DEI (29.9-30.0 MJ DE/day) had lighter piglet WnWT and reduced sow feed intake during lactation ($P<0.01$) compared to sows with high DEI in early gestation. In mid gestation, medium DEI (29.9-33.0 MJ DE/day) was associated with an increase in sow lactation intake ($P<0.001$) as well as greater TB ($P<0.05$) and BA. In late gestation, sow with high DEI (39.4-45.3 MJ DE/day) had heavier piglet BtWT ($P<0.05$) and WnWT ($P<0.05$) and greater sow lactation feed intake ($P<0.001$) compared to sows with very high DEI. Low LYS (11.0-15.0 g/day) in early gestation was associated with fewer TB and BA and reduced feed intake of sows during lactation ($P<0.01$) compared to high LYS. In mid gestation, low LYS was associated with lighter piglet WnWT ($P<0.05$) and reduced sow lactation intake ($P<0.001$) compared to medium LYS. In late gestation, low LYS was associated with reduced BA, BtWT and sow lactation intake compared to medium and high LYS ($P<0.05$). A total LYSin:DEI of medium, medium and low in early, mid and late gestation, respectively (0.54, 0.54 and 0.45-0.54 g: MJ DE, respectively) was associated with more TB, BA and sow lactation feed intake. In conclusion, this study showed that the quantity of DEI and LYS intake during gestation is associated with subsequent reproductive success. The optimum range of LYS intake during gestation (14.2-32.3 g/day) identified in the current study should be considered when reviewing current guidelines and recommendations should be developed for each stage of gestation, to optimise the reproductive performance of modern multiparous sows.

3.2 Introduction

The modern hyper-prolific sow is now capable of producing up to 30 or more pigs per sow annually (AHDB, 2016). However, there are growing concerns regarding the associated increased number of low birth-weight unviable piglets and higher pre-weaning mortality rates with large litters. The nutritional requirements for gestating and lactating sows were developed using data from less prolific sows, of a lower genetic merit than the modern animal (Ball et al., 2008). It is therefore questionable whether such recommendations are appropriate to meet the nutritional demands of the modern sow and her progeny (Moehn and Ball, 2013). Maternal nutrition during gestation and lactation is known to influence placental growth and foetal development (Gao et al., 2012), the number of piglets born alive (Allan and Bilkei, 2005) as well as pre-weaning piglet growth, through the effect on milk quality (Ramanau et al., 2004). Even if current nutritional recommendations are followed, it is likely that the genetic potential of the modern sow may not be fulfilled.

The effects of feed allowance during gestation on sow and piglet productivity have been extensively investigated (Lodge, 1969, Eastham et al., 1988). Recommendations for gestating sows include restricting feed intake to reduce back-fat deposition, while providing adequate energy for both sow maintenance and foetal growth. It has been widely studied that sow gestation intake is negatively correlated to feed intake in lactation which can result in energy and nutrient deficiency in the sow. This has an unfavourable impact on piglet growth and the sows' subsequent reproductive performance (Eissen et al., 2003, Thaker and Bilkei, 2005). Therefore, appropriate dietary composition during gestation, as well as feed allowance, is critical to ensure sufficient nutrient intake during lactation. With regards to the effects of gestation diet on piglet performance, Bee (2004) investigated the effect of digestible energy intake during the first 50 days of gestation on muscle fibre characteristics of the resulting progeny. Piglets from sows fed the high energy diet (43.57 MJ DE/day) grew slower during their lifetime, with a lower gain-to-feed ratio and higher fat deposition than progeny from sows fed the low energy diet (19.53

MJ DE/day). Heo et al. (2008) found that gilts with a high lysine intake during gestation and lactation produced heavier litters at birth and weaning, concurrent with faster piglet growth to weaning.

Association analyses of data from multiple studies enable the development of a comprehensive understanding of management procedures, nutritional strategies and animal characteristics, as well as their possible interactive associations. Results from an association analysis can therefore help identify nutritional approaches and diet composition during gestation to improve sow productivity, piglet viability and growth. In a meta-analysis of 23 experiments and 5 production data sets, Douglas et al. (2014) used treatment means to investigate the association between multiple factors, and their interactions, with gestating sow efficiency. Sow parity and feed intake during gestation was associated with piglet weaning weight, although piglet weaning weight differed by parity of the sow and both the energy and crude protein content of the gestation diet (Douglas et al., 2014). The objective of the present study, which utilised data from 8 different experimental studies, was to use individual sow records to determine the gestational DE and lysine intake levels, and LYSin:DEI associated with improved sow reproductive performance and litter characteristics at birth and weaning.

3.2.1 Hypotheses

- DEI and LYS levels during gestation will be associated with sow and piglet productivity, with greater DEI and LYS levels having a greater effect than lower levels.

- DEI and LYS levels associated with improved sow and piglet productivity will differ by stage of gestation, with higher levels of DEI and LYS in late gestation increasing sow productivity and piglet growth to weaning.
- Low LYSin:DEI ratio during gestation will have a negative influence on sow and piglet productivity compare to a high LYSin:DEI ratio.
- DEI and LYS levels during gestation which have been identified as being associated with improved sow productivity, will be higher than current recommended levels as they are based on less prolific sows.

3.3 Materials and Methods

3.3.1 Data

Data were available from the research farms at both the Teagasc Pig Development Department, Moorepark, Co. Cork, Ireland (52˚7N; 8˚16W) and the Agri-Food and Bioscience Institute (AFBI), Hillsborough Co. Down, Northern Ireland (54˚0N; 6˚1W) from the years 2005 to 2015 inclusive. Data were collated from original trial data sheets (electronic and paper documents) into an electronic masterfile and the distribution of data was assessed. Any data outliers were re-checked against original trial data in case of a typing error. If data point(s) fell outside the normal distribution of the data set, they were removed from the masterfile for analysis. Sows and piglets originated from 8 different studies which evaluated different gestation and lactation diet composition, feed allowance and timing of feeding (Lawlor et al., 2007b, Markham et al., 2009, Ryan et al., 2009, McNamara et al., 2011, Cottney, 2012, Lawlor et al., 2012, Walsh et al., 2012, Craig et al., 2016) (Table 1). A total of 11,572 piglet records and 876 multiparous sow records from 16 treatments were available for analysis. All sows were F1 cross (Large White x Landrace).

Information was available on the total number of piglets born per litter (TB), number of piglets born alive per litter (BA), individual piglet birth weight (BtWT) and wean weight (WnWT) as well as individual sow feed intake during different stages of gestation and lactation. Litter size reared was calculated by subtracting the number of piglets fostered out of the litter from total born alive and adding any piglets fostered in. Gestation dietary DE and LYS intakes were the focus of the study but whether a lactation diet influenced sow lactation intake was based on the results from the original trial studies (Lawlor et al., 2007b; Ryan et al., 2009; Lawlor et al., 2012; Craig et al., 2016). Diets that had a significant effect on the variables of interest were treated individually in the analysis and those with no significant effect were grouped together for the purpose of analysis in the present study. Information was also available on the characteristics of each gestation diet, including the estimated digestible energy content (MJ/kg) and lysine content (g/kg) from diet formulations. Actual digestible energy intake (DEI) and lysine intake (LYS) during gestation were calculated from the formulated diet composition and individual sow gestation feed intake. Diet composition was presented as g/kg (Table 3.1).

Table 3. 1. Data sources used in the analysis and associated fresh gestation diet composition

Source	Number of treatments	Animals/treatment	Feed	g/kg						
				CP[1]	Fibre	Ash	Oil	Valine[2]	Lysine[2]	DE[3]
Markham et al., 2009; Mc Namara et al., 2011*	5[4]	40	Wet	132	45.0	44.0	9.0	6.4	6.2	13.0
Walsh et al., 2012**	1[5]	200	Dry	150	36.7	48.3	7.3	7.1	9.0	13.14
Lawlor et al., 2007b**	1[5]	75	Wet	132	45.0	44.0	9.0	6.4	6.2	13.0
Lawlor et al., 2012**	1[5]	75	Wet	132	45.0	44.0	9.0	6.4	6.2	13.0
Ryan et al., 2009**	1[5]	120	Wet	132	45.0	44.0	9.0	6.4	6.2	13.0
Cottney, 2012a**	1[6]	67	Dry	141	45.5	45.1	45.3	▪	6.0	13.2
Cottney, 2012b*	5[7]	21	Dry	141	46.0	45.0	45.3	▪	6.0	13.2
Craig et al, 2016**	1[6]	109	Dry	147	51.0	48.4	41.1	▪	6.9	12.86

*Gestation diet trials.

**Lactation focused trials, gestation diet and production parameters measured.

▪Not measured.

[1] Crude Protein.

[2] Estimated values.

[3] Digestible Energy per Kilogram of fresh feed.

[4] T1:2.3kg/day (d0-112); T2:4.6kg/day (d25-50), 4.6kg/day (d50-80); T3:4.6kg/day (25-80), 5.7kg/day (d80-112) .

[5] 2.3kg/day (d0-114).

[6] 2.5kg/day (d0-79); 3.0kg/day (d80-114).

[7] T1:2.5kg/day (0-114); T2:2.5kg/day (d0-85), 3.0kg/day (d86-108), 2.5kg/day (d109-114); T3:2.5kg/day (d0-85), 3.0kg/day (d86-114); T4:2.5kg/day (d0-85),3.5kg/day (d86-108), 2.5kg/day (d109-114); T5:2.5kg/day (d0-85), 3.5kg/day (d86-108), 3.0kg/day (d109-114)

3.3.2 Animal management

All dry fed trials conducted in Moorepark used hoppers and liquid fed trials used the Big Dutchman feed systems (*Vechta Germany*). All trials conducted in AFBI involved dry feeding and used a Nedap electronic sow feeder (*Groenlo, Netherlands*) during gestation and wet and dry hoppers during lactation. Individual sow feed intake was recorded daily, in all trials. Gestation diets fed at the Teagasc Moorepark site were mainly barley-based and approximately 13.0 DE MJ/kg, while at AFBI Hillsborough gestation diets were barley-, maize- and wheat-based with digestible energy ranging between 12.9 to 13.2 DE MJ/kg. At birth, each piglet was weighed and given an ear notch or tattoo for identification which was replaced with a tag at 2 weeks old. At weaning, approximately 28 days of age, each piglet was again weighed. Cross fostering was carried out within 24 hours of birth with gestation trials standardising litters within treatment and lactation trials standardising litters across all animals. Trials in Moorepark standardised litters to a minimum of 9 pigs/sow, while trials in Hillsborough standardised litters to 12-14 pigs/sow. Cause of pre-weaning mortality was not recorded in each trial but when recorded the most common causes included stillbirths, lain on by sow and weakened by starvation.

3.3.3 Statistical analyses

Initially all dietary aspects were considered for analysis i.e. crude protein, fibre and feed intake but preliminary analysis of these variables were non-significant (P>0.05) and so no further analysis was conducted. The analysis was then focused on DEI and LYS variables. Actual mean DEI [MJ/day], LYS [g/day] and total lysine intake: digestible energy intake/day ratio (LYSin:DEI) [g: MJ DE] per sow were averaged for early (day 0-24), mid (day 25-80) and late (day 81-114) stages of gestation. Each intake variable was stratified within each stage into very high intake (VH), high intake (H), medium intake (M), low intake (L) and very low intake (VL) dependent on the distribution of the data (Table 3.2). The association between each dependent variable (TB, BA, BtWT, WnWT and sow lactation intake) with each independent variable DEI, LYS and LYSin:DEI stratum was determined for each dependent and independent variable separately using mixed models in the (PROC MIXED) procedure of SAS statistics (*version 9.3, SAS Institute Inc., Cary NC, US*). Fixed effects included in all models were location (i.e. Moorepark and Hillsborough), parity (2, 3, 4, 5, 6), month and year of farrowing and the stratum of DEI, LYS or LYSin:DEI for the gestation stage under investigation. Sow was included as a repeated effect with appropriate covariance structure for records within sow. LYSin:DEI was determined for the overall gestation period (day 0-114) with parity, month and year of farrowing as fixed effect and sow as a repeated effect in the model. When the dependent variable was BtWT, litter size was also included as a covariate in the statistical model. When the dependent variable was either WnWT or sow lactation intake, the variables litter reared, lactation diet and lactation length were also all included as covariates in the model. All model solutions for DEI and LYS are reported relative to VH or H group within each stage of gestation, while model solutions for LYSin:DEI are reported relative to the HHM group in gestation. Using an extreme group as the reference category allowed trends for the model solutions, as deviations from the reference, to be easily visualised.

Table 3. 2. Actual digestible energy intake (DEI), lysine intake (LYS) and total lysine: digestible energy intake ratio (LYS: DE) and the associated range per day

		Days of Gestation					
Variable	Group[1]	n	0-24	n	25-80	n	81-114
DEI (MJ/day)	VH		-	22	59.8	35	57.9
	H	257	30.4-33.0	75	43.8-45.9	66	39.4-45.3
	M	619	29.9-30.0	779	29.9-33.0	775	29.8-36.3
LYS (g/day)	H	313	17.3-20.5	226	20.5-22.1	320	21.5-32.3
	M		-	583	14.2-17.3	427	14.1-17.4
	L	563	11.0-15.0	67	11.0	129	11.2
LYSin:DEI[2]	H	204	0.68	204	0.69	81	0.71
(g:MJ DE)	M	109	0.54	109	0.54	204	0.67-0.69
	L	399	0.45-0.48	399	0.45-0.48	427	0.45-0.54
	VL	164	0.37	164	0.37	164	0.37

[1] VH-Very High; H-High; M-Medium; L-Low, VL-Very Low.

[2] LYSin:DEI analysed for the overall gestation period i.e. HHM is H-0.68, H 0.69 and M-0.67-0.69 g:MJ DE in early mid and late gestation, respectively

3.4 Results

As the studies and sites involved in the analysis differed, the average sow parity also differed, but the modal parity across all the data was 2. The average litter size and number of piglets born alive was 12.9 (SD=3.38) and 11.8 (SD=3.25), respectively. Piglets had an average birth and weaning weight of 1.54 kg and 7.67 kg (SD=0.377 kg and 1.904 kg), respectively. The average number of piglets weaned per litter was 10.3 (SD=2.17).

3.4.1 Digestible energy intake associations

Sow DEI ranged from 29.9 to 33.0 MJ/day in early gestation, 29.9 to 59.8 MJ/day in mid gestation and 29.8 to 57.9 MJ/day during late gestation (Table 3.2). The regression coefficients of the association of DEI and LYS with reproductive variables are reported relative to the high or very high group in each stage of gestation (Table 3.3). In early gestation, medium DEI was associated with a reduction of 46.95 kg in sow lactation intake and a 1.01 kg decrease in WnWT, both of which were significantly different from sows which had a high DEI intake (P=0.001 and P=0.003, respectively). There was no significant difference between DEI groups in early gestation for TB, BA and BtWT (P>0.05).

During mid-gestation (day 25-80), medium DEI (29.9-33.0 MJ/day) was associated with an increase of 1.86 BA and 49.67 kg in sow lactation feed intake when compared to very high DEI. When compared to high (43.8-45.9 MJ/day), medium DEI during mid-gestation resulted in more TB, BA (P<0.001) and greater sow lactation feed intake (P<0.001). There was no significant difference observed between DEI groups in mid gestation for both BtWT and WnWT (P>0.05).

In late gestation (day 81-114), no significant difference was detected between DEI groups for TB or BA. With regards to BtWT, reducing DEI intake from very high to high was associated with an increase in BtWT of 0.19kg; however, lowering DEI intake further to 29.8-33.0 MJ/day was associated with a reduction of 0.16 kg compared to high DEI. Similarly, a greater increase in WnWT was associated with high DEI than medium DEI and high DEI resulted in a heavier WnWT than very high DEI (P=0.018). High and medium DEI during late gestation were associated with an increase of 43.19 and 47.02 kg respectively, in sow lactation intake and both groups had higher intakes than very high DEI (P<0.001).

Table 3. 3. Model solutions (standard error in parenthesis) for the association of digestible energy intake (DEI) and lysine intake (LYS) during early (d0-24), mid (d25-80) and late (d81-114) gestation on total born, born alive, average piglet birth weight (kg), average piglet wean weight (kg) and fresh feed intake in lactation (kg)

Variable	Group[1]	Range	Total born[2]	Born alive[2]	Average birth weight[2]	Average wean	Lactation intake[2]
DEI(MJ/day)							
d0-24	H	30.4-33.0	0	0	0	0[a]	0[a]
	M	29.9-30.0	-1.35(0.93)	-1.29(0.89)	0.16(0.06)	-1.01(0.35)[b]	-46.95(10.54)[b]
d25-80	VH	59.8	-0.13(0.83)[ab]	-0.44(0.79)[a]	0.07(0.05)	0.06(0.27)	-4.07(7.86)[a]
	H	43.8-45.9	0[a]	0[a]	0	0	0[a]
	M	29.9-33.0	0.94(0.45)[b]	1.42(0.43)[b]	0.01(0.03)	0.13(0.15)	45.61(4.45)[b]
d81-114	VH	57.9	0	0	0 [a]	0[a]	0[a]
	H	39.4-45.3	-0.21(0.80)	0.11(0.77)	0.19(0.05) [b]	0.70(0.29)[b]	43.19(8.63)[b]
	M	29.8-36.3	0.55(0.61)	0.79(0.58)	0.03(0.04) [a]	0.38(0.20)[ab]	47.02(5.92)[b]
LYS							
d0-24	H	17.3-20.5	0[a]	0[a]	0 [a]	0	0[a]
	L	11.0-15.0	-1.18(0.43)[b]	-1.14(0.41)[b]	0.13(0.03) [b]	0.26(0.31)	-24.99(9.42)[b]
d25-80	H	20.5-22.1	0	0	0 [a]	0[ab]	0[ab]
	M	14.2-17.3	0.62(0.68)	0.58(0.65)	-0.08(0.04) [ab]	0.03(0.27)[a]	11.26(7.79)[a]
	L	11.0	0.35(0.62)	0.46(0.59)	-0.12(0.04) [b]	-0.38(0.29)[b]	-10.08(8.38)[b]
d81-114	H	21.5-32.3	0	0[a]	0	0	0[a]
	M	14.1-17.4	-0.01(0.48)	-0.01(0.46)[a]	-0.05(0.03)	-0.36(0.19)	6.44(8.03)[a]
	L	11.2	-0.58(0.45)	-0.98(0.42)[b]	-0.05(0.03)	-0.31(0.19)	-30.92(6.34)[b]

[1] VH-Very high, H-High, M-Medium, L-Low.

[2] All model solutions are relative to the very high or high group within each stage of gestation i.e. in mid gestation sows fed medium DEI were associated with an increase of 0.94 total born compared to sows fed high DEI in mid gestation.

[a, b] model solutions with different letters, within both trait and stage of gestation, are different (P<0.05) from each other

3.4.2 Lysine intake associations

LYS ranged from 11.0 to 20.5 g/day in early gestation, 11.0 to 22.1 g/day in mid gestation and 11.2 to 32.3 g/day during late gestation (Table 3.2). In early gestation, low LYS (11.5-15.0 g/day) was associated with a decrease of 1.18 TB, 1.14 BA and 24.99 kg in sow lactation intake but an increase of 0.13 kg in BtWT (Table 3.3). There was no significant difference between LYS groups in early gestation for WnWT (P>0.05).

During mid gestation, there was no significant difference between LYS groups in mid gestation for TB or BA. Low LYS in mid gestation was associated with a 0.12 kg decrease in BtWT compared to High LYS intake, but medium LYS was not significantly different from high or LYS (P>0.05). Medium LYS resulted in higher WnWT when compared to low LYS (P=0.03) but high LYS was not significantly different from medium or low LYS for WnWT (P>0.05). With regards to sow lactation intake, high LYS was not significantly different from Medium or Low LYS (P>0.05) but medium LYS was associated with an increase of 21.31 kg in sow lactation feed intake compared to low LYS (P <0.001).

In late gestation, low LYS fed sows had fewer BA and lesser sow lactation feed intake compared to high and medium LYS fed sows (P<0.05) (Table 3.3). No significant difference was observed between LYS groups in late gestation with regards to TB, BtWT and WnWT.

3.4.3 Lysine intake: digestible energy intake ratio associations

LYSin:DEI are for the overall gestation period i.e. HHM represents high LYSin:DEI ration in early and mid-gestation, and medium in late gestation, respectively (Table 2). All regression coefficients are shown relative to the HHM group (Table 3.4).

Very low (VL) LYSin:DEI throughout gestation was associated with a reduction of 1.21 TB, 1.57 BA and 53.04 kg sow lactation intake compared to HHM LYSin:DEI ($P<0.001$). Low (L) LYSin:DEI throughout gestation was significantly different from HHM LYSin:DEI with regards to sow lactation feed intake, with a decrease of 14.5 kg eaten when compared to HHM LYSin:DEI. LLH LYSin:DEI was associated with a decrease of 0.07 BA but was associated with an increase of 0.04 TB, 0.06 kg piglet BtWT and 0.07 kg piglet WnWT when compared to HHM LYSin:DEI ($P<0.01$). MML LYSin:DEI was associated with a 21.50 kg increase in sow lactation feed intake ($P=0.001$) but a reduction of 0.14 kg in piglet BtWT ($P=0.002$) compared to HHM LYSin:DEI. No significant difference was observed between MML and HHM LYSin:DEI with regards to TB, BA or WnWT. ($P<0.05$).

Table 3. 4. Model solutions (standard error in parenthesis) for the association of total lysine intake to DEI/day ratio intake (LYSin:DEI) during gestation (d0-114) on total born, born alive, average piglet birth weight (kg), average piglet wean weight (kg) and fresh feed in lactation (kg)

Variable	Group[1]	Total born[2]	Born alive[2]	Average birth weight[2]	Average wean weight[2]	Lactation intake[2]
LYSin:DEI (g/MJ DE)						
d0-114	HHM	0^{ab}	0^{ab}	0^{a}	0^{a}	0^{a}
	MML	1.15(0.69)^{b}	0.89(0.66)^{b}	-0.14(0.04)^{b}	-0.01(0.23)^{a}	21.50(6.67)^{b}
	LLH	0.04(0.74)^{ac}	-0.07(0.71)^{ab}	0.06(0.05)^{a}	0.70(0.24)^{b}	11.22(7.15)^{ab}
	LLL	-0.49(0.35)^{ac}	-0.52(0.34)^{a}	-0.004(0.02)^{a}	-0.11(0.12)^{a}	-14.49(3.37)^{c}
	VLVLVL	-1.21(0.37)^{c}	-1.57(0.35)^{c}	-0.01(0.02)^{a}	-0.20(0.12)^{a}	-53.04(3.60)^{d}

[1] H- High, M-Medium, L-Low, VL-Very Low.

[2] All model solutions are relative to the HHM group i.e. in gestation sows fed LLL LYSin: DEI were associated with a decrease of 0.49 total born compared to sows fed HHM LYSin: DEI in gestation.

$^{a, b, c, d}$ model solutions with different letters, within trait, are different (P<0.05) from each other.

3.5 Discussion

Identifying the optimal diet composition and feed allowance during key phases of gestation to promote improved reproductive performance will help to increase on farm output and efficiency. With nutritional research commonly focused on a particular aspect of the diet (e.g. specific nutrients or additives) and due to the complexity of feeding multiple diets in sow trials, there is little information in the literature that simultaneously evaluates both digestible energy and lysine intake at different stages of gestation, at a variety of levels. The aim of the present study was to address this knowledge gap, by using experimental data collected at two research sites and combining then for analysis, thus adding value to the data already collected from individual studies. As similar baseline data were collected in the trials conducted at both sites, the data sets could be merged and analysed as one, with the consequence of permitting 16 gestation treatments to be compared.

3.5.1 Digestible energy intake and sow productivity

The *Nutrient Requirements of Swine* (NRC, 2012) recommends between 30.2 and 35.8 MJ DE/day for multiparous sows to sustain sow maintenance and support both maternal and foetal growth during gestation. Indeed, Buitrago et al. (1974), investigated the effect of feeding less than one third of these recommendations during gestation (9.2 MJ DE/day), and found a reduction in both individual piglet birth weight and total litter weight, as well as in the number of muscle fibres in piglets, relative to a diet of 33.5 MJ DE/day. In the present study, the medium DEI (30 MJ DE/day) in early pregnancy, which was slightly lower than recommendations, was associated with a decrease in piglet weaning weight and sow lactation feed intake compared to a high DEI. Although there was only a very moderate difference between medium and high DEI, according to the classifications in the current study, the medium DEI in early gestation was likely insufficient to meet the demands of the sow and the developing piglets. This is to be expected, as it was lower than the recommended allowance. The relationship between energy intake and reproductive performance is not clear due to conflicting results in the literature. Bee (2004) reduced the energy intake of multiparous sows in early gestation from 43.57 to 19.53 MJ DE/day and found no effect on the number of piglets born alive, piglet birth weight, number of pigs weaned/litter or weaning weight. Contrary to this Hoving et al. (2011) suggest embryo survival can be improved with increased energy intake the first 4 weeks of pregnancy as litter size was greater for second and third parity sows fed 18.8 vs. 14.5 MJ DE/day. Similarly, a review by Kongsted (2005), indicates that both litter size and pregnancy rate may be influenced by very low energy intake in the first four weeks of gestation. A limitation of the current analysis is that DEI below 30.0 MJ DE/day was not investigated, yet the value of this analysis is that it utilises performance data from modern sows and large litters.

The present study found that, when sows were provided with a medium DEI in mid-gestation (29.9 to 33.0 MJ DE/day) there was an associated increase in piglets born alive and in sow lactation intake, when compared to very high DEI. DEI is commonly increased by increasing feed intake rather than the energy density of the diet. However, a negative consequence of a greater feed intake during mid-gestation is an increased maternal weight gain during gestation. This can impact negatively on lactation feed intake as sow body reserves are mobilised to meet the demands of the suckling litter (Dourmad, 1991).

In late gestation, feed intake and consequently DEI, is often increased to meet the increasing requirements of the developing foetuses and to ensure that feed intake following parturition commences at an increased plane. However, in a review by Campos et al. (2012) the authors concluded that additional energy in late gestation only marginally mitigates against the effects of larger litters such as increasing piglet birth weight. In agreement with the hypothesis, that a higher DEI intake in late gestation would be associated with increased sow and piglet productivity, this study found that a high (39.4 to 45.3 MJ DE/day) and medium (29.8 to 36.3 MJ DE/day) DEI in late gestation, were associated with an increase in born alive, piglet birth and wean weight, and sow lactation intake. Similarly, Gonçalves et al. (2016) found that an energy intake in late gestation of 39.7 MJ DE/day, which is similar to the medium intake in the current study, increased the birth weight of piglets born alive for all sows and gilts compared to sows on a low energy intake, 26.5 MJ DE/day. However, sows fed the high energy intake also had a reduced probability of piglets born alive and increased probability of stillbirths compared to sows fed the low energy intake.

Therefore, it is evident that DEI during early, mid and late gestation requires close monitoring as meeting both the nutritional needs of the sow and the developing foetus’ is crucial to optimise sow output. It was hypothesised that DEI levels associated with improved sow and piglet productivity would differ by stage of gestation and in agreement with this the current study found that the DEI levels identified as being associated with improved reproductive performance were 30.4-33.0, 29.9-33.0 and 29.8-36.3 MJ DE/day for early mid and late gestation, respectively. However, in disagreement with the hypothesis, the DEI levels identified in the present study are within the current recommended DEI range for gestation and suggest that these recommendations are appropriate.

3.5.2 Lysine intake and sow productivity

Amino acid requirements change as gestation progresses due to increasing demands for foetal and mammary gland growth and development. They also vary with regard to sow parity and body weight and are considerably less for older and heavier sows as there is no longer a requirement for growth (Pettigrew and Yang, 1997). Low feed intake during gestation will result in body fat and protein being mobilised to support foetal growth and milk production. Lysine is an important essential amino acid for the synthesis of protein and muscle growth. Pig diets are typically composed of cereal grains which are deficient in lysine. Therefore, lysine is considered to be the first limiting amino acid in typical grain-based pig diets. Recommendations suggest that between 8.9 to 14.7 g/day total lysine is required by a gestating multiparous sow dependent on pregnancy weight gain (40 to 60kg) (NRC, 2012).

In the present study, low LYS (11.0 to 15.0 g/day) in early gestation was associated with fewer total born, piglets born alive and less feed eaten during lactation but an increase in average piglet birth weight when compared to high LYS (17.3 to 20.5 g/day). These results suggest that low LYS in early gestation may impair ovulation and implantation, reducing overall litter size. Kusina et al. (1999) suggest that inadequate amino acid intake during gestation may impair foetal development and postnatal performance. However, the literature regarding lysine intake in gestation is limited. Lysine intakes during lactation are well documented. Indeed, low LYS during lactation has been shown to reduce luteinising hormone (LH) pulses which can delay ovulation and follicular development (Yang et al., 2009). Similarly, Yang et al. (2000) found that sows with low LYS (16 g/day) during lactation had reduced uterine weight, a lower percentage of large follicles and fewer oocytes matured to metaphase II compared to sow with medium and high lysine intake (36 and 56 g/day, respectively). On the contrary, although Mejia-Guadarrama et al. (2002) found that reduced LYS in lactation reduced ovulation rate, the number of viable embryos and subsequent litter size were unaffected. In the present study, the improvement in average piglet birth weight is likely a consequence of reduced litter size.

Zhang et al. (2011) investigated LYS levels from day 30 to 110 of gestation and reported an increase in total litter weight and piglet birth weight due to increasing LYS in the diet (14.3 to 22.2 g/day) compared to lower LYS intakes (10.12 to 16.8 g/day). Similarly, the current study found that increasing LYS intake from low to high (11.0 to 20.5-22.1 g/day) in mid gestation was associated with heavier piglet birth weight, however the current study found no association between LYS intakes during mid-gestation and total born, born alive. Likewise, Cerisuelo et al. (2009) found no association with litter size when LYS intake was increased from 15.5 to 31.0 g/day from day 45 to 85 of gestation.

In the present study, a low LYS intake (11.2 g/day) in late gestation was negatively associated with number born alive and sow lactation intake compared to medium and high LYS intake (14.-32.3 g/day). Similarly, Gómez-Carballar et al. (2013), reported a strong tendency for a lower ratio between BA and TB in 2nd parity sows fed low LYS over the last third of gestation compared to medium and high LYS (12.7 vs. 17.0-20.0 g/day). Contrary to these findings, Yang et al. (2009), found no effect of LYS on number born alive but sow body weight, back-fat thickness and body condition were improved and average litter birth weight increased by 1.25 kg was improved with high LYS (24 g/day) during late gestation compared to sows fed a low LYS diet (18 g/day). Similarly, Heo et al. (2008) reported no effect of LYS intake during late gestation on litter size or number born alive but average litter birth weight was increased when primiparous sows received a high LYS diet (24 g/day) from day 80 of gestation compared to sows fed a low LYS diet (18 g/day). With increased litter size, there is a greater demand for amino acids from the developing foetuses, therefore increasing LYS in gestation and in particular, late gestation could improve piglet birth weight and litter performance to weaning in modern sows. This is agreement with previous research by Moehn et al. (2011) and Samuel et al. (2012). As hypothesised, the LYS levels associated with improved reproductive performance in this study (17.3-20.5, 14.2-17.3, and 21.5-32.3 g/day for early, mid and late gestation, respectively) are higher than is currently recommended to optimise the multiparous sow reproductive performance. In line with previous studies, this research suggests that LYS levels in gestation and in particular late gestation need to be investigated further to determine optimal intake level.

3.5.3 Lysine intake: digestible energy intake ratio and sow productivity

Previous research focused on the ratio of LYSin:DEI of sow gestation diets is limited, indeed LYSin:DEI has been more widely research during lactation (Yang et al., 2000, Mejia-Guadarrama et al., 2002, Yang et al., 2009). In agreement with the hypothesis, very low and low LYSin: DEI (0.37 to 0.54 g LYS/MJ DE, respectively) throughout gestation negatively impacted reproductive performance in the present study. On the contrary, Cooper et al. (2001) found no effect of LYS during gestation on sow productivity but increased gestation energy intake (0.33 to 0.42 g:MJ DE), was correlated with increased born alive and piglet weight at birth. As a result of the current study, a LYSin:DEI of MML during gestation (0.54, 0.54 and 0.45-0.54 g:MJ DE for early, mid and late gestation, respectively) may be recommended as an area for further research as it was associated with improved total born, numbers born alive and sow lactation feed intake. Although MML LYSin:DEI during gestation was associated with a 0.14 kg reduction in average piglet birth weight this difference was lessened by weaning with only 0.01 kg reduction in average piglet weaning weight.

3.6 Conclusions

This study found that recommended DEI levels during gestation appear to be appropriate for the modern sow but that provision of lysine and the ratio between lysine and digestible energy in the ration need to be considered more carefully. The current analyses suggest that digestible energy intake of 30.4-33.0, 29.9-33.0 and 29.8-36.3 MJ DE/day during early, mid and late gestation optimises sow output, and that lysine intakes should be high (17.3-20.5 g/day), in early gestation, moderate (14.2-17.3 g/day), in mid gestation and higher again (21.5-32.3g/day) in late gestation. These nutrient intakes were associated with improved reproductive performance in this study and are higher than current recommendations (8.9 to 14.7 g/day total lysine) and therefore the lysine requirements for sows during gestation need to be revised. Future research should follow up on this work to determine the range of lysine intakes appropriate for specific stages of gestation to maximise the reproductive performance of modern multiparous sows.

Chapter 4

The effect of salmon oil and vitamin D_3 inclusion level in sow gestation diets on piglet vitality at birth and viability to weaning

4.1 Abstract

Replacing of soya oil with salmon oil and a higher level of vitamin D_3 in the sow's gestation diet could improve piglet survivability and growth to weaning. Therefore, the objective of this study was to compare the use of salmon oil with soya oil and evaluate the effect of a high level of vitamin D_3 in the sow gestation diet, on sow and piglet productivity. Crossbred (Large White × Landrace) multiparous sows (*n*= 120) were randomly assigned to treatment beginning on day 30 of gestation. The experiment was a 2 × 2 factorial arrangement with 2 factors for oil (soya or salmon oil; 2.5 % inclusion) and 2 factors for vitamin D_3 ['High' (2000 IU/kg) or 'Low' (800 IU/kg)] level of vitamin D_3. Dietary treatments were terminated at parturition and the experiment was terminated when sows were weaned at ~day 28 of lactation. Treatment had no effect on sow weight, back-fat depth, body condition score, gestation feed intake. Sows fed soya oil ate an average of 12.0 kg more during lactation than sows fed salmon oil ($P<0.01$). Litter size, number born alive, pre-weaning mortality and number weaned were unaffected by maternal dietary treatment. Piglets born to sows offered the soya oil and low vitamin D_3 diet during gestation had a higher average daily gain (ADG) from day 14 to weaning than all other treatment groups ($P<0.05$). Piglets from sows offered the soya oil during gestation had a greater Ponderal index ($P<0.001$) and BMI ($P=0.001$) on day 1 compared to those from sows offered the salmon oil. Oil type did not influence piglet vitality at birth and survivability to weaning. Piglets born to sows offered the high vitamin D_3 level were heavier on day 1 ($P<0.001$), however piglets born to sows offered the low vitamin D_3 level had greater ADG from day 14 to weaning ($P=0.007$) and were heavier at weaning ($P<0.05$). Salmon oil inclusion in the gestation diet increased the proportion of total n-3 fatty acids in sow plasma as well as colostrum, milk, piglet plasma, liver and brain (all $P<0.001$). High dietary vitamin D_3 increased 25(OH)D3 in sow plasma ($P<0.001$), vitamin D_3 and 25(OH)D3 in colostrum ($P<0.01$ and $P<0.001$, respectively) and piglet liver samples ($P<0.001$). Colostrum IgG increased with increased dietary vitamin D_3 level ($P<0.05$), but milk IgG on day 14 of lactation did not differ with gestation treatment. In conclusion, this study demonstrates that the fatty acid profile and vitamin D_3 status of piglets can be altered through the sows' gestation diet. However, increasing vitamin D_3 and total n-3 fatty acids circulating in the blood of the sow and key tissues in the offspring due to maternal treatment did not improve piglet productivity or piglet viability.

4.2 Introduction

Increasing litter size in sows has been accompanied by a concomitant increase in the proportion of low birth-weight piglets, many of which are not able to survive first few days of life (Edwards, 2002, Rutherford et al., 2013). With ~80 % of pre-weaning deaths occurring within the first week of life the majority can be attributed to crushing of piglets by the sows and low viability (Koketsu et al., 2006). This poses a major problem for the pig industry as concerns are raised regarding the increased mortality associated with these large litters. Improving piglet viability at birth and survivability to weaning is difficult as they are affected by multiple factors such as piglet birth weight, suckling ability, colostrum quality, milk yield and composition, disease prevalence as well as maternal nutritional status during both gestation and lactation (Milligan et al., 2002, Quesnel et al., 2012). Regarding maternal nutrition, formulating diets with the optimum nutrient content for maternal maintenance, growth and foetal growth during gestation is difficult as recommendations currently available were determined in experiments using less prolific sows of the past (Ball et al., 2008). As sow energy intake is generally restricted during gestation, high oil inclusion in the diet is generally avoided, however the use of oil sources which supply high levels of omega-3 fatty acids (n-3) may provide benefits to piglet growth.

The minimum requirement for the omega 6 fatty acid (n-6) Linoleic acid (LA) is 2.1 and 6.0 g/day for gestating and lactating sows (NRC, 2012). There are currently no recommended inclusion levels for n-3 oils in sow diets despite their benefits, such as increased n-3 fatty acid levels in colostrum, milk and piglet tissues as well as improved piglet vitality, having been widely investigated (Kim et al., 2007). Soya oil is rich in omega-6 (n-6) fatty acids and it is widely incorporated as an energy source in pig diets due to its relatively low cost and high concentration of poly-unsaturated fatty acids (PUFA) such as LA. LA (0.5-1.0 % inclusion) has been shown to increase piglet weight at weaning, increase protein to fat ratio in milk and milk yields as well as the immune capacity of piglets (Corino et al., 2009, Cordero et al., 2011, Lee et al., 2014) compared with no LA supplementation. Other research has focused on the inclusion rate and period of inclusion of n-3 PUFA rich oils, in particular fish oils for both sow gestation and lactation diets (Rooke et al., 2000, Rooke et al., 2001b). Fish oils such as salmon oil contain high levels of Docosahexaenoic acid (DHA), an n-3 fatty acid essential for both cognitive and visual development in neonates (Guesnet and Alessandri, 2011). Rooke et al. (2001a) reported that salmon oil in sow gestation diets (1.65 % inclusion) reduced pre-weaning mortality and increased n-3 fatty acid concentration in colostrum and piglet tissues. Furthermore, Laws et al. (2009) found that sows supplemented with fish oil (1.6 % inclusion) during the first half of gestation (day 0-60) had heavier piglets at birth in both the ‘normal’ (1.46-1.64 kg) and ‘light’ (<1.09 kg) birth weight categories, which exhibited increased neonatal growth to weaning.

As the majority of commercial pigs are produced indoors, supplemental dietary Vitamin D_3 is essential to maintain calcium homeostasis, bone health and immune function (Aranow, 2011, Lauridsen and Jensen, 2013). The current recommended minimum inclusion level for vitamin D_3 in sow gestation and lactation diets is 800 international units (IU)/kg (NRC, 2012). However, on UK and Irish pig farms vitamin D_3 is commonly included at an inclusion of 2000 IU/kg due to it being relatively cheap. Lauridsen et al. (2010) found that with increasing vitamin D_3 levels to 1400 IU or 2000IU compared to 200 or 800 IU, the number of piglets stillborn were reduced. Weber et al. (2014) reported that an inclusion level of 2000 IU/kg vitamin D_3 increased piglet weight gain to weaning compared to 200 IU/kg, although 200 IU/kg is well below the recommended 800 IU/kg inclusion level. Therefore, current commercial levels of 2000 IU/kg in sow gestation diets may improve sow productivity and piglet growth compared to the current recommended inclusion rate of 800 IU/kg.

Whilst previous studies have investigated fatty acids (type and inclusion) and vitamin D_3 levels in sow diets, none have focused on their combined or interactive effect. The objective of this study was to investigate the substitution of salmon oil for soya oil and two levels of vitamin D_3 inclusion (2000 vs. 800 IU/kg) in sow gestation diets, in a 2 × 2 factorial arrangement, as a solution to improve piglet vitality and viability at birth, reduce mortality pre-weaning and increase piglet growth to weaning.

4.2.1 Hypotheses

- A high level of vitamin D_3 and salmon oil inclusion in sow gestation diets will improve piglet vitality at birth i.e. higher vitality score, reduced time to first suckle, increased piglet birth weight and increase IgG levels in colostrum and milk.
- Salmon oil will extend the natural gestation length of sows compared to soya oil.
- Salmon oil inclusion in the gestation diet will increase the proportion of n-3 fatty acids, in particular DHA in colostrum, milk, and piglet blood plasma, brain and liver tissue at birth.
- Salmon oil will improve piglet vitality at birth and survivability to weaning through increased DHA levels.
- A high level of vitamin D_3 in the gestation diet will increase the level of 25(OH)D3 in blood plasma and milk.
- A high level of vitamin D_3 will improve piglet bone strength compared to a low level of vitamin D_3.

4.3 Materials and Methods

The study was conducted at the Agri-Food and Biosciences Institute, Hillsborough, Co. Down, Northern Ireland, from April 2016 to May 2017. The study was carried out under the regulations of the Department of Health, Social Services and Public Safety (DHSSPS) of Northern Ireland in accordance with the Animals (Scientific Procedures) Act 1986 (The Parliament of the United Kingdom, 1986).

4.3.1 Animals

Multiparous sows, parities two to nine *(n=120*), with a mean parity of 4.9 (SD=2.13) were randomly allocated to treatment on day 28 of gestation. Sows were blocked according to parity, body condition score and body weight prior to being randomly allocated to treatment. Sows were PIC F_1 cross (Large White × Landrace) and Danish Duroc was the terminal sire used. For each batch of sows, artificial insemination was completed over a 3-day period, with one insemination per day. Each sow was inseminated twice over the 3-day period. There were 14 batches with approximately 9 sows per batch.

4.3.2 Gestation Feeding and Management

During the first 14 days of gestation, sows were kept in groups of four in free-access cubicles with a pen at the rear (space allowance 2.76 m^2). After day 14, sows were moved to a large dynamic group of approximately 80 sows, where they were fed using a Nedap electronic sow feeder (*Nedap Livestock Management, 7141 DC Groenlo, the Netherlands*) until day 107 of gestation. Sows were offered 2.5 kg/day of gestation diet from weaning to day 85 of gestation and then 3.0 kg/day until day 107 at which stage sows were moved to the farrowing accommodation. Prior to the commencement of feeding the experimental diets on day 30 of gestation, all sows received the same gestation diet (12.9 MJ DE/kg, 14.02 g/kg CP and 0.7 g/kg total Lys) which contained 2.5 % soya oil and 2000 IU/kg vitamin D_3. A 2000 IU/kg level of vitamin D_3 is the common commercial level in the UK and Ireland (Table 4.1).

4.3.2.1 Dietary Treatments

Dietary treatments (Table 4.1) commenced on day 30 of gestation and the experiment was a 2 × 2 factorial arrangement. During initial trial design, salmon oil was considered to contribute to the vitamin D_3 levels, however vitamin D_3 levels in the salmon oil source used were too low and so the total dietary inclusion was from synthetic vitamin D_3. The two factors were: 1. Oil type [soya oil and salmon oil; 2.5 % inclusion (*Rossyew, Ltd, Greenock, Scotland, United Kingdom*)] and 2. Vitamin D_3 inclusion level (“High”; 2000 IU/kg and “Low”; 800 IU/kg). All dietary treatments were formulated to contain the same energy, protein and lysine content (12.9 MJ DE/kg, 14.02 g/kg CP and 0.7 g/kg total Lys). The feed was manufactured on site at the Agri-food and Bioscience Institute, Hillsborough (Northern Ireland) and it was offered in pellet form (6mm). Table 4.1 details the diet composition.

Table 4. 1. Ingredients, formulated and actual analysis of experimental diets on a fresh basis

	Gestation treatment				
Diet Number	1†	2	3	4	5
Oil	Soya	Soya	Salmon	Salmon	Lactation
Vitamin D$_3$[1]	High	Low	High	Low	
Ingredient (%)					
Barley	59.9	59.9	59.9	59.9	-
Wheat	-	-	-	-	40.0
Soyabean meal	11.2	11.2	11.2	11.2	21.3
Soya Hulls	10.0	10.0	10.0	10.0	-
Maize	5.4	5.4	5.4	5.4	33.9
Beet pulp	5.0	5.0	5.0	5.0	2.0
Soyabean oil	2.5	2.5	-	-	2.0
Salmon oil	-	-	2.5	2.5	-
Molaferm[2]	1.0	1.0	1.0	1.0	-
Lysine	-	-	-	-	0.26
Threonine	-	-	-	-	0.04
Mineral and Vitamin Premix[3]	5.0	5.0	5.0	5.0	2.5[4]
Formulated					
DE (MJ/kg)	14.8	14.8	14.8	14.8	14.5
CP (%)	16.0	16.0	16.0	16.0	17.0
CF (%)	8.8	8.8	8.8	8.8	2.4
Oil B (%)	5.5	5.5	5.5	5.5	4.7
DM (%)	87.5	87.5	87.5	87.5	84.9
Ash (%)	6.1	6.1	6.1	6.1	4.9
Lysine (%)	0.8	0.8	0.8	0.8	1.05
Vitamin D$_3$ (IU/kg)	2000	800	2000	800	2000
Actual					
DE, (calculated) MJ/kg[5]	15.1	15.2	15.5	16.1	17.2
CP (%)	12.7	12.3	11.7	12.1	18.7
CF (%)	8.0	7.1	6.8	5.6	2.0
NDF (%)	18.9	16.9	15.6	13.1	7.0
Oil B (%)	5.0	4.6	4.7	4.7	4.4
DM (%)	87.9	88.1	88.1	88.2	87.6
Ash (%)	4.7	4.8	4.5	3.8	4.5
Lysine (%)	0.60	0.62	0.54	0.62	1.01
Vitamin D$_3$ (IU/kg)	2710	1225	2800	1165	2290

†Control diet fed day 0-29 of gestation prior to commencement of experimental feeding on day 30 of gestation.

[1] High'-2000 IU/kg and 'low'- 800 IU/kg vitamin D$_3$

[2] Liquid blend of molasses used as a binding agent

[3] Gestation premix provided (per tonne of finished feed) 8.0 MIU vitamin A, 1.0 g Iodine from Calcium Iodate; 0.3 g Selenium from Sodium Selenite; 80.0 g Iron from Ferrous Sulphate; 30.0 g Manganese from Manganous Oxide; 12.0 g Copper from Copper Sulphate; 80.0 g Zinc from Zinc Oxide; 0.79 % Lysine. Premix containing either 2.0 MIU or 0.8 MIU vitamin D$_3$ per kg of finished feed. Sourced from Devenish Nutrition Ltd., Belfast, UK

[4] Lactation premix provided (per tonne of finished feed) 8.0 MIU vitamin A, 2.0 MIU vitamin D$_3$, 1.0 g Iodine from Calcium Iodate; 0.2 g Selenium from Sodium Selenite; 80.0 g Iron from Ferrous Sulphate; 30.0 g Manganese from Manganous Oxide; 12.0 g Copper from Cupric Sulphate; 80.0 g Zinc from Zinc Oxide. Sourced from Devenish Nutrition Ltd., Belfast, UK

[5] Calculated DE value (Morgan et al., 1987):DE (MJ/kg DM) =17.50+0.0078*CP+0.0157*Fat-0.0325*Ash-0.0149*NDF

4.3.3 Lactation Feeding and Management

Sows were moved to the farrowing accommodation on approximately day 107 of gestation and were housed in farrowing crates. There was an enclosed heated creep area for the piglets at the front of each crate. The temperature of both the farrowing room and piglet creep areas was set electronically, with the ambient temperature set at 19 °C for farrowing and reduced to 17.5 °C after 24 hours. The creep area was set at 30 °C and gradually reduced to 23 °C during the 7 days post farrowing. Sows were fed using wet and dry feeders and were offered 3 kg/day of their respective gestation treatment diets until the day of farrowing. Following parturition, all sows received the same lactation diet (14.5 MJ DE/kg, 17.0 g/kg CP and 1.05 g/kg total Lys) with feed allowance being increased by 0.5 kg/day to appetite. Individual sow feed allowance was weighed, offered manually and recorded, over 2 daily meals, with feed disappearance recorded as feed intake.

Sows were allowed to farrow naturally. For each sow, total born (TB), born alive (BA), born dead and mummified pigs were recorded. Within the first 12 hours of birth, piglets had their teeth clipped and tails docked. The tail and umbilical area was sprayed with iodine. Piglets were injected with 2 ml of an iron supplement (*Uniferon, Virbac Ltd., Suffolk, UK*) and given an ear tag to allow for individual identification throughout their lifetime. Cross-fostering was completed within 24 hours after farrowing and only occurred within treatment with litters standardised to approximately 14 piglets. All piglet mortalities were recorded. Piglets had free access to water from nipple drinkers and creep feed was not offered and sow troughs were high enough to prevent intake of sow feed. All piglets were individually weighed on day 1, 14 and 27 and were weaned at approximately day 28. All sows were wormed 1-week post farrowing with a Doramectin pour on solution (*Elanco, Priestly Road, Basingstoke, UK*) and between the months of October to February, sows were vaccinated in the second week of lactation against swine erysipelas and porcine parvovirus (*Porcilis Ery & Parvo, MSD Animal Health, Walton, Milton Keynes, UK*). All sows were vaccinated on day 70 of gestation for swine erysipelas (*Porcilis Ery, MSD Animal Health*).

4.3.4 Measurements

The sows were weighed and given a body condition and locomotion score, back-fat thickness was also measured, and blood samples were taken on day 28 and day 107 of gestation and at weaning. Back-fat depth was measured at the P_2 site (65 mm from the midline at the level of the last rib) with an ultrasonic backfat scanner (*Pig Scan-A-Mode backfat scanner, SKF Technology, Herlev, Denmark*). Body condition score (BCS) was measured using a 5-point scale and half scores were also used, with a score of 1 visually thin; with hips and back bone being very prominent and a score of 5 being the sow is fat and it is impossible to feel hipbones and backbone (Carr, 1998). Locomotion score was measured using a 5-point scale adapted from the method of Main et al. (2000) and Stavrakakis et al. (2015). Blood samples (2 × 10 ml) were obtained from each sow by jugular vein puncture into evacuated tubes, containing lithium heparin (170 IU). Plasma was prepared from the blood samples by centrifugation at 2500 g for 15 mins (*Mistral 3000E centrifuge, MSE, Lower Sydenham, UK*). Samples were stored pending analysis at -20 °C and -80 °C. Empty sow body weight was calculated using the following formula: sow empty weight (kg) = sow weight pre-farrowing day 107 (kg) – (total number of piglets born × 2.28) (NRC, 1998).

4.3.4.1 Piglet vitality measures

Litters from sows whose farrowings were attended (*n*=80) were used for vitality measures. For each piglet; the time of birth, birth interval, umbilical attachment (attached or broken), vitality score, as per the method of Baxter et al. (2008), sex and birth weight (*HS-15K electronic hanging scale, UWE, Ltd, Taiwan*) were recorded. A blood sample was then obtained from the piglets' umbilical cord and immediately tested for blood lactate concentration (mg/dl) using a Blood lactate monitor *(Arctic Medical Ltd, Folkestone, Kent, UK*). Each piglet was marked on their back with their litter birth order and observed for time to first suckle. On day 1, when all the piglets were approximately 24 hours old, the piglets were weighed to allow estimation of colostrum intake using the equation of Theil et al. (2014a),

$$\text{Colostrum intake (g)} = -106 + (2.26 \times WG) + (200 \times BWB) + (0.111 \times D) - (1{,}414 \times (WG/D)) + (0.0182 \times (WG/BWB)).$$

Where WG is piglet weight gain (g), BWB is piglet body weight at birth (kg) and D is the duration of colostrum suckling (mins).

As piglets were assessed at approximately 24 hours old, the duration of colostrum suckling (D) was included as 1440 mins. On day 1, crown-to-rump length, abdominal circumference and rectal temperature (*Sure Sign digital thermometer, CIGA Healthcare Ltd., Ballymena, UK*) were also recorded. Ponderal index and BMI were then calculated as per the method of Baxter et al. (2008). Piglet head and facial characteristics were visually scored for intra-uterine growth restriction (IGUR) according to the method of Hales et al. (2013).

4.3.4.2 Sow milk, piglet tissue and bone samples

Sows that farrowed unattended (n=40) were used to obtain colostrum, milk and piglet tissue samples. Colostrum samples were obtained within 4 hours after farrowing commencement and milk samples were collected on day 14 of lactation. To collect milk samples, piglets were prevented from suckling 1 hour prior to collection and 1 ml of oxytocin (*Oxytocin-S, MSD Animal Health, Milton Keynes, Buckinghamshire, UK*) was administered intramuscularly to the sows' neck. Approximately 80 ml of milk was obtained by hand across all mammary glands and 40 ml was stored at -20 °C (for fatty acid analysis) and at -80 °C for vitamin analysis (to ensure vitamin stability pending analysis).

Within 24 hours of birth, piglets were individually weighed and 1 piglet of mean birth weight per sow (*n*=10/treatment), balanced for sex, was euthanised by an injection of pentobarbital sodium (*Dolethal, Vetoquinol UK Ltd, Buckinghamshire, UK*). Immediately afterwards a blood sample was obtained by exsanguination, with plasma samples prepared as previously described. The piglets' brain and liver were removed, and weights recorded. Samples were macerated, vacuum packed and stored at -20 °C and -80 °C pending fatty acids and vitamin D_3 analysis. Both hind legs were also removed and stored at -20 °C for bone strength and bone mineral testing.

4.3.5 Fatty acid methyl esters (FAMEs) analysis

Blood plasma, colostrum, milk, liver and brain samples stored at -20 °C were analysed for fatty acid methyl esters (FAMEs). The analysis used 15 ml digestion tubes with screw caps as reaction vessels for all samples. Plasma, colostrum and milk samples were prepared using a rapid total lipid extraction method as per Bligh and Dyer (1959). Liver and brain samples were prepared as per the method of O'fallon et al. (2007). The methylated extracts (1 µl injection) were analysed on an Agilent 6890 GC with flame ionisation detector (FID), a 7683 series injector and autosampler, with a CP-Sil 88 100 m 0.25 diameter column (Agilent, Cheadle UK). Data acquisition from the resulting peaks was carried out using Openlab software (Agilent).

4.3.6 Vitamin D_3 analysis

4.3.6.1 Colostrum, milk and liver samples

Colostrum, milk, and liver samples stored at -80 °C were analysed for vitamin D_3 and 25(OH)D3 content. Samples were extracted as previously described by Strobel et al. (2013), with minor modifications. Homogenised liver (5 g) or colostrum/milk (15 g) were saponified with 0.5 g ascorbic acid, 15 ml ethanol and 6.0 g potassium hydroxide. In the case of liver, 15 ml distilled water was also added. The headspace of the vessel was flushed with nitrogen prior to securing the stopper. Samples were placed in an orbital incubator shaking at 125 rev/min and held at 25 °C for at least 16 hours. The saponified sample was then transferred to an Agilent 50 ml chem-elut cartridge (*Agilent Technologies UK Ltd, Cheshire, UK*), allowed to absorb for 15 mins and then eluted with 3 × 50 ml petroleum ether. The eluent was collected and concentrated to approximately 0.5 ml. The reduced extract was then concentrated to dryness under a gentle nitrogen stream before being reconstituted in 1 ml hexane. Extracts were centrifuged at 1730 g for 10 mins *(sigma 3-15k centrifuge, Sigma-Aldrich Company Ltd, Dorset, England)* and the supernatant collected. Vitamin D_3 and 25(OH)D3 were eluted using solid phase extraction (SPE) cartridges as previously described by Trenerry et al. (2011). Both fractions were evaporated to dryness under a gentle nitrogen stream and reconstituted in 500 µl methanol. Any extracts that appeared cloudy were centrifuged at 3893 g for 10 min before derivatisation. The derivatisation reaction method was modified from Ding et al. (2010). A 100 µl aliquot of the final extract was transferred to a LC vial with a 100 µl aliquot of either 0.5 mg/ml 4-Phenyl-1, 2, 4-triazoline-3, 5-dione (PTAD) in acetonitrile for milk or 5 mg/ml PTAD in acetonitrile for liver, vortexed and allowed to react for at least an hour before liquid chromatography- mass spectrometry (LCMS) analysis.

4.3.6.2 Blood samples

Blood plasma samples stored at -80 °C were analysed for 25(OH)D3 content. Plasma (200 µl), 60 µl of 1000 ng/ml deuterated 25(OH)D3 internal standard and 60 µl of acetonitrile were added to an Eppendorf and mixed using a vortex mixer. Then 280 µl of a precipitation solution of methanol: acetonitrile: 10 % aqueous zinc sulphate (5:2:1) was added to the Eppendorf and the sample vortexed. The samples were then centrifuged at 3893 g for 10 mins. A 200 µl aliquot of the supernatant was transferred to a 400 µl insert in a LC vial. Samples were then analysed by LCMS.

4.3.6.3 LCMS analysis of Vitamin D_3 samples

The sample extracts were analysed on the liquid chromatography-mass spectrometer (LCMS) *(Nexra X2 UHPLC/HPLC system, Shimadzu, Kyoto, Japan*). For colostrum, milk and liver samples a 150 × 2.00 mm polar endcapped reverse-phase C18 column was used (*Phenomenex, Macclesfield, UK*). When analysing plasma samples, a 100 × 2.10 mm polar endcapped reverse-phase C18 column was used (*Phenomenex, Macclesfield, UK*). Data acquisition was carried out using Analyst software (*AB Sciex, Warrington, UK*) version 1.6.2 with data processing and quantitation carried out using MultiQuant software (*AB Sciex, Warrington, UK*) version 3.0.

4.3.7 Bone analysis

A 3-point bending testing was used to determine the bone strength of the left femur. The bones were dissected from the hind legs and thawed at room temperature for approximately 14 hours (overnight). Once thawed the femur bones were weighed and bone length and diameter were measured using digital callipers. The breaking strength test was conducted on each bone, using an Instron materials testing machine *(Model 3366, Instron, High Wycombe, Buck, UK*) and a 3-point bending jig *(Instron 5KN Flexure fixture 3-point bend*). Using a 50 kgF load cell with a crosshead speed of 25mm/min and an attached anvil measuring 50 mm in length and 10 mm wide, force was applied to the midpoint of the same facial plane of each bone supported by two supports 40 mm apart. The bone breaking point was detected and force (kgF), strain and stress (kgcm^2) were obtained using the Instron system software (*Bluehill version 3*), with force given as bone strength (kgF).

4.3.8 Quantification of Immunoglobulin G

The concentration of immunoglobulin G (IgG) in colostrum and milk was assayed using specific pig- ELISA kits *(Bethyl Laboratories Inc., Universal Biologicals, Cambridge, UK)*. The IgG was quantified according to the manufacturer’s instructions.

4.3.9 Statistical Analysis

All continuous response variables were modelled using linear mixed model methodology (REML). Binary and count variables were modelled using generalized linear mixed model methodology (GLM) with a binomial distribution and logit link function for the binary variables and a Poisson distribution and logarithm link function for the count variables. In all analyses, nursing sow and batch where included as random effects, while parity and treatment were included as fixed effects. For each response variable additional explanatory variables were fitted as fixed effects. A backwards elimination procedure was applied to these additional fixed effects for each response variable so that only variables that were significant at the (P<0.05) level remained in the final model in each case. All models were fitted using residual maximum Likelihood in the statistical software package GenStat (*18th edition, VSN Internal Ltd, Hemel Hampstead, UK*). If differences detected were significant, comparisons between groups were conducted with the fisher’s least significant difference test. Ordinal variables were fitted with the same linear mixed modelling strategy using a proportional odds model in the statistical package Stata (*version 14.2, StataCorp LLC, 4905 Lakeway Drive, College Station, Texas 77845-4512, USA)*.

4.4 Results

4.4.1 Diet composition

In this study, the results from chemical analysis of the diets differed somewhat from the formulated analysis (Table 4.1). In particular, diet 3 had a lower crude protein (CP) value than the other diets. The amino acid content (AA) was also reduced. The diet 4 had lower crude fibre (CF) value than all other diets. Sub-samples of the diets were analysed and had consistently lower CP or CF than other diets. As the same batch of ingredients were used in the manufacturing of each diet and all four diets were made in parallel, the reduced CP and CF are unexplainable. The fatty acid composition (C4:0 to C22:6c) of the dietary treatments were analysed, with mean fatty acid values greater than 1.0 g/100g total fatty acids reported (Table 4.2). As intended, the different oil types changed the profile of fatty acids in the diets. The most pronounced differences were the presence of C20:5c and C22:6c, the increase in the proportion of C13:0, C16:0 as well as a decrease in C18:2c, when salmon oil was included in the diet compared with soya oil. As a result, diet 3 and 4 contained more saturated and n-3 fatty acids but had a lower n-6: n-3 fatty acid ratio than diet 1 and 2. Fatty acids below 1.0 g/100g total fatty acids accounted for approximately 2.0 % and 4.5 % of the fatty acid content of the soya and salmon oil diets, respectively. Although values of <1.0 g/100g total fatty acids are not reported they are included when applicable in the total saturated, monounsaturated fatty acid (MUFA), polyunsaturated fatty acid (PUFA), n-3 and n-6 calculations. Vitamin D_3 content of the diets are mean values from 2 determinations extracted from bulked samples of finished feed. The gestation diets were formulated to contain either 2000 IU/kg (high) or 800 IU/kg (low) vitamin D_3 level but actual values were on average 2755 IU/kg in the high vitamin D_3 level diets and 1195 IU/kg in the low vitamin D_3 level diets. The vitamin D_3 level in the gestation diets were greater than expected and may be a result of contribution of vitamin D_3 from raw materials, but the author is confident this did not impact on the findings of the study. Actual DE and CP levels in the lactation diet, 17.2 MJ DE/kg and 18.8 g/kg CP, differed from expected levels. Actual Vitamin D_3 level in the lactation diet was 2290 IU/kg.

Table 4. 2. Fatty acid composition (g/100g total fatty acids) of experimental diets fed during gestation

	Gestation treatment			
Diet number	1†	2	3	4
Oil	Soya	Soya	Salmon	Salmon
Vitamin D_3[1]	High	Low	High	Low
Fatty acid[2]				
C13:0	38.38	37.62	41.41	42.97
C16:0	14.78	14.62	15.26	15.47
C18:0	2.67	2.79	2.29	2.22
C18:1c9	18.97	19.33	24.72	24.13
C18:1c11	1.76	1.71	2.32	2.30
C18:2c	53.45	53.30	36.52	38.10
C18:3cn3	5.94	5.99	5.70	5.70
C20:1c	<1.00	<1.00	2.32	2.10
C20:5c	<1.00	<1.00	1.91	1.75
C22:6c	<1.00	<1.00	2.59	2.26
Total:				
Saturated[3]	57.08	56.25	61.66	63.23
MUFA[4]	21.39	21.71	30.76	29.84
PUFA[5]	59.82	59.57	48.67	49.59
n-3[6]	6.21	6.14	11.21	10.64
n-6[7]	53.62	53.44	37.46	38.96
n-6:n-3[8]	8.63	8.70	3.34	3.66

†Control diet fed day 0-29 of gestation prior to commencement of experimental feeding on day 30 of gestation

[1] High'-2000 IU/kg and 'low'- 800 IU/kg vitamin D_3

[2] Fatty acids are reported as g/100g of total fatty acids with a reporting limit of 1.0 g/100g. Values presented are mean percentages of total lipid fraction from 2 determinations extracted from bulked samples of diet.

[3] Saturated- saturated fatty acids

[4] MUFA- monounsaturated fatty acids

[5] PUFA- polyunsaturated fatty acids

[6] n-6- omega 6 fatty acids

[7] n-3- omega 3 fatty acids

[8] n-6: n-3 ratio-omega 6 fatty acid: omega 3 fatty acid ratio

4.4.2 Sow characteristics

There was no significant interaction between oil type and vitamin D_3 level on any sow performance measures (P>0.05). Average sow parity was 4.9 (SEM=0.2). Mean sow live-weight and back-fat depth on day 28 of gestation was 241.7 kg (SEM=2.15) and 19.6 mm (SEM=0.35), respectively. At day 107 of gestation average sow live-weight was 284.0 kg (SEM=3.60) and back-fat depth was 21.6 mm (SEM= 0.40). The average sow gestation length was 116.5 days (SEM=0.20) and lactation length averaged 26.5 days (SEM=0.20). At weaning mean sow live-weight was 260.3 kg (SEM=2.3) and back-fat depth was 19.8 mm (SEM=0.42). There was a significant effect of oil type on sow lactation feed intake (P<0.01) where sows offered diets containing soya oil ate on average 12.0 kg more during lactation than sows offered diets containing salmon oil. There was no effect of gestation dietary treatment on any other sow measures recorded (P>0.05).

4.4.3 Litter performance

There was no significant interaction between oil type and vitamin D_3 level on any litter performance measure recorded (P>0.05). Similarly, there was no significant direct effect of oil type or vitamin D_3 level in sow gestation diets on any litter performance measures recorded (P>0.05). Mean total born and number of piglets born alive was 14.9 (SEM=0.32) and 14.4 (SEM=0.31), respectively. As litters were standardised to 14 piglets within 24 hours of farrowing, average litter size after fostering was 13.7 (SEM=0.23). The mean number weaned was 11.4 (SEM=0.21). Mean total litter weight at birth was 20.7 kg (SEM=0.33) and coefficient of variation (CV) of litter birth weight was

21.2 % (SEM=1.14). The average daily gain (ADG) of litters was 2710 g/day (SEM=72.34) and mean pre-weaning mortality was 16.9 % (SEM=1.77). The average litter weight weaned was 90.95 kg (SEM=1.53) and CV of litter wean weight was 19.1 % (SEM=0.77). The number of mummified piglets and piglets fostered in and out were recorded but due to low numbers statistical analysis was not performed.

4.4.4 Piglet vitality measures

In this study, a total of 1143 piglets from 80 litters were used for vitality measures. There was no interaction between oil type and vitamin D_3 level during gestation for the vitality measures of piglets ($P>0.05$). There was a greater probability of piglets receiving a mild IUGR score ($P<0.01$) and having a greater Ponderal index ($P<0.001$) and BMI ($P=0.001$) if born to sows offered a diet containing soya oil compared to piglets born to sows offered a diet containing salmon oil (Table 4.3). Piglets born to sows offered a diet containing a high level of vitamin D_3 during gestation; were 0.08 kg heavier at birth ($P=0.003$) and 0.1 kg heavier on day 1 ($P=0.001$), had a longer crown-rump length ($P=0.001$) and a lower Ponderal index ($P<0.05$) compared to piglets born to sows offered a diet containing a low level of vitamin D_3 (Table 4.3). There was no significant effect of sow gestation treatment on piglet birth interval, vitality score, blood lactate level, time to first suckle, birth to day 1 weight change or colostrum intake ($P>0.05$). The average birth interval between piglets was 13.6 mins (SEM=0.46) and the modal vitality score was 2 (SEM= 0.02). The mean piglet blood lactate level at birth was 71.9 mg/dL (SEM=0.94), and time to first suckle was 22.3 mins (SEM=0.41). Piglets gained on average 40.7 g (SEM=3.65) from birth to day 1 and had an average colostrum intake of 388.8 g (SEM=5.58) in the first 24 hours after birth. With regard to piglet birth order, piglets with a low birth order i.e. born earlier in the farrowing process had a greater probability of receiving a higher vitality score than piglets with a high birth order i.e. born later in farrowing (P<0.001), (Figure 4.1). Furthermore, time to first suckle was reduced for piglets born later in farrowing, (P<0.001), (Figure 4.2).

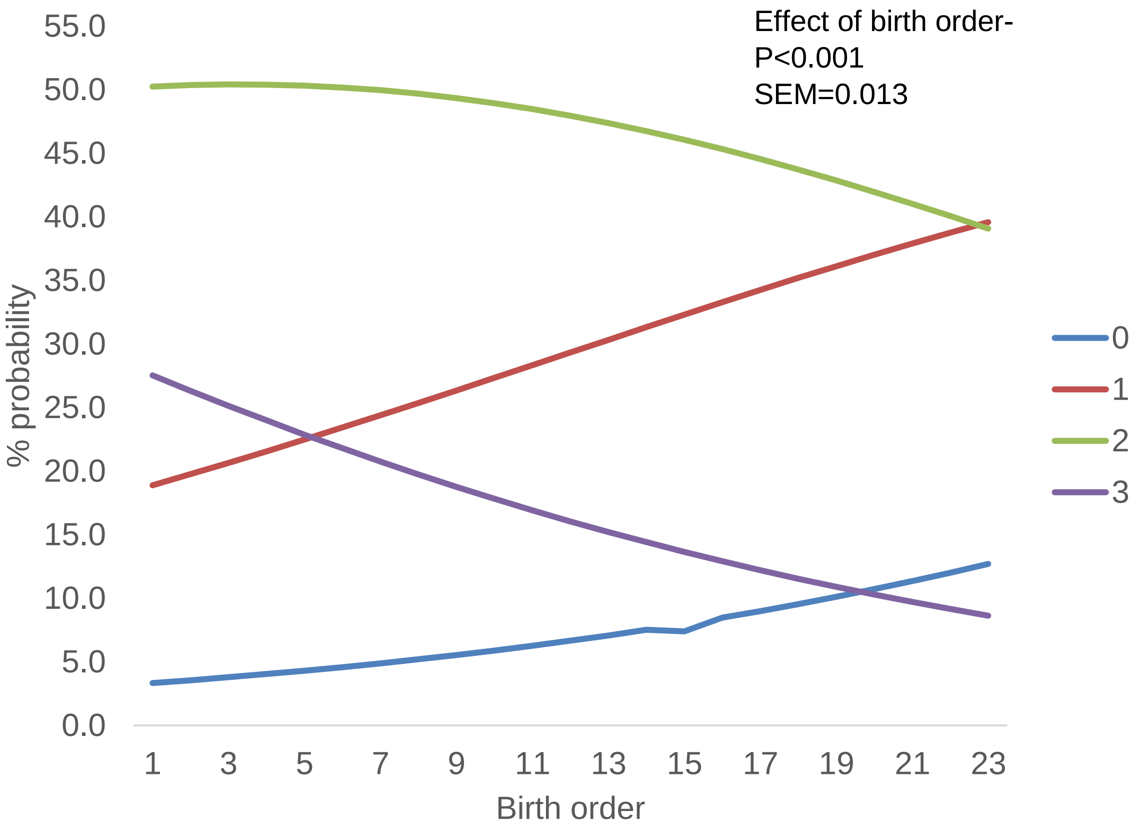

Figure 4. 1. Percentage probability of piglets with a vitality score of 0, 1, 2 and 3 at initial scoring after birth dependent on their birth order.
A score of 0 =low viability, 3= high viability.

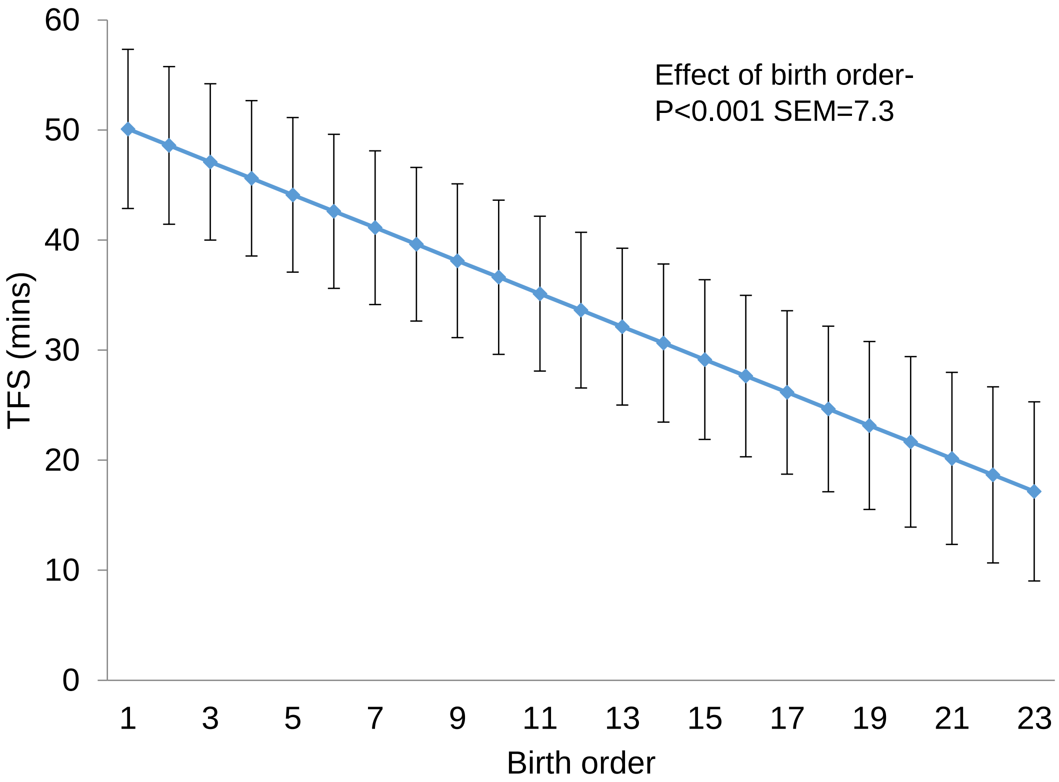

Figure 4. 2. Piglet birth order and time taken to first suckle (TFS) (mins).

4.4.5 All piglets

A total of 1841 piglets from 120 litters (30 per treatment) were used to evaluate growth performance to weaning. There was a significant interactive effect between oil type and vitamin D_3 level with regards to piglet ADG ($P<0.05$). Piglets born to sows offered a diet containing soya oil and a low level of vitamin D_3 had a greater average daily gain (ADG) from day 14 to weaning than all other treatment groups, gaining on average 28.7 g/day more than piglets born to sows offered a diet containing soya oil and a high level of vitamin D_3 ($P<0.05$), (Figure 4.3). There was no effect of oil type on piglet growth performance to weaning ($P>0.05$). Piglets born to sows offered a diet containing high vitamin D_3 level were heavier on day 1 ($P<0.001$), than piglets born to sows offered a diet containing a low vitamin D_3 level. However, piglets born to sows offered a diet containing a low vitamin D_3 level during gestation had greater ADG from day 14 to weaning ($P=0.007$) and as a result were 0.24 kg heavier at weaning ($P<0.05$) compared to piglets born to sows offered a diet containing a high vitamin D_3 level, (Table 4.4).

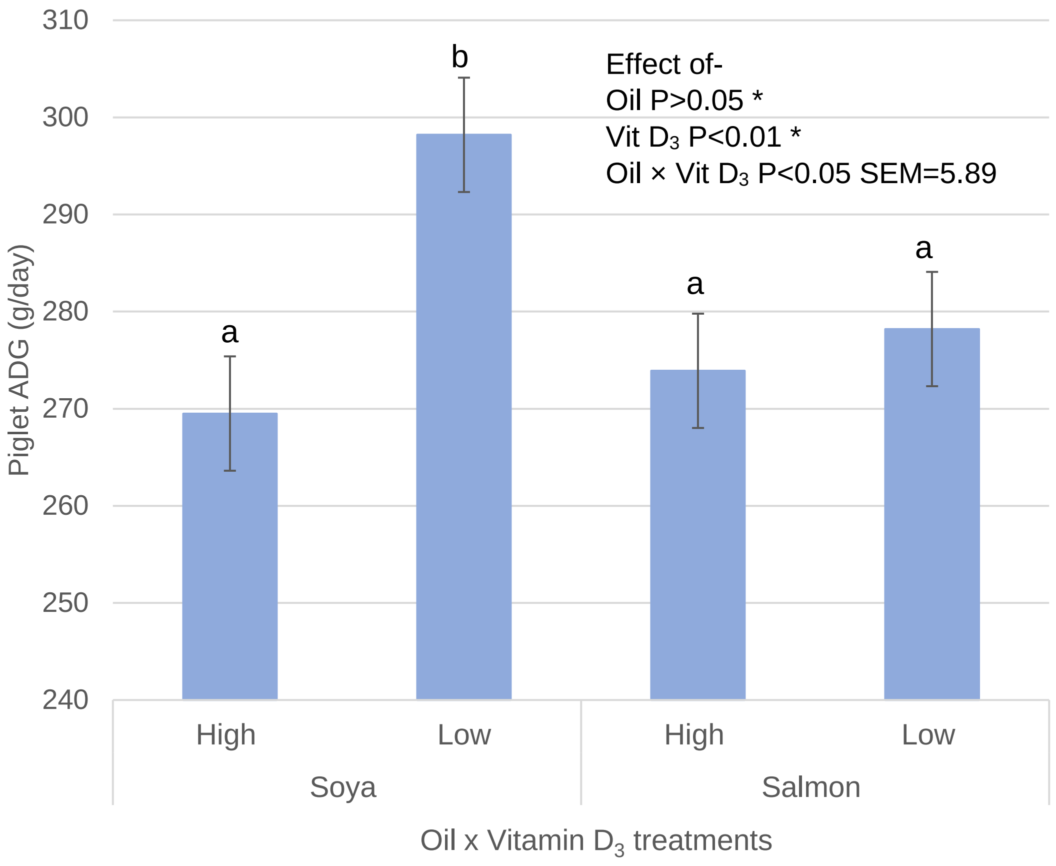

Figure 4. 3. The interactive effect of oil type and vitamin D_3 level ('High' or 'Low') on piglet average daily gain (ADG) (g/day) from day 14 to weaning. ^{a,b} Means with different superscripts are different ($P<0.05$). *Direct effects of oil type or vitamin D_3 level are shown in table 4

Table 4. 3. The effect of sow gestation dietary treatment on piglet vitality measures (*n=1143*).

	Oil type				Vitamin D_3 level[1]			
Variable	Soya	Salmon	SEM[2]	*P*-value	High	Low	SEM[2]	*P*-value
Birth interval (mins)	18.1	20.3	2.27	0.481	21.0	17.4	2.24	0.275
Birth weight (kg)	1.4	1.3	0.02	0.309	1.4	1.3	0.02	0.003
Blood lactate (mg/dl)	64.4	66.2	2.13	0.705	63.2	67.5	1.95	0.120
Time to first suckle (mins)	36.2	39.3	1.96	0.233	36.3	39.8	1.72	0.152
Day 1 weight (kg)	1.5	1.4	0.02	0.082	1.5	1.4	0.02	0.001
Weight change (birth-day1)	59.3	62.7	7.81	0.574	68.1	53.8	6.71	0.134
Colostrum intake (g)	413.3	403.6	12.39	0.810	421.3	395.5	10.34	0.082
Crown-rump (cm)	26.83	27.00	0.171	0.166	27.24	26.59	0.143	0.001
Abdominal circumference	23.77	23.42	0.169	0.22	23.77	23.41	0.149	0.081
Day 1 temperature (˚C)	37.52	38.18	0.441	0.314	37.58	38.13	0.441	0.379
Ponderal index[3]	76.23	70.22	0.921	<0.001	72.20	74.25	0.737	0.039
BMI[4]	20.29	18.82	0.218	0.001	19.65	19.46	0.184	0.473

[1] ‘High’-2000 IU/kg and ‘low’- 800 IU/kg vitamin D_3

[2] SEM- standard error of the mean

[3] Ponderal index- (birth weight (kg)/ crown-rump length (m))^3

[4] BMI- body mass index (birth weight/ crown-rump length)^2

Table 4. 4. The effect of sow dietary treatment during gestation on piglet weights on day 1, day 14 of lactation and at weaning (*n=1841*).

	Oil type				Vitamin D_3 level[1]			
Variable	Soya	Salmon	SEM[2]	*P*-value	High	Low	SEM[2]	*P*-value
Day 1 weight (kg)	1.48	1.40	0.02	0.08	1.49	1.39	0.02	<0.001
Day 14 weight (kg)	4.5	4.6	0.06	0.487	4.6	4.6	0.06	0.606
Wean weight (kg)	8.1	8.0	0.08	0.196	8.0	8.2	0.08	0.023
ADG[3] day 1 to wean (g/day)	247	244	2.96	0.407	243	248	2.96	0.182
ADG day 1 to day 14 (g/day)	221	222	3.47	0.950	219	223	3.45	0.477
ADG day 14 to wean (g/day)*	284	276	4.31	0.199	272	288	4.29	0.007

[1] 'High'-2000 IU/kg and 'low'- 800 IU/kg vitamin D_3

[2] SEM- standard error of the mean

[3] ADG- average daily gain (g/day)

*Interactive effects between oil type and Vitamin D_3 level on ADG day 14 to wean shown in figure 3.

4.4.6 Fatty acid composition

4.4.6.1 Sow blood plasma

There was no significant interactive effect between oil type and vitamin D_3 level on sow blood plasma fatty acid profile ($P>0.05$). Similarly, sow blood plasma fatty acid concentrations were not affected by vitamin D_3 level ($P>0.05$) but were influenced by both oil type and sampling day (Table 4.5). Fatty acid profile did not differ between groups at the start of the experiment ($P>0.05$). As a result of salmon oil being included in the gestation diet, there was a decrease in the proportion of the PUFAs C18:2c ($P<0.001$) and C20:4c5 ($P<0.001$), but an increase in the proportion of the MUFA C18:1c11 ($P<0.01$) and the n-3 fatty acids C22:6c ($P<0.001$) and C20:5c ($P<0.001$) in blood plasma on day 107 of gestation compared to when the gestation diet contained soya oil. On average total n-3 fatty acids in plasma increased by 5.59 g/100g and total n-6 decreased by 9.32 g/100g between day 28 and day 107 of gestation for sows offered the diet containing salmon oil ($P<0.001$). Oil type in the gestation diet did not influence the total proportion of saturated, MUFA or PUFA in the blood plasma ($P>0.05$) at any time point. Feeding the diet containing salmon oil increased the total n-3 fatty acid concentration ($P<0.001$) and decreased total n-6 fatty ($P<0.001$) acid concentration in blood plasma compared to feeding the diet containing soya oil.

4.4.6.2 Colostrum and milk

There was no significant interactive effect between oil type and vitamin D_3 level on colostrum or milk fatty acid composition ($P>0.05$). Colostrum and milk fatty acid composition was not affected by dietary vitamin D_3 level either ($P>0.05$).

As expected, the fatty acid composition of colostrum and milk samples were influenced by oil type and day of sampling (Table 4.6). Feeding salmon oil decreased the proportion of C18:2c in colostrum and in milk ($P<0.001$) and C20:4c5 in colostrum ($P<0.001$), but increased C22:5c and C22:6c in colostrum ($P<0.001$) compared to when soya oil was included in the diet. However, these differences were no longer present in the milk samples taken at day 14 of lactation. Feeding a gestation diet containing salmon oil decreased the proportion of total PUFA ($P<0.01$) and n-6 fatty acids ($P<0.001$) and increased the proportion of total MUFA ($P<0.01$) and n-3 fatty acids ($P<0.001$) in colostrum and milk compared to feeding a gestation diet containing soya oil.

Table 4. 5. Fatty acid composition (g/100g total fatty acids) of sow plasma before and after feeding diets containing soya or salmon oil during gestation.

	Soya oil			Salmon oil				Oil	Day	Oil × Day
Fatty acid[1]	d28[2]	d107[2]	wean	d28	d107	wean	SEM[3]	*P*-value	*P*-value	*P*-value
C16:0	16.2	15.9	17.0	16.1	16.3	16.6	0.265	0.875	0.028	0.355
C16:1c	<1.00	<1.00	1.10	<1.00	1.02	1.13	0.041	0.015	<0.001	0.082
C18:0	13.5	14.3	15.9	13.7	13.8	15.1	0.325	0.286	<0.001	0.286
C18:1c9	16.2	18.5	20.4	16.2	18.9	20.5	0.431	0.605	<0.001	0.848
C18:1c11	1.56^{ab}	1.66^{b}	1.97^{c}	1.53^{a}	1.82^{d}	1.87^{cd}	0.040	0.932	<0.001	0.010
C18:2c	35.5^{a}	33.2^{b}	28.9^{c}	35.1^{ab}	29.2^{c}	29.3^{c}	0.626	0.010	<0.001	<0.001
C18:3cn3	1.76	1.46	0.88	1.65	1.71	0.95	0.067	0.035	<0.001	0.107
C20:4c5	7.1^{a}	6.2^{b}	6.1^{b}	7.1^{a}	3.5^{c}	5.3^{d}	0.244	<0.001	<0.001	<0.001
C20:5c	0.64^{ab}	0.58^{a}	0.64^{ab}	0.61^{a}	3.52^{c}	0.85^{b}	0.083	<0.001	<0.001	<0.001
C22:5cn3	1.36	1.66	1.61	1.56	2.01	1.66	0.067	0.002	<0.001	0.098
C22:6c	0.61^{ad}	0.57^{a}	0.36^{b}	0.62^{ad}	2.69^{c}	0.78^{d}	0.073	<0.001	<0.001	<0.001
Total:										
Saturated[4]	31.4	32.0	34.4	31.6	32.2	33.5	0.473	0.937	<0.001	0.436
MUFA[5]	19.1	21.7	24.3	19.2	22.7	24.5	0.500	0.292	<0.001	0.606
PUFA[6]	48.3	45.1	40.0	48.1	44.3	40.4	0.653	0.764	<0.001	0.567
n-3[7]	4.39^{a}	4.32^{a}	3.49^{b}	4.48^{a}	10.07^{c}	4.28^{a}	0.185	<0.001	<0.001	<0.001
n-6[8]	43.8^{a}	40.7^{b}	36.3^{c}	43.4^{a}	34.1^{d}	35.9^{cd}	0.641	<0.001	<0.001	<0.001

[1] Reporting limit of 1.0 g/100g total fatty acids.

[2] d28 & d107 -day 28 and day 107 of gestation

[3] SEM-standard error of the mean

[4] Saturated- saturated fatty acids

[5] MUFA- monounsaturated fatty acids

[6] PUFA- polyunsaturated fatty acids

[7] n-6- omega 6 fatty acids

[8] n-3- omega 3 fatty acids

[a,b,c,d] Means with different superscripts within a row are different ($P<0.05$) *$P<0.05$ **$P<0.01$ ***$P<0.001$

Table 4. 6. Fatty acid composition (g/100g total fatty acids) of sow colostrum and milk samples after feeding diets containing soya or salmon oil during gestation.

	Soya oil		Salmon oil			Oil	Day	Oil × Day
Fatty acid[1]	Colostrum	Milk[2]	Colostrum	Milk	SEM[3]	*P*-value	*P*-value	*P*-value
C14:0	1.60	3.38	1.85	3.35	0.091	0.230	<0.001	0.120
C16:0	21.0	33.1	20.8	30.8	0.642	0.051	<0.001	0.120
C16:1c	2.52	9.22	2.81	8.50	0.384	0.589	<0.001	0.189
C18:0	5.05	4.58	5.34	4.58	0.126	0.260	<0.001	0.261
C18:1c9	27.7	26.2	31.1	29.5	0.835	<0.001	0.060	0.996
C18:1c11	2.32	2.03	2.84	2.32	0.064	<0.001	<0.001	0.074
C18:2c	31.5^{a}	16.5^{b}	23.9^{c}	15.7^{d}	0.801	<0.001	<0.001	<0.001
C18:3cn3	2.99	1.49	3.12	1.43	0.091	0.722	<0.001	0.277
C20:4c5	1.01^{a}	0.42^{b}	0.67^{c}	0.39^{b}	0.036	<0.001	<0.001	<0.001
C22:5cn3	0.54^{a}	0.21^{b}	1.24^{c}	0.28^{a}	0.036	<0.001	<0.001	<0.001
C22:6c	0.18^{a}	0.06^{b}	1.51^{c}	0.18^{a}	0.041	<0.001	<0.001	<0.001
Total Saturated[4]	28.7^{a}	42.2^{b}	29.5^{a}	39.8^{c}	0.719	0.262	<0.001	0.033
MUFA[5]	33.20	38.19	37.65	41.22	0.865	<0.001	<0.001	0.412
PUFA[6]	37.8^{a}	19.4^{b}	32.1^{c}	18.7^{b}	0.976	0.002	<0.001	0.011
n-3[7]	3.99^{a}	1.91^{b}	6.68^{c}	2.07^{b}	0.162	<0.001	<0.001	<0.001
n-6[8]	33.9^{a}	17.5^{b}	25.9^{c}	16.7^{b}	0.853	<0.001	<0.001	<0.001

[1] Reporting limit of 0.01 g/100g total fatty acids.

[2] Milk samples were collected on day 14 of lactation

[3] SEM-standard error of the mean

[4] Saturated- saturated fatty acids

[5] MUFA- monounsaturated fatty acids

[6] PUFA- polyunsaturated fatty acids

[7] n-6- omega 6 fatty acids

[8] n-3- omega 3 fatty acids

[a,b,c,d] Means with different superscripts within a row are different ($P<0.05$) $*P<0.05$ $**P<0.01$ $***P<0.001$

4.4.6.3 Piglet blood plasma

There was no significant interactive effect between oil type and vitamin D_3 level or a direct effect of vitamin D_3 level on the fatty acid composition of piglet blood plasma or tissues ($P>0.05$). The type of oil fed to sows during gestation changed the proportion of fatty acids in piglet plasma at birth (Table 4.7). Feeding a gestation diet containing salmon oil increased the proportion of C16:1c ($P<0.01$), C18:1c9 ($P<0.01$), C18:1c11 ($P<0.05$), C20:5c ($P<0.001$) and C22:6c ($P<0.001$) in piglet blood plasma at birth when compared to piglets from sows offered a gestation diet containing soya oil. However, feeding a gestation diet containing soya oil increased the proportion of C18:2c ($P<0.01$) and C20:4c5 ($P<0.01$) in piglet blood plasma at birth compared to piglets from sows offered a gestation diet containing salmon oil. As a result total PUFA ($P<0.05$) and n-6 fatty acids ($P<0.001$) were increased in the plasma of piglets at birth when they were born to sows offered diets containing soya oil whereas total MUFA ($P<0.01$) and n-3 fatty acids ($P<0.001$) were greater in the plasma of progeny born to sows offered diets containing salmon oil.

4.4.6.4 Piglet liver and brain samples

The fatty acid profile of liver and brain samples collected at birth, differed as a result of feeding the different oils to sows during gestation (Table 4.8). With regards to the liver, piglets born to sows offered a diet containing salmon oil had lower proportions of C18:1t ($P<0.01$), C18:2t ($P<0.01$), C18:2c ($P<0.01$), C18:3cn6 ($P<0.001$), C21.0 ($P=0.01$), C20:2c11 ($P<0.05$) and C20:4c5 ($P<0.001$), but greater proportions of C20:3c8 ($P<0.05$), C24:0 ($P<0.001$), C24:1c ($P<0.05$), C22:5cn3 ($P<0.001$) and C22:6c ($P<0.001$). Consequently, there was a greater proportion of n-3 fatty acids (P<0.001) and lower proportion of n-6 fatty acids (P<0.001) in the piglet liver as a result of feeding salmon oil. With regards to piglet brain, the proportion of the n-3 fatty acids, C22:5cn3 (P<0.001) and C22:6c (P<0.001) as well as total n-3 fatty acids (P<0.001) and the PUFA C20:3c8 (P<0.001) and total PUFA (P<0.001) increased when sows were offered a diet containing salmon oil. The proportions of the saturated fatty acids, C14:0 (P<0.05), C15:0 (P<0.05), C16:0 (P<0.01), C17:0 (P=0.01) and C18:0 (P<0.01) as well as the n-6 fatty acids C18:3cn6 (P<0.05) and C20:4c5 (P<0.05) decreased, reducing the total proportions of saturated and n-6 fatty acids in the brains of progeny from sows offered a diet containing soya oil in gestation.

Table 4. 7. Fatty acid composition (g/100g total fatty acids) of piglet plasma at birth after feeding sows diets containing soya or salmon oil during gestation.

Fatty acid[1]	Soya oil	Salmon oil	SEM[2]	*P*-value
C14:0	1.04	1.16	0.064	0.203
C16:0	21.4	22.2	0.494	0.249
C16:1c	2.49	3.33	0.176	0.002
C18:0	11.3	10.3	0.386	0.103
C18:1c9	21.4	24.8	0.822	0.006
C18:1c11	3.32	3.91	0.194	0.039
C18:2c	22.3	17..0	1.292	0.006
C18:3cn3	1.32	1.39	0.090	0.549
C20:4c5	5.94	4.15	0.373	0.002
C20:5c	<1.00	2.14	0.150	<0.001
C22:6c	1.20	2.59	0.165	<0.001
Total:				
Saturated[3]	36.0	35.5	0.588	0.550
MUFA[4]	28.5	33.3	1.056	0.003
PUFA[5]	33.6	29.5	1.270	0.027
n-3[6]	4.15	7.18	0.307	<0.001
n-6[7]	29.5	22.27	1.254	<0.001

[1] Reporting limit of 1.0 g/100g total fatty acids.

[2] SEM-standard error of the mean

[3] Saturated- saturated fatty acids

[4] MUFA- monounsaturated fatty acids

[5] PUFA- polyunsaturated fatty acids

[6] n-6- omega 6 fatty acids

[7] n-3- omega 3 fatty acids

*P<0.05 **P<0.01 ***P<0.001

Table 4. 8. Fatty acid composition (g/100g total fatty acids) of piglet liver and brain samples collected at birth after feeding sows diets containing soya or salmon oil during gestation.

	Liver				Brain			
Fatty acid[1]	Soya	Salmon	SEM[2]	*P*-value	Soya	Salmon	SEM	*P*-value
C14:0	1.61	1.59	0.123	0.913	0.90	0.85	0.015	0.018
C15:0	0.32	0.29	0.019	0.244	0.17	0.16	0.005	0.015
C16:0	20.7	20.4	0.404	0.664	25.4	24.8	0.171	0.007
C17:0	0.66	0.60	0.024	0.084	0.29	0.27	0.006	0.010
C18:0	13.5	14.1	0.432	0.365	22.1	21.5	0.085	<0.001
C18:1t	0.42	0.37	0.013	0.009	0.20	0.18	0.020	0.416
C18:1c9	21.6	22.5	0.673	0.354	16.1	16.5	0.199	0.149
C18:1c11	5.73	5.74	0.227	0.993	5.42	5.33	0.036	0.068
C18:2t	0.03	0.03	0.001	0.003	0.02	0.02	0.001	0.647
C18:2c	14.0	10.9	0.709	0.002	0.75	0.73	0.033	0.649
C18:3cn6	0.41	0.28	0.018	<0.001	0.040	0.035	0.002	0.029
C20:1c	0.42	0.46	0.017	0.136	0.52	0.56	0.021	0.186
C18:3cn3	0.63	0.56	0.043	0.286	-	-	-	-
C21:0	0.010	0.008	0.001	0.010	0.010	0.013	0.001	<0.001
C20:2c	0.54	0.43	0.037	0.042	0.06	0.06	0.004	0.637
C22:0	0.08	0.08	0.005	0.742	0.10	0.11	0.003	0.627
C20:3c8	0.79	0.96	0.048	0.015	0.43	0.64	0.017	<0.001
C22:1c	0.11	0.10	0.003	0.874	0.17	0.17	0.008	0.947
C20:3c11	0.15	0.17	0.012	0.426	0.09	0.10	0.005	0.617
C20:4c5	9.42	7.13	0.424	<0.001	12.5	11.5	0.272	0.015
C23:0	0.03	0.02	0.002	0.330	0.02	0.02	0.002	0.998
C22:2c	0.03	0.03	0.003	0.990	0.01	0.01	0.001	0.549
C24:0	0.22	1.05	0.111	<0.001	0.51	0.64	0.019	<0.001
C24:1c	0.21	0.26	0.013	0.024	0.15	0.11	0.020	0.193
C22:5cn3	0.69	1.17	0.060	<0.001	0.34	0.74	0.033	<0.001
C22:6c	2.83	5.25	0.188	<0.001	11.0	12.5	0.125	<0.001
Total:								
Saturated[3]	37.4	38.1	0.425	0.286	49.6	48.4	0.255	0.002
MUFA[4]	32.6	33.4	1.047	0.586	24.5	24.8	0.251	0.402
PUFA[5]	29.4	28.1	1.141	0.397	25.6	26.8	0.210	<0.001
n-3[6]	4.49	7.96	0.268	<0.001	11.8	13.8	0.150	<0.001
n-6[7]	24.9	20.1	0.948	<0.001	13.8	13.0	0.257	0.032

[1] Reporting limit of 0.01 g/100g total fatty acids.

[2] SEM-standard error of the mean

[3] Saturated- saturated fatty acids

[4] MUFA- monounsaturated fatty acids

[5] PUFA- polyunsaturated fatty acids

[6] n-6- omega 6 fatty acids

[7] n-3- omega 3 fatty acids

4.4.7 Vitamin D_3

As mentioned above, there was no significant interactive effect between oil type and vitamin D_3 level on sow blood plasma, colostrum, milk or piglet liver samples analysed ($P>0.05$). There was also no direct effect of oil type on sow blood plasma, colostrum, milk or piglet liver samples analysed ($P>0.05$).

4.4.7.1 Blood plasma

Vitamin D_3 dietary level and day of sampling had an interactive effect on circulating levels of 25(OH)D3 in sow plasma (Figure 4.4). The content of 25(OH)D3 in sow plasma did not differ between groups at the start of the experiment (d28 of gestation) ($P>0.05$). sows offered a diet containing a low level of vitamin D_3 had significantly less circulating levels of 25(OH)D3 ($P<0.001$), with an average of 9.95 ng/ml less 25(OH)D3 in plasma on day 107 of gestation, compared to sows offered a diet containing a high level of vitamin D_3. However, regardless of dietary vitamin D_3 level during gestation, there was no difference between sow plasma 25(OH)D3 levels at weaning ($P>0.05$). Piglet blood plasma samples collected at birth were analysed for circulating 25(OH)D3 but levels were below detection limits (<3.0 ng/ml).

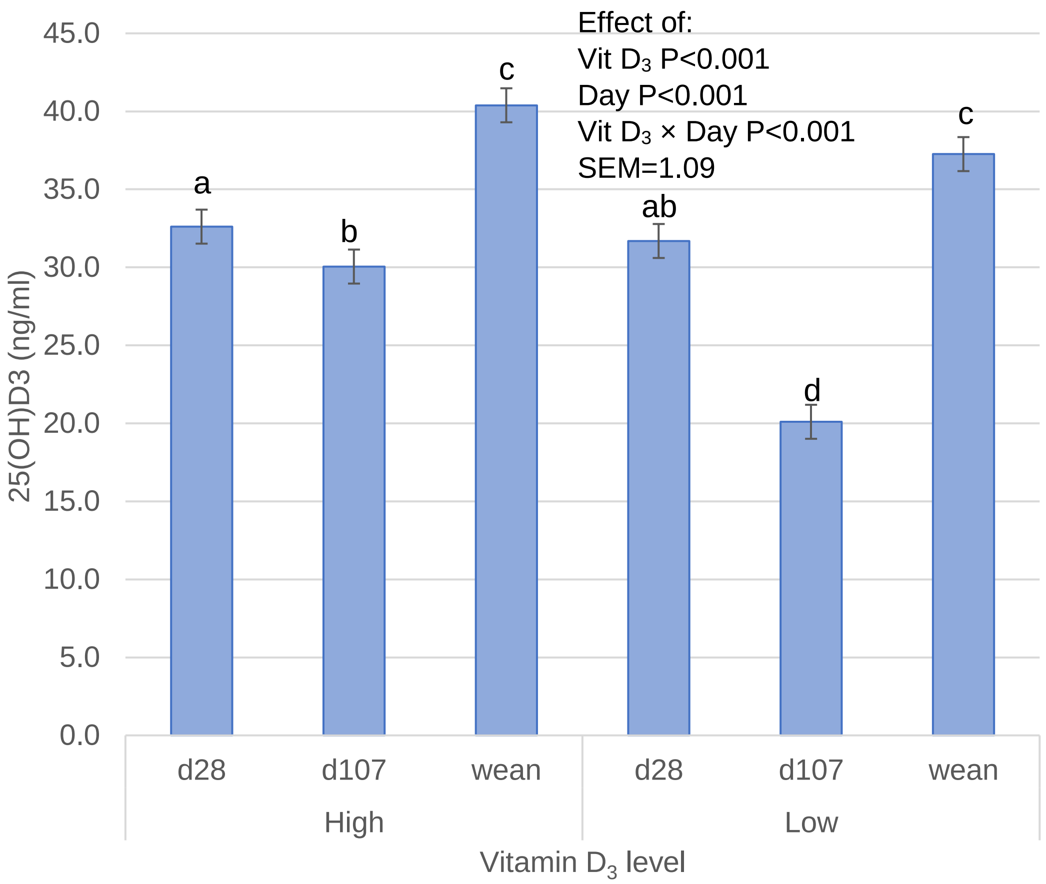

Figure 4. 4. Sow plasma 25(OH)D3 (ng/ml) before and after feeding diets containing high (2000 IU/kg) or low (800 IU/kg) vitamin D_3 during gestation. $^{a, b, c, d}$ Means with different superscripts are different ($P<0.05$)

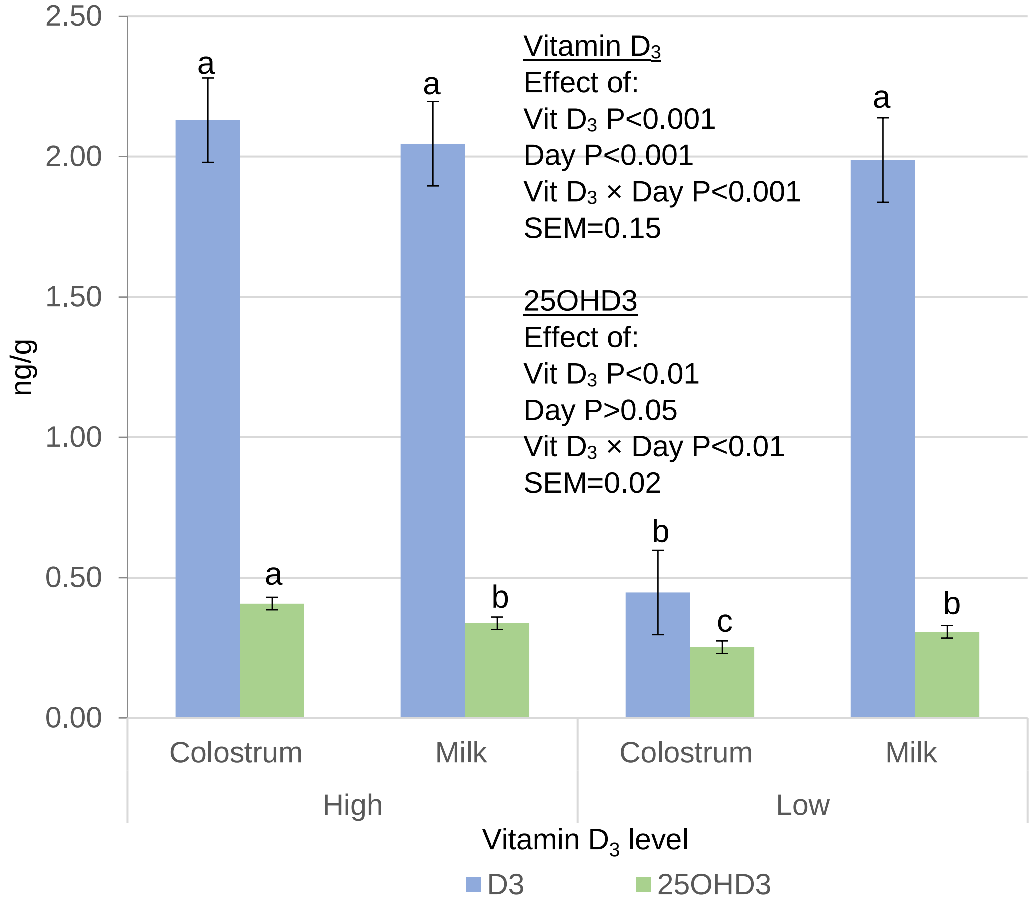

Figure 4. 5. Vitamin D_3 and 25(OH)D3 levels (ng/g) in colostrum and day 14 milk samples after feeding sows diets containing high (2000 IU/kg) or low (800 IU/kg) vitamin D_3 during gestation.

$^{a, b, c}$ Means with different superscripts within variable are different ($P<0.05$).

4.4.7.2. Colostrum and milk

There was a significant interactive effect between dietary vitamin D_3 levels during gestation and day of sampling on colostrum and milk vitamin D_3 ($P<0.001$) and 25(OH)D3 ($P<0.01$) levels (Figure 4.5). Vitamin D_3 level in colostrum and milk samples were not different when sows were offered a diet containing a high level of vitamin D_3 ($P>0.05$). When sows were offered a diet containing a low level of vitamin $D_{3,}$ vitamin D_3 content in colostrum was significantly reduced ($P<0.05$), but there was a significant increase in milk vitamin D_3 content at day 14, which was similar to colostrum and day 14 milk from sows offered a diet containing a high level of vitamin D_3 ($P>0.05$). The 25(OH)D3 level decreased between colostrum and day 14 milk samples when a diet containing a high level of vitamin D_3 was offered to sows ($P<0.05$). However, 25(OH)D3 level increased between colostrum and day 14 milk samples when a low level of vitamin D_3 was offered to sows ($P<0.05$). Although regardless of sow dietary vitamin D_3 level during gestation, 25(OH)D3 levels in milk at day 14 did not differ ($P>0.05$).

The liver of progeny born to sows offered a diet containing a high level of vitamin D_3 during gestation had on average 0.937 ng/g more vitamin D_3 ($P<0.001$) and 0.122 ng/g more 25(OH)D3 ($P<0.001$) at birth compared to the liver of piglets born to sows offered a low level of vitamin D_3 in gestation.

4.4.8 IgG concentration of colostrum and milk

There was no interactive effect between oil type and vitamin D_3 level on IgG concentrations in colostrum and milk ($P>0.05$). There was also no direct effect of oil type on IgG concentrations ($P>0.05$). Concentrations of IgG were also influenced by vitamin D_3 dietary level and day of sampling ($P<0.05$). IgG was greatest in colostrum samples from sows offered a diet containing a high level of vitamin D_3, with an average of 269.0 mg/ml colostral IgG, 85.9 mg/ml more colostral IgG than sows offered a diet containing a low level of vitamin D_3. However, milk IgG did not differ between sows offered a diet containing the high (1.3 mg/ml) or low (0.3 mg/ml) dietary vitamin D_3 levels ($P>0.05$).

4.4.9 Bone measurements in piglets

There was a significant interactive effect between oil type and vitamin D_3 level on the F. strain value of piglet femur bones ($P<0.05$). The femur bone of piglets born to sows offered a diet containing soya oil and a low level of vitamin D_3, had the greatest F. strain value (0.43) but it was only significantly different from piglets born to sows offered a diet containing salmon oil and a low level of vitamin D_3 (0.37) ($P<0.05$). Piglets born to sows offered a diet containing soya oil and a high level of vitamin D_3 had a F. strain value of 0.39 which was not significantly different from any other treatment groups ($P>0.05$).

4.5 Discussion

Determining an appropriate oil source and vitamin D_3 inclusion level in sow gestation diets to improve reproductive performance as well as piglet survivability and growth to weaning should promote sow output and overall farm efficiency. Current recommendations suggest 800 IU/kg vitamin D_3 is required for gestating and lactating sows (NRC, 2012). However, levels of up to 2000 IU/kg are commonly included in commercial sow diets as vitamin D_3 is relatively inexpensive. Currently the literature is conflicting and often compares the form of vitamin D_3 rather than the inclusion level. Oils are commonly used to increase the energy density of pig diets, but they also provide the opportunity to alter the fatty acid composition of diets, tissues and milk. Previous research has documented the benefits of feeding fish oils and increasing vitamin D_3 level in sow diets separately, but to date both have not been evaluated simultaneously. Therefore, the aim of the present study was to address this knowledge gap, by evaluating the effect of salmon oil compared to soya oil and vitamin D_3 level during gestation on animal production parameters as well as fatty acid and vitamin D_3 status in the blood, milk and tissue samples from sows and piglets. During initial trial design the 2 x 2 factorial arrangement allowed for a contribution of vitamin D_3 from salmon oil, however the salmon oil source used had low levels approximately 7 IU/g and so the vitamin D_3 levels formulated in the diet were from the addition of synthetic vitamin D_3. However, the 2 x 2 arrangement allowed for any oil and vitamin D_3 interactions on immunity and growth to be examined.

4.5.1 Gestation diets

The actual composition of the gestation diets differed somewhat from the formulation with regards to CF, CP and DE. However, this should not have impacted on the findings of the study, as oil content was similar between all dietary treatments and the difference between high and low vitamin D_3 levels were proportional to the expected levels.

4.5.2 Oil type and vitamin D_3 interactive effects

In disagreement with the hypothesis, the only interactive effects observed between oil type and vitamin D_3 levels were for the ADG of piglets between day 14 and weaning and the strength of piglet femur bones. It was found that the ADG of piglets from day 14 to weaning was greater for those born to sows offered a diet containing soya oil and a low level of vitamin D_3. Offering sows a gestation diet with salmon oil and a low level of vitamin D_3 significantly reduced piglet femur bone strain (meaning the bones bent less during mechanical testing) compared to the other treatments. However, it is unlikely these results are biologically significant as overall piglet weight at weaning and overall bone strength were unaffected. Therefore, it is suggested that the effects of salmon oil and vitamin D_3 are not additive. This result is surprising as oils and vitamin D_3 affect different biological pathways it was hypothesised their effect would be additive but as this was not the case further research is needed to elucidate underlying mechanisms.

4.5.3 Dietary oil type

Gestation dietary treatment did not affect any sow measures with the exception of sow lactation feed intake which was greater for sows offered diets containing soya oil during gestation (168.6 kg) compared to sows offered diets containing salmon oil (156.5 kg). This difference could be due to increased fibre level in the diets containing soya oil compared to diets containing salmon oil (7.6 vs. 6.2 g/kg CF), or that the sows adapted more readily to the lactation diet as it was also a soya oil-based diet. Oils such as salmon oil which are high in unsaturated fatty acids can be prone to lipid peroxidation which may reduce palatability but with peroxidation <10 mEq/kg this was not the case for diets in this trial. Even though feed intake during lactation was reduced for salmon oil fed sows, there was no detrimental effect of dietary treatment on sow weight, back-fat depth or BCS throughout the experimental period. Oil type during gestation did not influence litter size or the number of piglets born alive, but due to the low number of sows used in this study, the experiment would not have had sufficient statistical power to determine differences for these parameters. The current study found that salmon oil did not improve pre-weaning mortality or piglet growth to weaning. Conversely Rooke et al. (2001a) observed that although salmon oil led to lighter piglets at birth, it did reduce pre-weaning mortality due to a decrease in the number of crushed piglets and an increase piglet growth through increased suckling behaviour.

It was hypothesised that salmon oil would improve piglet vitality at birth, however in the current study salmon oil in sow gestation diets did not improve piglet vitality at birth in the present study. Similarly, Tanghe et al. (2014) reported no effect on piglet vitality when n-3 PUFA were added to the maternal diet during gestation and lactation as salmon or linseed oil, although they did find that farrowing duration was increased. Conversely Rooke et al. (1998) reported fish oils to have a negative effect on piglet vitality. N-3 fatty acids are thought to affect prostaglandin production which is important for the onset of parturition (Gulliver et al., 2012), so inducing sows to farrow may reduce piglet vitality at birth as piglets are born prematurely. Therefore it was hypothesised salmon oil would increase the natural gestation length of sows, however in the present study, oil type did not affect gestation length even though sows were allowed to farrow naturally, indicating that salmon oil does not improve piglet vitality at birth.

As uterine capacity is limited, embryos experience competition for space and placental area (Foxcroft et al., 2006). Even moderate uterine crowding (15. vs. 9 embryos at day 30) can cause piglets to be born with some degree of intra-uterine growth restriction (IUGR) (Town et al., 2004). In the current study, soya oil lessened the effect of uterine crowding as even though there was no difference in litter size, piglets born to soya oil fed sows were more likely to receive a mild IUGR score than their salmon oil counterparts. Piglet body shape is also an important factor influencing survivability. In the present study, Ponderal index and BMI was reduced for progeny from sows fed salmon oil during gestation, but number born dead, and pre-weaning mortality did not differ for the oil types used in the current study. Baxter et al. (2008) found that stillborn piglets had lower body mass and Ponderal indices, meaning they were disproportionately thin and longer than surviving piglets. Indeed, if two piglets have similar body weights, the piglet with a greater BMI has an increased chance of survival (Hales et al., 2013), which may be due to increased muscle and glycogen stores (Amdi et al., 2013a). Therefore, results from this study suggest that salmon oil may have improved piglet survivability as even with reduced Ponderal index and BMI no difference in pre-weaning mortality rates was detected.

Piglet vitality was influenced by piglet birth order, with piglets born earlier in farrowing having a greater probability of a higher vitality score than piglets born later in the farrowing process. Piglets born later in the farrowing process are more likely to experience asphyxia (Alonso-Spilsbury et al., 2005), which can be detected through an increase in piglet blood lactate level (Herpin et al., 1996). In the present study there was no difference detected in piglet umbilical blood lactate levels. Tuchscherer et al. (2000) found that piglets born earlier in farrowing, reach the udder and suckle quicker. On the contrary, the current study found that piglets born later in farrowing had reduced time to first suckle. As piglets are able to identify auditory, olfactory and visual cues immediately following birth (Parfet and Gonyou, 1991) they likely use environmental cues to locate the udder (Skok and Škorjanc, 2014). Therefore, as farrowing progresses, the smell of litter mates, milk and suckling sounds may have encouraged piglets born later to the udder sooner. With larger litter sizes, piglets compete with more litter mates for access to teats (Andersen et al., 2011), which can reduce colostrum intake by 10 % for each additional piglet born (Devillers et al., 2007). Nonetheless, birth order did not influence colostrum intake in the current study. Typically, piglets actively teat sample and suckle for 2-3 hours after birth then rest and colostrum ejections although brief are frequent (Castren et al., 1989), thus piglets born later in farrowing, may have had less competition from earlier born litter mates to access colostrum.

The fatty acid composition of sow blood plasma and milk can be attributed to dietary treatment (Rooke et al., 1998, Rooke et al., 2001c). In this study, as expected salmon oil increased docosahexaenoic acid C22:6c (DHA), docosapentaenoic acid C22:5cn3 (DPA) and eicosapentaenoic acid C20:5c (EPA) and reduced linoleic acid C18:2 (LA) and arachidonic acid C20:4c5 (ARA) in sow plasma on day 107 of gestation compared to soya oil. Similarly, Amusquivar et al. (2010) found lower ARA but increased DHA in plasma at day 105 of gestation and at day 7 of lactation of sows supplemented with fish oil from day 60 to day 115 of gestation. Taugbøl et al. (1993) reported higher EPA, DPA and DHA in colostrum of sows supplemented with cod liver oil. Similarly, in the present study, salmon oil increased DPA and DHA in colostrum but EPA levels in both colostrum and milk were below the detectable limits (<0.01 g/100g total fatty acids). Interestingly in the current study, DHA and DPA levels in day 14 milk from sows offered diets containing salmon oil during gestation were still higher than milk from sows offered a diet containing soya oil. This suggests that n-3 fatty acids from salmon oil treatment during gestation may have been stored in adipose tissues and mobilised later in lactation (Amusquivar et al., 2010). Indeed n-3 PUFAs have been shown to be selectively stored and mobilised from the adipose tissues of rats (Raclot, 2003). Mitre et al. (2005) reported a higher concentration of IgG in colostrum and milk at day 14 and 28 of sows fed shark-liver oil. Contrary to this, the current study found that dietary oil type did not affect IgG levels in colostrum or milk, but instead they differed by stage of lactation which is agreement with previous research (Laws et al., 2009).

In agreement with Rooke et al. (1998), in utero exposure to n-3 fatty acids in the present study altered the fatty acid profile of piglet plasma and tissues. The proportions of DHA and EPA in the plasma of progeny that were euthanised within 24 hours of birth, from sows offered a diet containing salmon oil was similar to maternal plasma at day 107 of gestation, suggesting fatty acid transfer from the sow across the placenta to the foetus. Indeed, hepatic $\Delta 5$ and $\Delta 6$ desaturase have been detected in the foetal pig as early as day 45 of gestation, with expression increasing with age (McNeil et al., 2005). The liver and brain are important organs when investigating n-3 fatty acids, as in humans dietary ALA is converted to EPA and DHA in the liver (Holub, 2002), while n-3 fatty acids are important for brain function (Innis, 2007). In the current study, salmon oil increased total n-3 and decreased total n-6 fatty acids in both piglet brain and liver samples, furthermore demonstrating that n-3 fatty acids can transfer from the sow to piglet in utero. Brain samples in the current study contained the greatest proportion of n-3 fatty acids especially DHA, although ALA was below detection limits. Similarly, Sampels et al. (2011) found that DPA and DHA were significantly increased, but only trace amounts of ALA were found in brain tissue. Reduced ALA in brain tissue may be due to ALA being used for synthesis of longer PUFA such as DHA (Innis et al., 1999). However, human studies have shown selectivity of PUFA placental transfer of DHA over ALA (Haggarty et al., 1997).

It is important to note that although gestation diets in the present study were offered right up to farrowing which is not normal practise, the results concur with previous studies that offered dietary treatments until late gestation. Thus, the n-3 fatty acids in salmon oil did transfer into the sow blood and to the piglet blood, brain and liver in utero as well as sow colostrum and milk but there was no benefit to piglet performance and vitality. Therefore, increasing the dietary level of n-3 fatty acids through the use of fish oil may not be a useful dietary strategy for the pig industry to improve piglet vitality or growth performance to weaning.

4.5.4 Vitamin D_3 level effect

Corroborating the observation of Lauridsen et al. (2010), there was difference between dietary vitamin D_3 levels with regards to sow body condition score, back-fat depth or feed intake in the current study. In the present study, dietary vitamin D_3 level did not influence litter size or numbers born alive or dead. Contrary to this, Lauridsen et al. (2010) reported a reduction in the number stillborn with increased doses of vitamin D_3 (1400 IU and 2000 IU). Although there is no clear mechanism for reduced number stillborn, in human studies, placental tissues were found to be key sites for the vitamin D receptor (VDR) and the production of 1, 25- dihydroxyvitamin D_3 (1, 25(OH)$_2$D3); the active form of vitamin D_3 (Zehnder et al., 2002, Vigano et al., 2003). This may influence placental development and subsequent foetal growth (Murthi et al., 2016). With regards to the present study, it was found that 2000 IU vitamin D_3 in sow gestation diets increased piglet birth and day 1 weight. It has been reported that litter and piglet birth weights increased with 25(OH)D3 supplementation compared to 2000 IU vitamin D_3 (Weber et al., 2014), which may be a result of enhance skeletal growth potential (Hines et al., 2013). Discrepancies between the current study and Weber et al. (2014) may be explained by maternal 25(OH)D3 plasma levels as sows offered a diet with high level of vitamin D_3 (2755 IU/kg) in the current study and that of 25(OH)D3 supplemented sows in Weber et al. (2014) are comparable.

Lauridsen et al. (2010) observed a dose response to vitamin D_3 on piglet ADG in the second week of lactation, with 800 IU resulting in greater piglet body weight gain than their 200 IU dose. In the present study, progeny from sows offered the diet with a low vitamin D_3 level (1195 IU/kg) had greater

ADG from day 14 to weaning than progeny from sows offered the diet containing a high vitamin D_3 level (2755 IU/kg) and as a result piglets were heavier at weaning. It is well documented that vitamin D_3 is important for muscle development and function (Ceglia, 2008), as vitamin D receptor (VDR) knockout mice suffer reduced body size and weight (Burne et al., 2005). Considering the results of Lauridsen et al. (2010) and this study it suggests that diets with lower vitamin D_3 (800- 1100 IU/kg) are adequate to maximise the body gain of progeny. However, the importance of vitamin D_3 in maintaining piglet weight increases as lactation progresses as calcium mediated transport mechanisms become activated (Weber et al., 2014). Therefore, differences in piglet growth could also be influenced by milk production. Nevertheless, as milk production was not measured in this study further investigation is needed.

Vitamin D_3 is hydroxylated to 25(OH)D3 in the liver and as the major circulating form of vitamin D_3 it is an indication of vitamin D status (Zhu and DeLuca, 2012). Increasing the vitamin D_3 level in sow gestation diets increased sow plasma 25(OH)D3 levels to 34.4 ng/ml, which is still within the normal range (15-60 ng/ml 25(OH)D3) (Lauridsen and Jensen, 2013). However, sow plasma 25(OH)D3 was lower on day 107 of gestation compared to day 28, even when sows were offered the diet with a high level of vitamin D_3. Previous studies in dairy cows found that as plasma calcium levels decrease, 25(OH)D3 is activated to form $1,25(OH)_2D3$, which enhances intestinal calcium absorption (Horst et al., 1994). Therefore, the decrease in sow plasma 25(OH)D3 at day 107 may be a result of increased calcium metabolism for impending milk production.

In the current study, as hypothesised colostrum vitamin D_3 and 25(OH)D3 levels were significantly increased for sows offered the diet with a high level of vitamin D_3. This agrees with previous research that increasing maternal vitamin D_3 increases vitamin D_3 in colostrum (Flohr et al., 2014). On the contrary Weber et al. (2014) found that dietary vitamin D_3 level did not influence colostrum 25(OH)D3 of multiparous sow. In the present study milk vitamin D_3 and 25(OH)D3 was not affected by dietary vitamin D_3 levels. This was to be expected as a common lactation diet containing 2000 IU vitamin D was fed to all sows. In agreement with Lauridsen et al. (2010), the present study observed that plasma 25(OH)D3 in piglet serum collected at birth was below detection limits. Thus, increasing maternal dietary vitamin D_3 does not improve the circulating vitamin D_3 status of the piglet. However previous research demonstrated that vitamin D readily crosses the placental barrier (Clements and Fraser, 1988, Goff et al., 1984) and may influence piglet vitamin D stores (Rortvedt and Crenshaw, 2012). Indeed, this supported in the present study where liver vitamin D_3 and 25(OH)D3 was increased in progeny born to sows fed 2000 IU during gestation.

Vitamin D_3 also plays an important role in both the innate and adaptive immune systems (O'Brien and Jackson, 2012). B cells are directly targeted by 1,25(OH)$_2$D3, which inhibits cell proliferation, differentiation and immunoglobulin secretion (Baeke et al., 2010). Interestingly, in the present study, increasing the vitamin D_3 level in sow gestation diets increased colostrum IgG concentration. Indeed, regardless of vitamin D_3 treatment, IgG concentration of colostrum, in the present study, was found to be greater than previous research findings (Hurley, 2015). However, Bourne and Curtis (1973) demonstrated that all colostrum IgG is derived from the serum of sows, while in milk, 70 % of IgG is produced locally in mammary tissues. Sow serum IgG was not analysed in the present study.

Vitamin D_3 plays an important role in calcium and phosphorous metabolism and is therefore crucial for sow bone strength and integrity (Lauridsen et al., 2010). Progeny bone measures are also influenced by maternal dietary vitamin D_3 level (Rortvedt and Crenshaw, 2012), with vitamin D_3 levels below 2000 IU found to negatively impact piglet bone health at weaning (35 days old) (Witschi et al., 2011). In disagreement with the hypothesis, piglet femur bone measures were not affected by maternal dietary vitamin D_3 level in the current study. Indeed, the overall lack of treatment effect on bone measures may be a factor of age as piglet bones were collected at birth.

Overall increasing maternal dietary vitamin D_3 improved the vitamin D_3 status of both the sow and piglets, increased piglet birth and day 1 weight and colostrum IgG concentration, however no subsequent effect on piglet growth to weaning was found.

4.6 Conclusion

In conclusion, this study demonstrates that the dietary oil type and vitamin D_3 level offered to sows during gestation influences the fatty acid profile and vitamin D_3 status, respectively, of sow blood, colostrum and milk and piglet blood and tissues. However, the addition of salmon oil and therefore a greater proportion of n-3 fatty acids did not improve piglet survival and growth to weaning compared to a soya oil-based diet. A high level of dietary vitamin D_3

(which represents levels used commercially) did not improve piglet survivability or growth to weaning compared to a lower level of vitamin D_3. Therefore, in this study a salmon oil-based diet with a high level of vitamin D_3 did not provide any additional benefits to piglet growth and survivability. The findings from the work suggest a soya oil-based diet with a vitamin D_3 inclusion level of ~1000 IU/kg during gestation is sufficient to optimise growth and survivability for the modern prolific sow and her progeny. As dietary treatments ceased at parturition future work should investigate the type of oil and vitamin D_3 level fed to sows during lactation and its effect on piglet growth and survivability to weaning.

Chapter 5

The effect of dietary salmon oil or soya oil in flat or phase fed lactating sows and the fatty acid profile of colostrum and milk and litter performance to weaning

5.1 Abstract

In sow lactation diets, substituting soya oil for salmon oil and offering a phased dietary regimen to increase the energy density of the diet in late lactation may provide a nutritional strategy to improve piglet growth to weaning. The objective of this study was to examine the effect of soya oil and salmon oil in sow lactation diets and increasing the energy density of the diet in late lactation on sow and piglet productivity to weaning as well as the fatty acid profile of milk, piglet blood and tissues at weaning. In this study crossbred (Large White × Landrace) multiparous sows (*n*=100) were randomly assigned to treatment beginning on day 105 of gestation until weaning. Dietary treatments were arranged as a 2 × 2 factorial experiment. The factors were: 1. Oil (soya or salmon oil) and 2. Dietary regimen Flat (14.5 MJ DE/kg diet offered until weaning) or Phased (14.5 MJ DE/kg diet offered until day 14 of lactation followed by a second diet containing 15.5 MJ DE/kg offered from day 15 until weaning). There was an oil * dietary regimen interaction on total n-3 fatty acids in colostrum and milk ($P<0.01$). Treatment had no effect on sow live-weight, back-fat depth or BCS to weaning ($P>0.05$). Sow feed intake (week 3), milk yield, litter gain and ADG from day 7-14 and day 21-28 of lactation were all increased when sows were offered diets containing salmon oil ($P<0.05$). There was also tendency for pre-weaning mortality rate to be reduced when sows were offered diets containing salmon oil ($P=0.06$). Offering sows a phased energy regimen in late lactation increased sow energy intake in week 3 and 4 of lactation and overall lactation energy intake (both $P<0.01$). However, overall lactation efficiency was not improved ($P>0.05$). Salmon oil inclusion increased the total proportion of n-3 fatty acids in colostrum, milk (both $P<0.001$), piglet plasma ($P<0.01$), adipose, liver and muscle (all $P<0.001$). Increasing sow dietary energy level in late lactation increased the total n-3 fatty acids in colostrum and milk ($P<0.001$), piglet adipose ($P<0.01$) and piglet muscle ($P<0.05$). However, piglet growth to weaning did not improve. Thus, a lactation diet containing soya oil and a flat feeding regimen with an energy level of 15.0 MJ DE/kg is appropriate for the modern sow and her progeny.

5.2 Introduction

As the global demand for pork continues to rise, increasing the number of piglets weaned per litter at a good weaning weight represents a key challenge. Piglet weight at weaning is a major determinant of post-weaning performance (Klindt, 2003). However, sow milk yield is a limiting factor for the growth of nursing piglets (Quesnel et al., 2015). The amount of milk needed for 1g of live-weight gain increases as lactation progresses with, Theil et al. (2002) reporting that 317, 531 and 582 g/day of milk was needed to maintain piglet live-weight in weeks 1, 2 and 3, respectively. Therefore, considerable energy is needed to support milk production. A digestible energy intake of 14.05 MJ DE/kg is recommended for lactating sows of >parity 2 with a litter size of 11.5 and a litter average daily gain (ADG) of 190-270 g/day (NRC, 2012). However, the EU average litter size is currently 13.8 piglets born alive (AHDB, 2017), therefore research into the nutritional requirements of modern prolific lactating sows is needed to better support the growth of piglets reared in these larger litters.

Increasing energy density in the lactation diet may better support the demands of the suckling litter whilst minimising catabolism of maternal body reserves. Park et al. (2008) found that a high energy diet (14.7 MJ/kg DE) in lactation reduced sow body weight and back-fat loss and increased piglet growth to weaning compared to a low energy diet (14.2 MJ/kg DE). Craig et al. (2017) also reported an increase in litter ADG when a high energy diet (15.8 MJ/kg DE) was offered compared to normal diet (15.2 MJ/kg DE). However, feed intake commonly levels off in late lactation due to limited gut capacity, therefore increasing the dietary energy density during this time could help improve sow energy intake in late lactation. Achieving this could increase milk production and subsequently piglet growth in late lactation.

Oils are commonly used in pig diets due to their high energy availability compared to cereals and currently 6.0 g/day of the omega-6 (n-6) fatty acid, linoleic acid (LA), is recommended for lactating sows (NRC, 2012). Oil inclusion in late gestation and during lactation has been found to influence the fatty acid composition of milk, increase the output of fat and energy in milk and improve piglet gain from birth to weaning (Lauridsen and Danielsen, 2004). Whilst soya oil is commonly used in pig diets and represents a rich source of n-6 fatty acids, fish oils, such as salmon oil contains a high level of n-3 fatty acids and have been found to reduced pre-weaning mortality and improve the growth of suckling pigs (Rooke et al., 2001a, Mateo et al., 2009). Although, the benefits of n-3 oil have been widely researched there are currently no recommended inclusion levels for omega- 3 (n-3) fatty acids in sow diets.

The objective of this study was to examine the effect of soya oil and salmon oil in sow lactation diets and increasing the energy density of the diet in late lactation on sows and piglet productivity to weaning as well as the fatty acid profile of milk, piglet blood and tissues at weaning. Piglet growth, transfer of fatty acids from feed to milk and to piglets as well as piglet immune status at weaning were investigated.

5.2.1 Hypotheses

- Salmon oil inclusion and increasing dietary energy level in late lactation through a phased feeding regimen will increase sow milk yield and the proportion of n-3 fatty acids transferred to piglets through the milk, which will increase piglet growth and IgG concentration in blood serum at weaning.
- Salmon oil inclusion in the lactation diet will increase piglet vigour at birth and survivability to weaning through increased piglet suckling duration and frequency in the first 24 hours after birth and increased proportion of n-3 fatty acids present in colostrum and milk.
- Piglets from sows offered diets containing salmon oil will have increased proportion of n-3 fatty acids in blood plasma and tissues collected at weaning.
- Salmon oil in the lactation diet will increase IgG concentration in piglet serum at weaning compared to soya oil.

- A phased feeding regimen with increased energy level in late lactation will minimise sow body fat and condition loss during lactation compared to a flat feed regimen.
- Increased sow energy intake in late lactation will increase sow milk yield and subsequently increase the growth of the suckling litter to weaning.

5.3 Materials and methods

This study was conducted at the Agri-Food and Bioscience Institute, Hillsborough, Co. Down, Northern Ireland, from May 2017 to January 2018. The study was carried out under the regulation of the Department of Health, Social Services and Public Safety (DHSSPS) of Northern Ireland in accordance with the Animals (Scientific Procedures) Act 1986 (The Parliament of the United Kingdom, 1986).

5.3.1 Animals

Multiparous sows, parities two to nine (*n*=100), with a mean parity 4.4 (SD=3.21) were blocked according to parity, body condition score and body weight prior to being randomly allocated to treatment on day 105 of gestation. Sows were PIC F_1 cross (Large White × Landrace) and Danish Duroc was the terminal sire used. For each batch of sows, artificial insemination was completed over a 3-day period. Each sow was inseminated twice over the 3 days period. There were 10 batches with approximately 10 sows per batch.

5.3.2 Gestation Feeding and Management

During the first 14 days of gestation, sows were kept in groups of four in free-access cubicles with a pen at the rear (space allowance 2.76 m^2). After day 14, sows were moved to a large dynamic group of approximately 80 sows, where there were fed using a Nedap electronic sow feeder (*Nedap Livestock Management, 7141 DC Groenlo, the Netherlands*) until day 105 of gestation. Sows were offered 2.5kg/day of the same barley-based diet (12.9 MJ DE/kg, 14.02 g/kg CP and 0.7 g/kg total Lys) from weaning to day 85 of gestation and then 3.0kg/day until they moved to the farrowing accommodation on day 105 of gestation.

5.3.3 Lactation Feeding and Management

Sows were moved to the farrowing accommodation on approximately day 105 of gestation and were housed in farrowing crates. There was an enclosed heated creep area for the piglets at the front of each crate. The temperature of both the farrowing room and piglet creep areas was set electronically, with the ambient temperature set at 19 °C for farrowing and thereafter reduced to 17.5 °C. The creep area was set at 30 °C and gradually reduced to 23 °C during the 7 days post farrowing. Sows were fed using wet and dry feeders and were offered 3 kg/day of their respective lactation diet until the day of farrowing, after which feed allowance was increased by 0.5 kg/day to appetite. Individual sow feed allowance was recorded, weighed and offered manually over 2 daily meals, with feed disappearance recorded as feed intake.

Sows were induced to farrow with 2 ml of Lutalyse (*Zoetis Service LLC, New Jersey, U.S.A*) on day 114 of gestation. Drying paper and 2 heat lamps were placed at the back of each sow at farrowing. For each sow, total born (TB), born alive (BA), born dead and mummified pigs were recorded. Within the first 12 hours of birth, piglets had their teeth clipped and tails docked. The tail and umbilical area was sprayed with iodine. Piglets were injected with 2 ml of an iron supplement (*Uniferon, Virbac Ltd., Suffolk, UK*) and given an ear tag to allow for individual identification throughout their lifetime. Cross-fostering was completed within 24 hours after farrowing and occurred within oil treatments, with litters standardised to approximately 14 piglets as far as possible. The weight and cause of all piglet mortalities were recorded. Piglets had free access to water from nipple drinkers and creep feed was not offered with sow troughs high enough to deter piglets from consuming any sow feed. Piglets were weaned at approximately day 28. Sow weaning to service interval (WSI) was recorded. All sows were wormed 1-week post farrowing with a Doramectin pour on solution (*Elanco, Priestly Road, Basingstoke, UK*) and between the months of October to February, sows were vaccinated in the second week of lactation against swine erysipelas and porcine parvovirus (*Porcilis Ery & Parvo, MSD Animal Health, Milton Keynes, UK*). All sows were vaccinated at day 70 of gestation for swine erysipelas (*Porcilis Ery, MSD Animal Health, Milton Keynes, UK*).

5.3.4 Dietary Treatments

Dietary treatments commenced on day 105 of gestation, on entry to the farrowing crate. Dietary treatments were provided in a 2 × 2 factorial arrangement (Table 5.1). The factors were: 1. Oil (soya or salmon oil *[Rossyew, Ltd, Greenock, Scotland, United Kingdom]* and 2. Dietary regimen

Flat (14.5 MJ/kg DE, 17.0 g/kg CP, 1.2 g/kg Lys, diet offered for 28 days of lactation) or Phased (14.5 MJ/kg DE diet offered until day 14 of lactation and an immediate change to a second diet containing 15.5 MJ/kg DE, 17.0 g/kg CP, 1.3 g/kg Lys, offered from day 15 to day 28 of lactation). The feed was manufactured on site at the Agri-food and Bioscience Institute, Hillsborough (Northern Ireland) and diets were offered in meal form.

5.3.5 Measurements

5.3.5.1 Sow measures

Sows were weighed on day 105 of gestation and at weaning. Back-fat depth and body condition score (BCS) were measured on day 105, 110 and 114 of gestation and on day 1, 7, 14, 21 and 28 of lactation. Back-fat depth was measured at the P_2 position (65 mm from the midline at the level of the last rib) with an ultrasonic back-fat scanner *(Pig Scan-A-Mode back-fat scanner, SFK Technology, Herlev, Denmark)*. BCS was scored using a 5-point scale and half scores were also used, with a score of 1 being the sows were visually thin; hips and back bone very prominent and a score of 5 being the sows were fat; it was impossible to feel hipbones and backbone. Sow empty body weight was calculated using the formula: sow empty weight (kg) = sow weight pre-farrowing, day 105 (kg) – (total number of piglets born × 2.28) (NRC, 1998). Sow lactation efficiency was calculated by dividing sow energy input during lactation by total litter gain (kg), where energy input was calculated by adding the total energy intake from feed during lactation to the energy gained from weight lost during lactation (assuming every 1 kg loss=12.5 MJ DE) (Close and Cole, 2000).

Sow eye, udder and rectal temperature were recorded on day 105, 110 and 114 of gestation and day 1 of lactation. Rectal temperature was recorded using a digital thermometer (*Sure Sign digital thermometer, CIGA Healthcare Ltd., Ballymena, UK*). Sow eye and udder temperature were recorded using an Infrared (IR) thermal camera *(FLIR T650sc, FLIR Systems UK, West Malling, Kent, UK)*, with emissivity set to 0.95. The camera was held approximately 40 cm from the right eye and a 20 second video was recorded. When measuring udder temperature all piglets were separated from the sows in the creep area, and when the sow was standing, the camera was held approximately 40 cm from the udder and a 60 second video was taken from the top (nearest the sows' front legs) to bottom of the udder. Videos were analysed using FLIR Tools (version 4.1), which allowed for temperature measurements of the whole image or part of the image defined by shapes or free drawing tools. For each sow a still image of the open eye was analysed using an elliptical shaped tool, with minimum, maximum and average temperatures recorded. For each sow a still image of the second, fourth and sixth teat along the udder were analysed using the elliptical shaped tool, with minimum, maximum and average temperatures recorded. Colostrum samples (*n=20*/treatment) were obtained within 4 hours after farrowing had commenced and milk samples were collected on day 14 and 21 of lactation. To collect milk samples, piglets were prevented from suckling 1 hour prior to collection and 1 ml of oxytocin was administered intramuscularly in the sows' neck. Approximately 80 ml of milk was obtained by hand from all mammary glands and stored at -20 °C pending analysis. Sow milk yield was calculated as piglet gain × 4.2 (Van der Peet-Schwering et al., 1998).

Table 5. 1. Ingredients formulated and actual analysis of experimental diets on a fresh basis (%)

	Soya oil		Salmon oil	
	Flat[1]	Phased[2]	Flat[1]	Phased[2]
Ingredient (%)				
Wheat	28.2	30.0	28.2	30.0
Maize	40.0	33.8	40.0	33.8
Soya	16.7	16.6	16.7	16.6
Full fat soya	10.0	10.0	10.0	10.0
Soya oil	1.79	5.98	-	-
Salmon oil	-	-	1.79	5.98
Lysine	0.12	0.27	0.12	0.27
Threonine	0.0	0.08	0.0	0.08
Methionine	0.0	0.06	0.0	0.06
Mineral and Vitamin premix[3]	3.2	3.2	3.2	3.2
Formulated				
Dry matter (%)	84.8	85.4	84.8	85.4
CP (%)	17.0	17.0	17.0	17.0
CF (%)	2.88	2.80	2.88	2.80
Oil A (%)	5.67	9.62	5.67	9.62
DE (MJ/kg)	14.5	15.5	14.5	15.5
Total Lysine (%)	1.20	1.30	1.20	1.30
Total Threonine (%)	0.77	0.83	0.77	0.83
Total Methionine (%)	0.35	0.41	0.35	0.41
Total Tryptophan (%)	0.20	0.20	0.20	0.20
Ash (%)	5.00	5.00	5.00	5.00
Calcium (%)	0.67	0.67	0.67	0.67
Phosphorus (%)	0.55	0.54	0.55	0.54
Actual				
Dry matter (%)	87.3	88.1	87.4	88.3
CP (%)	17.7	17.9	18.0	17.4
CF (%)	2.20	1.95	2.10	1.90
Oil A (%)	5.54	9.56	5.52	10.2
DE (MJ/kg)	15.0	15.9	15.0	15.9
Total Lysine (%)	1.19	1.33	1.23	1.29
Total Threonine (%)	0.74	0.81	0.72	0.79
Total Methionine (%)	0.32	0.38	0.31	0.38
Total Tryptophan (%)	0.17	0.19	0.19	0.18
Ash (%)	4.75	4.80	4.85	5.00
Calcium (%)	0.68	0.73	0.68	0.79
Phosphorus (%)	0.49	0.46	0.46	0.45

[1] 14.5 MJ/kg DE diet offered for 28 d of lactation

[2] 15.5 MJ/kg DE diet offered from d15 to 28 of lactation

[3] Premix provided (per tonne of finished feed) 8.0 MIU vitamin A, 2.0 MIU Vitamin D_3 750.0 gm Methionine, 1250.0 gm Threonine, 2800.0 gm Lysine, 1.0 gm Iodine from Calcium Iodate, 0.2 gm Selenium from Sodium selenite, 80.0 gm Iron from Ferrous Sulphate, 30.0 gm Manganese from Manganous Oxide, 12.0 gm Copper from Cupric Sulphate, 80.0 gm Zinc from Zinc Oxide, 125.0 gm Antioxidant from BHA/BHT. Sourced from Devenish Nutrition Ltd., Belfast, UK.

5.3.5.2 Litter and piglet measures

The first 48 hours of each farrowing was recorded to allow for litter suckling duration and frequency to be analysed. Videos were analysed for the first 24 hours after farrowing was complete, which in this study was defined as after the expulsion of the placenta. The duration of each suckling bout and the frequency were recorded. A suckling bout was defined as more than 60 % of the litter actively suckling and a bout was finished when more than 60 % of the piglets were no longer suckling or if the sow terminated suckling by rolling onto the udder or standing up. All piglets were individually weighed at birth, day 1, 5, 7, 14, 21 and 28 of lactation. Litter and piglet mean weight, ADG and within litter coefficient of variation (CV) of weight were calculated. A sub sample (*n=10*/treatment) of piglets were used for dissection. One piglet of mean weaning weight per litter, balanced for sex was selected for dissection on day 28 of lactation. Blood samples were obtained by jugular vein puncture into evacuated tubes, one containing silicone coating and one with lithium heparin coating (170 IU). Serum and plasma samples were prepared from the blood samples by centrifugation at 2500 G force for 15 mins (*Mistral 3000E centrifuge, MSE, Lower Sydenham, UK*), with samples stored at -20 °C pending analysis. At weaning selected piglets were euthanised by an injection of pentobarbital sodium (*Dolethal, Vetoquinol UK Ltd, Buckinghamshire, UK*). Once euthanised piglets were individually scanned using a Dual Emission X-Ray Absorptiometry (DXA) scanner (*Stratos DR Bone Densitometer, DMS, Mauguio, France*) whole body scan to determine body and bone composition i.e. total fat mass, total lean mass, bone mineral content and density. Each piglet was then dissected, and the liver removed, and weight recorded.

Samples were macerated, vacuum packed and stored at -20 °C pending analysis. A 10 cm^2 P_2 muscle sample from the right side of the piglet was also removed. The skin layer was removed and discarded. The subcutaneous fat layer was removed, and both the fat and muscle sample weights were recorded before samples were macerated, vacuum packed and stored at -20 °C pending analysis.

5.3.6 Fatty acid methyl esters (FAMEs) analysis

Plasma, colostrum, milk, liver, muscle and fat samples stored at -20 °C were analysed for Fatty acid methyl esters (FAMEs). Plasma, colostrum and milk samples were prepared using a rapid method total lipid extraction as per the method of Bligh and Dyer (1959). Liver, muscle and fat samples were prepared as per the method of O’fallon et al. (2007). Methylated samples were stored at -20 °C until they were analysed on the Gas Chromatograph (GC). The methylated extract (1 µl injection) were analysed on an Agilent 6890 GC with FID, a 7683 series injector and autosampler, with a CP-Sil 88 100 m 0.25 diameter column (*Agilent, Cheadle, UK*). Data acquisition was carried out using Openlab software (*Agilent*).

5.3.7 Quantification of Immunoglobulin G

Serum concentration of immunoglobulin G (IgG) was assayed using specific pig-ELISA kits *(Bethyl Laboratories Inc., Universal Biologicals, Cambridge, UK)*. The IgG was quantified according to the manufacturer’s instructions.

5.3.8 Statistical analysis

Sow, litter and piglet variables recorded until day 14 of lactation and colostrum and day 14 milk samples were analysed for the effect of oil treatment only. Sow, litter and piglet performance variables from day 15 until weaning as well as the fatty acid profile of day 21 milk samples, piglet blood plasma and tissues collected at weaning were analysed as per the 2 × 2 experimental arrangement, for the interactive effect between oil type and energy level as well as the direct effects of oil and energy. All continuous response variables and repeated measures were modelled using linear mixed model methodology (REML). Binary and count variables were modelled using generalized linear mixed model methodology (GLM) with a binomial distribution and logit link function for the binary variables and a Poisson distribution and logarithm link function for the count variables. In all analyses, parity and treatment were included as fixed effects, while day was included as an additional fixed effect where applicable. In the analysis of sow, litter and temperature variables and piglet blood and tissue fatty acids, batch was included as a random effect in the model. When analysing piglet weight and weight gain to weaning, batch and nursing sow nested within batch were included as random effects in the model, while batch and day nested within nursing sow were random effects in the model when analysing the proportion of fatty acids in colostrum and milk. When analysing sow body condition and weight, sow body temperatures and litter weight and gain as repeated measures, batch and day were included as random effects in the model. When analysing piglet weight and weight gain to weaning as repeated measures the random effects in the model were batch, sow nested within batch and day nested within sow. For each response variable additional explanatory variables were fitted as fixed effects. A backwards elimination procedure was applied to these additional fixed effects for each response variable so that only variables that were significant at the (P<0.05) level remained in the final model in each case. All models were fitted using residual maximum Likelihood in the statistical software package GenStat (*18th edition, VSN Internal Ltd, Hemel Hampstead, UK*). If differences detected were significant, comparisons between groups were conducted with the fisher's least significant difference test.

5.4 Results

5.4.1 Diet composition

While the actual analysis of diets revealed that DE and CP levels were higher than formulated, they were broadly in line with the target differences between treatments (Table 5.1). The fatty acid composition (C4:0 to C22:6c) of diets were analysed, with mean fatty acid values above 1.0 g/100 g total fatty acids reported (Table 5.2). With regards to oil type, diets containing salmon oil had more saturated MUFA and n-3 fatty acids and lower proportions of PUFA, n-6 fatty acids and n-6:n3 fatty acid ratio than diets containing soya oil. Furthermore, the changes were proportional to salmon oil inclusion in the diet i.e. 9.6 % inclusion in the higher energy diet (15.5 MJ DE/kg) compared with 5.7 % inclusion in the diet lower energy diet (14.5 MJ DE/kg). The concentration of fatty acid in diets containing soya oil were similar irrespective of inclusion level of soya oil. Fatty acids below the detection limit (1.0 g/100g total fatty acids) are not reported but were represented in total saturated MUFA, PUFA, n-3 and n-6 calculations, and contributed approximately 2.0 %

to the fatty acid content in diets containing soya oil and between 4.0-5.0 % of the fatty acid content in diets containing salmon oil.

Table 5. 2. Fatty acid composition (g/100g total fatty acids) of experimental diets fed during gestation.

	Soya oil		Salmon oil	
Fatty acids[1]	Flat[2]	Phased[3]	Flat[2]	Phased[3]
C14:0	0.11	0.08	0.71	1.44
C16:0	12.0	11.4	11.9	11.0
C16:1c	0.17	0.13	0.74	1.44
C18:0	3.16	3.38	2.82	2.70
C18:1c9	22.2	23.0	26.6	31.5
C18:1c11	1.30	1.36	1.68	2.27
C18:2c	53.7	53.0	44.4	33.5
C20:1c	<1.00	<1.00	1.31	2.49
C18:3cn3	5.60	6.03	5.43	5.45
C24:0	<1.00	<1.00	<1.00	1.81
C22:6c	<1.00	<1.00	1.11	2.38
Total:				
Saturated[4]	16.4	16.0	17.3	17.9
MUFA[5]	24.1	24.8	30.7	38.5
PUFA[6]	53.8	53.2	46.4	37.8
n-3[7]	5.71	6.11	7.00	8.78
n-6[8]	53.7	53.1	44.9	34.6
n-6:n-3[9]	9.41	8.69	6.42	3.94

[1] Fatty acids are reported as g/100g of total fatty acids with a reporting limit of 1.0 g/100g. Values presented are mean percentages of total lipid fraction from 2 determinations extracted from bulked samples of diet.

[2] 14.5 MJ/kg DE diet

[3] 15.5 MJ/kg DE diet

[4] Saturated- saturated fatty acids

[5] MUFA- monounsaturated fatty acids

[6] PUFA- polyunsaturated fatty acids

[7] n-6- omega 6 fatty acids

[8] n-3- omega 3 fatty acids

[9] n-6:n-3 ratio-omega 6 fatty acid: omega 3 fatty acid ratio

5.4.2 Sow characteristics

Since the phased energy regimen was not effective until day 15 of lactation, its impact is reported from day 15 only. There was no interaction between dietary oil type and energy regimen and no direct effects of oil type or energy regimen on sow back-fat depth or BCS from day 21 to weaning ($P<0.05$). Over the duration of the experiment sow back-fat depth or BCS were not affected by oil type ($P>0.05$) but were influenced by day ($P<0.001$). Sow back-fat depth increased in late gestation from 21.2 mm on day 105 to 21.5 mm on day 114 and decreased during lactation by 3.2 mm from 21.1 mm on day 1 of lactation to 17.9 mm at weaning. Sow BCS decreased from day 105 of gestation until weaning, with BCS on day 14 and 21 of lactation significantly lower than BCS from day 105 to day 7 of lactation ($P<0.05$) but not from BCS at weaning ($P>0.05$). Sow live-weight was not influenced by sow dietary treatment, with sows weighing on 270.1 kg (SEM= 2.75 kg) on day 105 of gestation and 254.1 kg (SEM=2.23 kg) at weaning.

There was no interactive effect between oil type and energy regimen on overall sow lactation feed intake ($P>0.05$). Sow feed intake in week 1 and 2 of lactation was not influenced by dietary oil type ($P>0.05$), but sows offered a diet containing salmon oil ate on average 3.5 kg more feed in the third week of lactation compared to sows offered a diet containing soya oil ($P<0.05$) (Table 5.3). Feed intake in the last week of lactation was unaffected by dietary oil treatment ($P>0.05$). Dietary energy regimen did not affect sow feed intake during week 3 and 4 of lactation ($P>0.05$), however, feeding a diet with higher energy level from day 15 of lactation to weaning increased sow energy intake in this period ($P<0.01$) as well as overall lactation energy intake ($P<0.01$).

Despite this sow lactation efficiency was not improved (P>0.05). Sow live weight at weaning and weaning to service interval were not affected by dietary treatment (P>0.05).

Table 5. 3. The effect of oil type in sow lactation diets and energy regimen in late lactation on sow lactation feed intake (kg) and lactation energy intake (MJ DE).

	Oil type				Energy regimen			
Variable	Soya	Salmon	SEM[1]	*P-value*	Flat[2]	Phased[3]	SEM	*P-value*
Feed intake, kg								
Week 1	30.23	29.53	0.700	0.482	-	-	-	-
Week 2	49.76	50.07	0.916	0.813	-	-	-	-
Week 3	58.07	61.55	1.226	0.048	59.29	60.33	1.220	0.552
Week 4	61.94	64.31	2.133	0.435	61.23	65.01	2.131	0.226
d1-14	80.01	79.58	1.376	0.829	-	-	-	-
d15-28	119.9	125.6	2.919	0.172	120.3	125.1	2.911	0.256
d1-28	200.0	205.3	3.634	0.315	199.1	206.2	3.622	0.170
Energy intake, MJ DE								
d1-14	1160	1154	19.955	0.829	-	-	-	-
d15-28	1798	1886	43.59	0.161	1745	1940	43.48	0.002
d1-28	2961	3042	53.89	0.300	2887	3115	53.71	0.004

[1] SEM- standard error of the mean

[2] 14.5 MJ/kg DE diet offered for 28 d of lactation

[3] 14.5 MJ DE/kg diet offered from day 1 to 14 of lactation and 15.5 MJ/kg DE diet offered from day 15 to 28 of lactation

There was no interactive effect between oil type and energy regimen on sow milk yield (P>0.05). Sows offered diets containing salmon oil produced on average 1.15 and 1.73 L/day more milk from day 7 to 14 and day 21 to 28 of lactation, respectively, than sows offered lactation diets containing soya oil (P<0.05). There was no effect of energy regimen on sow milk yield in late lactation (P>0.05). Independent of dietary treatment, sow milk yield was affected by day of lactation (P<0.001; Figure 5.1). Milk yield significantly decreased on day 5 (P<0.05) of lactation but increased again on day 7 of lactation. Milk yield peaked at day 14 and plateaued to day 28 of lactation (P>0.05).

Sows offered the diet containing soya oil had higher rectal temperature than sows offered the salmon oil diet (37.9 and 37.8 °C, respectively) (P<0.05). Sow eye and udder temperatures were not influenced by dietary oil type (P>0.05). Independent of dietary treatment, day of sampling influenced sow body temperature (P<0.001; Figure 5.2). Sow rectal temperature was highest on day 1 of lactation (P<0.05) and sow rectal temperature on day 110 and 114 were higher than day 105 of gestation (P<0.05). Sow eye temperature recorded on day 105 and 110 of gestation were similar (P>0.05). Sow eye temperature was lowest at 33.5 °C on day 114 of gestation but increased by 2.3 °C to 35.8 °C on day 1 of lactation. Average udder temperatures recorded on day 105, 110, 114 of gestation and day 1 of lactation were significantly different from each other (P<0.05) with udder temperature decreasing by 1.3 °C from 34.9 °C on day 105 to 33.6 °C on day 114 of gestation and increasing by 3.6 °C from day 114 of gestation to 37.2 °C on day of 1 lactation.

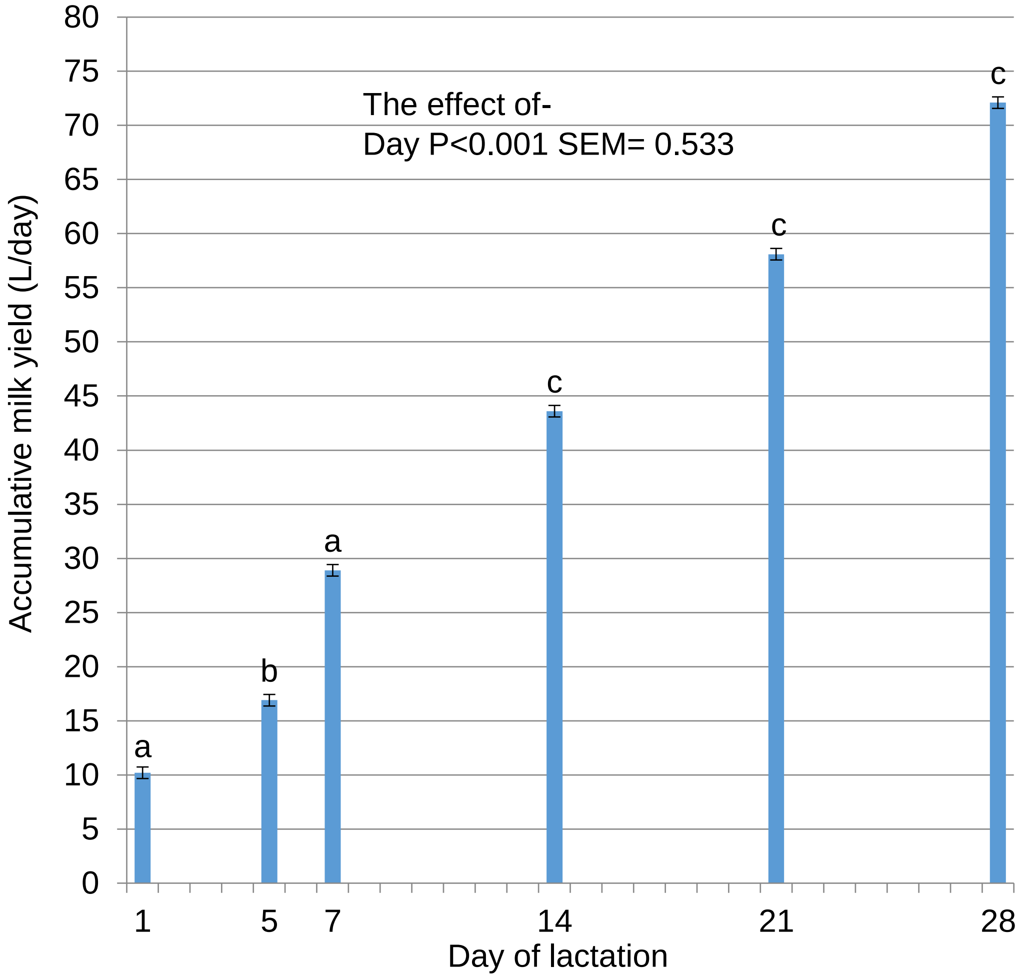

Figure 5. 1. Accumulative sow milk yield over a 28-day lactation.
$^{a, b, c}$ Means with different superscripts are different (P<0.05)

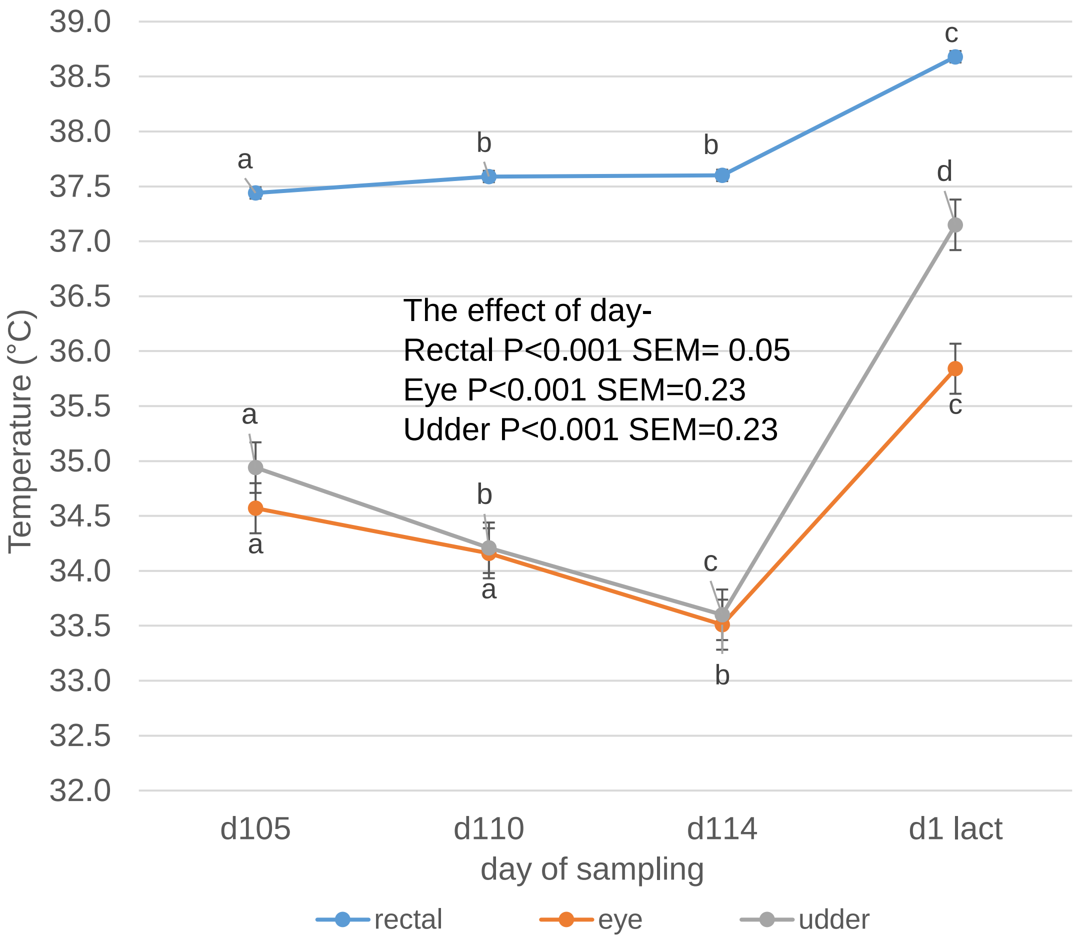

Figure 5. 2. The effect of day of sampling (day 105, 110 and 114 of gestation and day 1 of lactation) on average sow rectal, eye and average udder temperature (°C).

$^{a, b, c, d}$ Means with different superscripts within variable are different ($P<0.05$)

5.4.3 Litter performance

There was no interaction between oil type and energy regimen for any litter performance measures (P>0.05). There was no effect of oil type on total born, born alive, number of piglets stillborn (P>0.05). Mean total born and born alive were 15.7 (SEM=0.32) and 14.1 (SEM=0.33), respectively. As litters were standardised to 14 piglets within 24 hours, the mean litter size after fostering was 13.8 (SEM=0.16). Sows offered a diet containing salmon oil had a reduced pre-weaning mortality rate compared to sows offered a diet containing soya oil (9.87 vs. 13.35 %, respectively) (P=0.06). The average number of piglets weaned per litter was 12.2 (SEM=0.16) and pre-weaning mortality rate was 11.2 % (SEM=1.07). Mean total litter live-weight at birth was 19.6 kg (SEM=0.47) and total litter weaning weight averaged 104 kg (SEM=1.81). Litters from sows offered diets containing salmon oil during lactation had increased litter weight gain from day 7 to 14 (0.5 kg/day; P<0.01) and day 21 to 28 of lactation (0.4 kg/day; P<0.05) (Table 5.4), compared to litters from sows offered diets containing soya oil. The co-efficient of variation in litter weight from birth to weaning was not influenced by sow dietary treatment (P>0.05). Litter suckling duration and frequency in the first 24 hours post-farrowing did not differ between dietary oil types (P>0.05). Energy regimen did not influence litter performance to weaning (P>0.05; Table 5.4). As expected, day had a significant effect on litter growth to weaning (P<0.001). Litter live-weight was not significantly different between birth and day 1 (P>0.05) but thereafter litter live-weight increased significantly as lactation progressed (P<0.001). Similarly litter average daily gain increased throughout lactation

(P<0.001), while variation in litter weight decreased as lactation progressed from 22.4 % at birth to 17.5 % at weaning (P<0.001).

Table 5. 4. The effect of oil type in sow lactation diets and energy regimen in late lactation on litter weight (kg) and litter average daily gain (ADG) (kg/day) from birth to weaning.

	Oil type				Energy regimen			
Variable	Soya	Salmon	SEM[1]	*P-value*	Flat[2]	Phased[3]	SEM	*P-value*
Litter weight, kg								
Birth	20.89	21.65	0.425	0.209	-	-	-	-
Live-born	19.18	20.03	0.542	0.269	-	-	-	-
d1	19.53	20.44	0.484	0.19	-	-	-	-
d14	54.72	57.51	1.442	0.174	-	-	-	-
d21	78.76	82.06	1.989	0.244	79.16	81.36	1.989	0.518
d28	102.5	105.5	1.884	0.275	102.4	105.5	1.867	0.254
Litter ADG, kg/day								
Week 1	1.74	1.49	0.162	0.278	-	-	-	-
Week 2	3.33	3.81	0.116	0.004	-	-	-	-
Week 3	3.41	3.53	0.120	0.493	3.40	3.55	0.120	0.380
Week 4	3.15	3.56	0.128	0.024	3.28	3.44	0.127	0.372
d1-28	2.94	3.03	0.061	0.301	2.94	3.02	0.060	0.387

[1] SEM- standard error of the mean

[2] 14.5 MJ/kg DE diet offered for 28 d of lactation

[3] 14.5 MJ DE/kg diet offered from day 1 to 14 of lactation and 15.5 MJ/kg DE diet offered from day 15 to 28 of lactation

5.4.4 Piglet growth to weaning

In the current study, a total of 1145 piglets were used to evaluate growth performance to weaning. There was no interaction between oil type and energy regimen on piglet live-weight or weight gain from day 14 to weaning (P>0.05). Dietary oil type offered to sows did not influence piglet weight during the suckling period. Mean piglet birth weight was 1.35 kg (SEM= 0.010) and average piglet weight at weaning was 8.5 kg (SEM=0.052). Piglet ADG from day 5 to 7 (P<0.001) was greatest for piglets from sows offered diets containing soya oil, with piglets gaining on average 80 g/day more compared to piglets from sows offered diets containing salmon. However, piglet ADG at any other time point and overall piglet gain from birth to weaning where unaffected by dietary oil type (P>0.05). There was no effect of energy regimen on piglet growth performance to weaning (P>0.05).

When analysed as repeated measures, there was no interaction between oil type and energy regimen on piglet growth in late lactation to weaning (P>0.05). There was a significant interaction between oil type and day of lactation on piglet ADG from birth to weaning (P<0.001; Figure 5.3). Irrespective of maternal dietary treatment, piglet weight increased from birth to weaning (P<0.001) and piglet ADG increased until day 14 and plateaued until weaning (P<0.001).

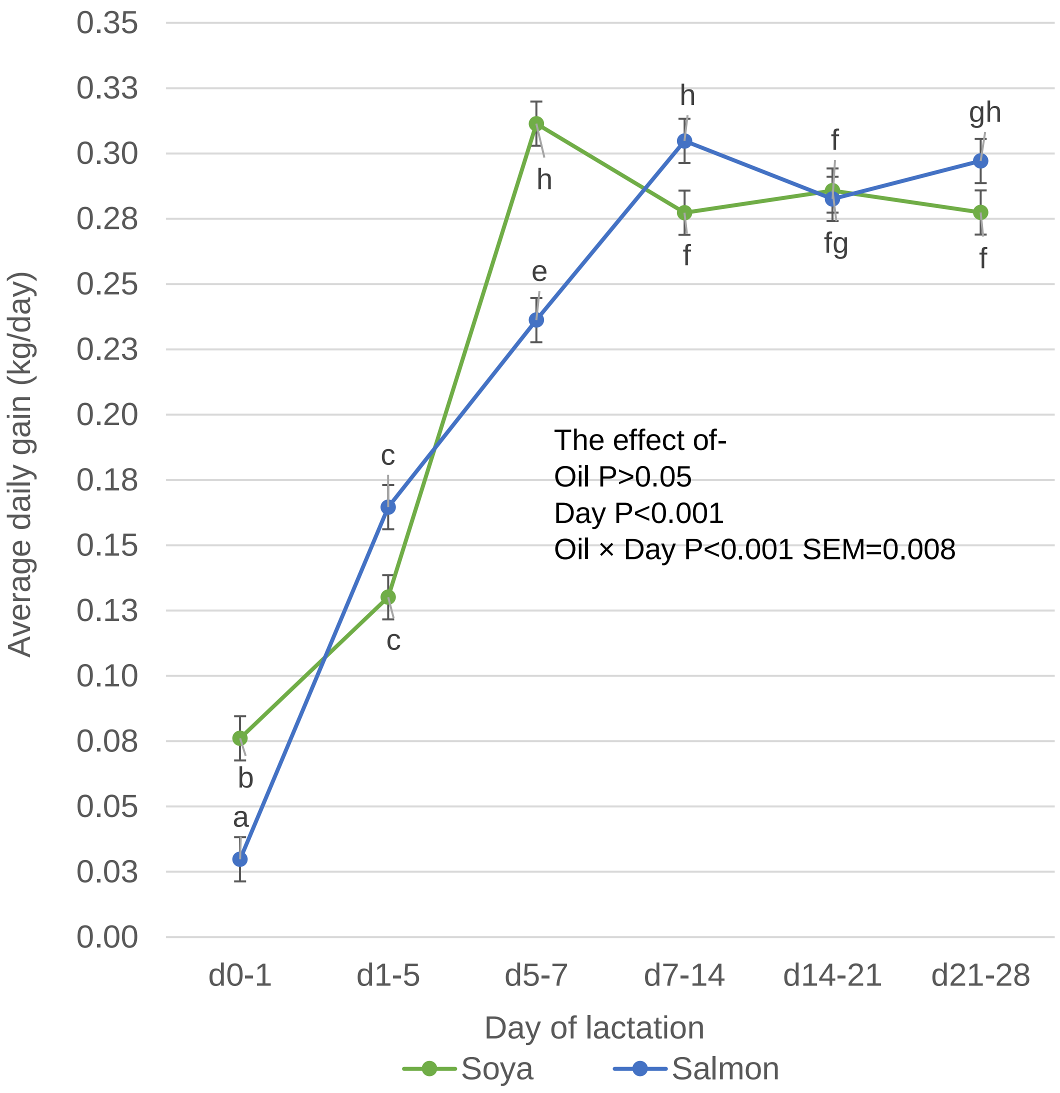

Figure 5. 3. The interactive effect of oil type and day on piglet average daily gain (ADG) (kg/day) from birth (day 0) to weaning (day 28).
^{a,b,c,d,e,f,g,h} Means with different superscripts are different ($P<0.05$)

5.4.5 Colostrum and milk FAMEs

There was a significant interaction between oil type and energy regimen in late lactation on the fatty acid profile of milk collected on day 21 of lactation ($P<0.05$) (Table 5.5). Offering sows a diet containing salmon oil and the phased energy regimen increased the proportions of C18:t, C20:1c, ($P<0.001$), C22:1c ($P<0.001$), C20:3c11 ($P<0.01$), C22:2c ($P<0.01$), C20:5c, C24:1c, C22:5cn3 and C22:6c (all $P<0.001$), and decreased proportions of C18:2c ($P<0.001$) compared to all other treatment groups. No significant difference was observed between sows offered soya oil diets regardless of energy regimen ($P>0.05$). Therefore offering sows the salmon oil and the phased energy regimen significantly increased the proportion of n-3 fatty acids ($P<0.001$) and decreased the ratio of n6:n3 ($P<0.001$), whereas the proportion of total PUFA ($P<0.001$) and n-6 fatty acids was greatest in milk at day 21 from sows offered soya oil and the phased energy regimen. There was no interaction between oil type and energy regimen for the proportion of saturated and MUFA in sows' milk at day 21 ($P>0.05$).

As expected, there was a significant interaction between dietary oil type and day of sampling on the fatty acid composition of colostrum and milk at day 14 and day 21. (Table 5.6). Although the total proportion of saturated and MUFA were unaffected by sow lactation dietary treatment and day ($P>0.05$), the proportion of total PUFA ($P<0.05$) and n-6 fatty acids ($P<0.001$) were highest in colostrum (day 0) samples of sows offered diets containing soya oil. Offering sows a diet containing salmon oil significantly increased the proportion of n-3 fatty acids ($P<0.01$) in colostrum (day 0), but the ratio of n6:n3 fatty acids ($P<0.001$) was lowest in day 21 samples.

Table 5. 5. Fatty acid composition (g/100g total fatty acids) of sow milk samples collected on day 21 of lactation after offering sows diets containing soya or salmon oil and a flat or phased dietary regimen.

	Soya oil		Salmon oil			Oil	Energy	Oil × Energy
Fatty acid[1]	Flat[2]	Phased[3]	Flat	Phased	SEM[4]	*P-value*	*P-value*	*P-value*
C4:0	0.03	0.03	0.03	0.03	0.002	0.527	0.742	0.939
C6:0	0.03	0.03	0.03	0.03	0.002	0.627	0.463	0.867
C8:0	0.04	0.03	0.04	0.04	0.002	0.006	0.169	0.567
C10:0	0.20	0.19	0.26	0.23	0.013	<0.001	0.083	0.606
C12:0	0.27	0.23	0.31	0.29	0.011	<0.001	0.016	0.325
C14:0	3.28^{b}	2.86^{a}	3.83^{c}	3.96^{c}	0.117	<0.001	0.241	0.024
C14:1c	0.20	0.16	0.25	0.23	0.015	<0.001	0.026	0.340
C15:0	0.09	0.09	0.11	0.12	0.006	<0.001	0.960	0.451
C16:0	31.5	29.8	33.5	30.9	0.868	0.092	0.017	0.609
C16:1c	8.09	6.55	9.34	7.98	0.419	0.002	0.001	0.828
C17:0	0.20	0.19	0.21	0.19	0.012	0.462	0.160	0.951
C18:0	4.49	4.45	4.07	3.79	0.164	0.002	0.335	0.449
C18:1t	0.15^{b}	0.12^{a}	0.18^{c}	0.29^{d}	0.009	<0.001	<0.001	<0.001
C18:1c9	27.3	25.7	26.0	26.5	1.015	0.755	0.595	0.292
C18:1c11	1.80	1.58	1.76	1.83	0.087	0.237	0.421	0.113
C18:2c	18.4^{b}	23.4^{c}	15.5^{a}	16.3^{a}	0.534	<0.001	<0.001	<0.001
C20:0	0.11	0.12	0.11	0.11	0.003	0.052	0.235	0.330
C18:3cn6	0.09	0.09	0.08	0.07	0.009	0.040	0.974	0.751
C20:1c	0.29^{a}	0.26^{a}	0.39^{b}	0.72^{c}	0.028	<0.001	<0.001	<0.001
C18:3cn3	1.83	2.45	1.75	2.43	0.075	0.490	<0.001	0.713
C21:0	0.02	0.02	0.02	0.02	0.001	0.856	0.235	0.142
C20:2c	0.38	0.37	0.37	0.48	0.029	0.110	0.090	0.060
C22:0	0.04	0.05	0.04	0.05	0.002	0.470	0.080	0.283
C20:3c8	0.09	0.09	0.10	0.11	0.005	0.060	0.353	0.334
C22:1c	0.06^{a}	0.05^{a}	0.09^{b}	0.17^{c}	0.004	<0.001	<0.001	<0.001

C20:3c11	0.12^{a}	0.12^{a}	0.13^{a}	0.18^{b}	0.009	<0.001	0.003	0.003
C20:4c5	0.36	0.35	0.32	0.28	0.012	<0.001	0.066	0.391
C22:2c	0.04^{a}	0.04^{a}	0.05^{b}	0.06^{c}	0.002	<0.001	<0.001	0.001
C24:0	0.07	0.08	0.07	0.04	0.015	0.140	0.666	0.147
C20:5c	0.05^{a}	0.06^{a}	0.25^{b}	0.70^{c}	0.021	<0.001	<0.001	<0.001
C24:1c	0.03^{a}	0.04^{a}	0.08^{b}	0.12^{c}	0.004	<0.001	<0.001	<0.001
C22:5cn3	0.18^{a}	0.21^{a}	0.34^{b}	0.66^{c}	0.024	<0.001	<0.001	<0.001
C22:6c	0.07^{a}	0.09^{a}	0.42^{b}	1.10^{c}	0.040	<0.001	<0.001	<0.001
Total:								
Saturated[5]	40.4	38.2	42.6	39.8	0.926	0.045	0.009	0.713
MUFA[6]	37.7	34.4	37.8	37.3	0.873	0.088	0.038	0.099
PUFA[7]	21.6^{b}	27.3^{c}	19.3^{a}	22.4^{b}	0.609	<0.001	<0.001	0.038
n-3[8]	2.26^{a}	2.93^{b}	2.89^{b}	5.07^{c}	0.128	<0.001	<0.001	<0.001
n-6[9]	19.4^{b}	24.4^{c}	16.4^{a}	17.3^{a}	0.540	<0.001	<0.001	<0.001
n6:n3[10]	8.65^{c}	8.30^{c}	5.72^{b}	3.45^{a}	0.158	<0.001	<0.001	<0.001

---

[1] Milk fatty acids are reported as g/100g of total fatty acids with a reporting limit of 0.01 g/100g.

[2] 14.5 MJ/kg DE diet offered for 28 d of lactation

[3] 14.5 MJ DE/kg diet offered from day 1 to 14 of lactation and 15.5 MJ/kg DE diet offered from day 15 to 28 of lactation

[4] SEM- standard error of the mean

[5] Saturated- saturated fatty acids

[6] MUFA- monounsaturated fatty acids

[7] PUFA- polyunsaturated fatty acids

[8] n-6- omega 6 fatty acids

[9] n-3- omega 3 fatty acids

[10] n-6:n-3-omega 6 fatty acid: omega 3 fatty acid ratio

[a,b,c,d] Means with different superscripts within a row are different ($P<0.05$)

Table 5. 6. The effect of sow dietary oil type and day of sampling on the fatty acid composition (g/100g total fatty acids) of sow colostrum (d0), day 14 and 21 (d14, d21) milk samples

	Soya oil			Salmon oil				Oil	Day	Oil × Day
Fatty acid[1]	d0[2]	d14[2]	d21[2]	d0	d14	d21	SEM[3]	*P-value*	*P-value*	*P-value*
C4:0	-	0.03	0.03	-	0.02	0.03	0.001	0.343	<0.001	0.156
C6:0	-	0.03	0.03	-	0.03	0.03	0.001	0.243	<0.001	0.102
C8:0	0.00^{a}	0.04^{bc}	0.04^{b}	0.00^{a}	0.04^{b}	0.04^{c}	0.001	0.818	<0.001	0.034
C10:0	0.00^{a}	0.22^{c}	0.20^{b}	0.00^{a}	0.23^{c}	0.25^{c}	0.008	0.474	<0.001	0.004
C12:0	0.03^{a}	0.27^{c}	0.25^{b}	0.04^{a}	0.28^{c}	0.30^{d}	0.008	0.124	<0.001	0.002
C13:0	0.01	0.01	0.01	0.02	0.01	0.01	0.001	<0.001	0.017	0.332
C14:0	1.35^{a}	3.33^{d}	3.09^{c}	1.56^{b}	3.56^{d}	3.88^{e}	0.081	<0.001	<0.001	<0.001
C14:1c	0.02^{a}	0.20^{bc}	0.18^{b}	0.02^{a}	0.21^{cd}	0.24^{d}	0.009	0.023	<0.001	0.007
C15:0	0.13^{c}	0.09^{a}	0.09^{a}	0.15^{d}	0.10^{a}	0.12^{b}	0.004	<0.001	<0.001	0.007
C16:0	19.6	32.5	30.7	20.0	31.6	32.1	0.496	0.176	<0.001	0.150
C16:1c	1.98	8.40	7.36	2.24	8.63	8.62	0.267	0.01	<0.001	0.124
C17:0	0.29	0.18	0.19	0.30	0.19	0.20	0.007	0.236	<0.001	0.769
C18:0	4.65^{bcd}	4.54^{bcd}	4.44^{b}	4.79^{bd}	4.45^{bc}	3.94^{a}	0.116	0.189	<0.001	0.027
C18:1t	0.16^{b}	0.13^{a}	0.13^{a}	0.26^{d}	0.18^{c}	0.24^{d}	0.007	<0.001	<0.001	<0.001
C18:1c9	26.6	26.2	26.5	28.1	27.8	26.3	0.676	0.067	0.349	0.338
C18:1c11	2.10	1.75	1.68	2.24	1.94	1.80	0.055	0.001	<0.001	0.748
C18:2c	35.5^{e}	18.3^{b}	20.9^{c}	31.7^{d}	16.0^{a}	15.9^{a}	0.503	<0.001	<0.001	<0.001
C20:0	0.12^{ab}	0.12^{ab}	0.12^{a}	0.13^{b}	0.11^{a}	0.11^{a}	0.003	0.559	0.005	0.009
C18:3cn6	0.32	0.09	0.09	0.34	0.10	0.07	0.010	0.383	<0.001	0.103
C20:1c	0.23^{a}	0.25^{b}	0.27^{c}	0.30^{b}	0.40^{c}	0.56^{d}	0.020	<0.001	<0.001	<0.001
C18:3cn3	3.22	1.85	2.15	3.13	1.79	2.09	0.065	0.181	<0.001	0.959
C21:0	0.04	0.02	0.02	0.04	0.02	0.02	0.001	0.682	<0.001	0.547
C20:2c	0.65	0.35	0.37	0.66	0.40	0.42	0.017	0.062	<0.001	0.276
C22:0	0.04	0.05	0.05	0.04	0.04	0.05	0.001	0.58	<0.001	0.053
C20:3c8	0.34	0.09	0.09	0.35	0.10	0.10	0.008	0.027	<0.001	0.853

C22:1c	0.05^{a}	0.06^{bc}	0.05^{ab}	0.06^{b}	0.09^{d}	0.13^{e}	0.004	<0.001	<0.001	<0.001
C20:3c11	0.22	0.11	0.12	0.25	0.14	0.16	0.006	<0.001	<0.001	0.604
C20:4c5	1.09	0.38	0.35	1.01	0.36	0.30	0.020	<0.001	<0.001	0.065
C22:2c	0.08^{d}	0.04^{a}	0.04^{a}	0.08^{d}	0.05^{b}	0.05^{c}	0.002	<0.001	<0.001	0.002
C24:0	0.18^{b}	0.07^{a}	0.08^{a}	0.45^{c}	0.09^{a}	0.05^{a}	0.015	<0.001	<0.001	<0.001
C20:5c	0.08^{abc}	0.06^{ab}	0.06^{a}	0.09^{ac}	0.22^{d}	0.47^{e}	0.019	<0.001	<0.001	<0.001
C24:1c	0.08^{b}	0.04^{a}	0.03^{a}	0.11^{d}	0.07^{b}	0.10^{c}	0.004	<0.001	<0.001	<0.001
C22:5cn3	0.57^{c}	0.19^{a}	0.20^{a}	0.84^{d}	0.35^{b}	0.50^{c}	0.021	<0.001	<0.001	<0.001
C22:6c	0.23^{b}	0.08^{a}	0.09^{a}	0.71^{d}	0.40^{c}	0.76^{d}	0.035	<0.001	<0.001	<0.001
Total:										
Saturated[4]	26.5	41.5	39.3	27.5	40.8	41.2	0.556	0.013	<0.001	0.111
MUFA[5]	31.1	36.9	36.0	33.1	39.1	37.7	0.625	0.002	<0.001	0.859
PUFA[6]	42.3^{e}	21.5^{b}	24.5^{c}	39.2^{d}	19.9^{a}	20.8^{ab}	0.582	<0.001	<0.001	0.040
n-3[7]	4.32^{c}	2.29^{a}	2.60^{ab}	5.03^{d}	2.90^{b}	3.98^{c}	0.118	<0.001	<0.001	0.006
n-6[8]	38.0^{e}	19.2^{b}	21.9^{c}	34.1^{d}	17.0^{a}	16.8^{a}	0.511	<0.001	<0.001	<0.001
n6:n3[9]	8.79^{e}	8.41^{d}	8.45^{de}	6.80^{c}	5.94^{b}	4.57^{a}	0.141	<0.001	<0.001	<0.001

[1] Colostrum and milk fatty acids are reported as g/100g of total fatty acids with a reporting limit of 0.01 g/100g.

[2] d0, 14, 21- day 0 (colostrum), day 14 and day 21 of lactation milk samples

[3] SEM- standard error of the mean

[4] Saturated- saturated fatty acids

[5] MUFA- monounsaturated fatty acids

[6] PUFA- polyunsaturated fatty acids

[7] n-6- omega 6 fatty acids

[8] n-3- omega 3 fatty acids

[9] n-6:n-3-omega 6 fatty acid: omega 3 fatty acid ratio

[a,b,c,d,e] Means with different superscripts within a row are different (P<0.05)

5.4.6 Piglet blood plasma and tissue FAMEs

There was a significant interactive effect between oil type and energy regimen on piglet blood plasma fatty acid profile at weaning ($P<0.05$). Offering sows a soya oil diet and a phased energy regimen, decreased the proportion C18:1c11 ($P<0.05$) and increased the proportion of C18:2c ($P<0.05$) and total n-6 fatty ($P<0.05$) acids in piglet blood plasma at weaning compared to all other sow dietary treatments ($P<0.05$). Offering sows a diet containing salmon oil and the phased dietary regimen increased the proportion of C24:0 ($P<0.01$) in piglet blood plasma samples compared to all other dietary treatments ($P<0.05$), but the proportion of C24:0 did not differ between the plasma of piglets from sows offered soya oil regardless of dietary energy regimen ($P>0.05$) (Table 5.7).

Table 5. 7. Fatty acid composition (g/100g total fatty acids) of piglet blood plasma at weaning after offering sows diets containing soya or salmon oil and a flat or phased dietary regimen during lactation.

	Soya oil		Salmon oil			Oil	Energy	Oil × Energy
Fatty acid[1]	Flat[2]	Phased[3]	Flat	Phased	SEM[4]	*P-value*	*P-value*	*P-value*
C14:0	1.25	0.97	1.44	1.29	0.108	0.024	0.055	0.558
C16:0	28.1	26.8	27.4	28.9	1.158	0.531	0.957	0.236
C16:1c	4.43	3.15	4.99	3.65	0.292	0.078	<0.001	0.923
C18:0	12.1	12.9	11.0	12.7	0.516	0.211	0.021	0.412
C18:1c9	17.2	14.9	17.3	17.0	0.595	0.062	0.041	0.085
C18:1c11	1.91^{a}	1.61^{b}	1.96^{a}	1.92^{a}	0.060	0.005	0.007	0.035
C18:2c	25.4^{a}	29.7^{b}	24.8^{a}	23.6^{a}	1.010	0.002	0.138	0.011
C18:3cn3	0.97	1.20	1.23	1.30	0.104	0.094	0.167	0.445
C20:4c5	4.55	4.58	3.53	2.41	0.451	0.001	0.235	0.213
C24:0	0.16^{a}	0.17^{a}	0.87^{b}	1.75^{c}	0.156	<0.001	0.007	0.009
C22:6c	0.92	1.08	2.18	2.04	0.294	<0.001	0.988	0.620
Total:								
Saturated[5]	42.6	41.4	41.3	45.3	1.375	0.348	0.295	0.073
MUFA[6]	23.7	19.8	24.5	23.0	0.806	0.018	0.002	0.145
PUFA[7]	33.5	38.4	33.7	31.3	1.838	0.069	0.539	0.055
n-3[8]	2.75	3.19	4.49	4.39	0.483	0.005	0.734	0.577
n-6[9]	30.8^{a}	35.2^{b}	29.2^{a}	26.9^{a}	1.431	0.002	0.495	0.025
n6:n3[10]	12.8	12.7	7.4	7.2	1.010	<0.001	0.864	1.00

[1] Plasma fatty acids are reported as g/100g of total fatty acids with a reporting limit of 1.0 g/100g.

[2] 14.5 MJ/kg DE diet offered for 28 d of lactation

[3] 14.5 MJ DE/kg diet offered from day 1 to 14 of lactation and 15.5 MJ/kg DE diet offered from day 15 to 28 of lactation

[4] SEM- standard error of the mean

[5] Saturated- saturated fatty acids

[6] MUFA- monounsaturated fatty acids

[7] PUFA- polyunsaturated fatty acids

[8] n-6- omega 6 fatty acids

[9] n-3- omega 3 fatty acids

[10] n-6:n-3-omega 6 fatty acid: omega 3 fatty acid ratio

[a,b,c] Means with different superscripts within a row are different (P<0.05)

5.4.6.1 Adipose tissue

There was an interactive effect between oil type and energy regimen on the proportion of fatty acids in piglet adipose tissue collected at weaning. Piglets at weaning from sows offered a diet containing soya oil and the phased energy regimen had a greater proportion of C18:2c ($P<0.01$) than all other treatment groups ($P<0.05$), but no difference was detected between piglets from sows offered diets containing salmon oil regardless of energy regimen ($P>0.05$) (Table 5.8). Therefore, the total proportions of PUFA and n-6 fatty acids (both $P<0.01$) were greatest in the adipose tissue of piglets from sows offered diets containing soya oil and phased dietary regimen. Feeding sows a diet containing salmon oil and the phased energy regimen increased the proportion of the MUFAs C20:1c ($P<0.001$), C22:1c ($P<0.001$), C24:1c ($P<0.01$) and the n-3 PUFAs C20:3c11 ($P<0.05$), C20:5c ($P<0.01$), C22:5cn3 ($P<0.05$), C22:6c ($P<0.05$) as well as the n-6 PUFA C22:2c ($P<0.01$) in the adipose tissue of piglets compared to all other treatment groups ($P<0.05$). However, the total proportions of MUFA and n-3 fatty acids in piglet adipose tissues were not influenced by sow dietary treatment ($P>0.05$).

Table 5. 8. Fatty acid composition (g/100g total fatty acids) of piglet adipose tissue collected at weaning after offering sows diets containing soya or salmon oil and a flat or phased dietary regimen during lactation.

	Soya oil		Salmon oil			Oil	Energy	Oil × Energy
Fatty acid^{1}	Flat^{2}	Phased^{3}	Flat	Phased	SEM^{4}	*P-value*	*P-value*	*P-value*
C10:0	0.01	0.01	0.01	0.01	0.001	0.001	0.031	0.737
C12:0	0.06	0.05	0.06	0.06	0.002	<0.001	0.304	0.180
C14:0	1.78	1.68	2.03	2.11	0.076	<0.001	0.903	0.216
C14:1c	0.06	0.05	0.08	0.07	0.004	<0.001	0.179	0.375
C15:0	0.06	0.07	0.07	0.08	0.005	0.021	0.274	0.906
C16:0	25.9	25.7	26.8	26.5	0.558	0.148	0.731	0.900
C16:1c	6.69	6.17	7.45	6.89	0.236	0.003	0.030	0.953
C17:0	0.17	0.18	0.19	0.18	0.010	0.187	0.794	0.244
C17:1c	0.21	0.19	0.24	0.20	0.010	0.103	0.004	0.198
C18:0	6.87	6.44	6.96	6.44	0.307	0.870	0.137	0.884
C18:1t	0.11	0.10	0.11	0.11	0.007	0.839	0.291	0.858
C18:1c9	32.3	29.7	32.5	32.1	0.648	0.047	0.038	0.099
C18:1c11	3.24	2.76	3.40	3.09	0.112	0.029	<0.001	0.455
C18:2c	18.5^{a}	22.8^{b}	15.8^{c}	17.0^{c}	0.447	<0.001	<0.001	0.001
C20:0	0.10	0.08	0.10	0.09	0.005	0.577	0.016	0.342
C18:3cn6	0.07	0.08	0.07	0.07	0.006	0.076	0.632	0.490
C20:1c	0.48^{a}	0.34^{b}	0.55^{a}	0.64^{c}	0.029	<0.001	0.509	<0.001
C18:3cn3	1.63	2.04	1.55	1.87	0.051	0.020	<0.001	0.351
C20:2c	0.54	0.50	0.50	0.54	0.021	0.945	0.947	0.054
C20:3c8	0.15	0.14	0.15	0.14	0.006	0.904	0.177	0.540
C22:1c	0.02^{a}	0.02^{b}	0.03^{a}	0.04^{c}	0.003	<0.001	0.651	<0.001
C20:3c11	0.16^{a}	0.15^{a}	0.17^{ab}	0.19^{b}	0.008	0.004	0.626	0.033
C20:4c5	0.31	0.32	0.28	0.27	0.013	0.003	0.878	0.413
C22:2c	0.02^{ab}	0.02^{a}	0.02^{b}	0.03^{c}	0.001	<0.001	0.631	0.006
C20:5c	0.06^{a}	0.04^{a}	0.12^{b}	0.20^{c}	0.017	<0.001	0.060	0.004
C24:1c	0.01^{ab}	0.01^{a}	0.02^{b}	0.02^{c}	0.001	<0.001	0.714	0.005

C22:5cn3	0.19[a]	0.14[a]	0.31[b]	0.40[c]	0.032	<0.001	0.515	0.025
C22:6c	0.12[a]	0.07[a]	0.32[b]	0.47[c]	0.047	<0.001	0.332	0.035
Total:								
Saturated[5]	35.0	34.2	36.2	35.5	0.593	0.044	0.226	0.930
MUFA[6]	43.0	39.2	44.2	43.1	0.687	<0.001	0.001	0.065
PUFA[7]	21.8[a]	26.3[b]	19.3[c]	21.2[a]	0.412	<0.001	<0.001	0.002
n-3[8]	2.15	2.42	2.47	3.11	0.131	<0.001	0.001	0.165
n-6[9]	19.6[a]	23.9[b]	16.8[c]	18.0[c]	0.448	<0.001	<0.001	0.001
n6:n3[10]	9.44	9.88	6.84	6.09	0.434	<0.001	0.723	0.168

---

[1] Adipose fatty acids are reported as g/100g of total fatty acids with a reporting limit of 0.01 g/100g.

[2] 14.5 MJ/kg DE diet offered for 28 days of lactation

[3] 14.5 MJ DE/kg diet offered from day 1 to 14 of lactation and 15.5 MJ/kg DE diet offered from day 15 to 28 of lactation

[4] SEM- standard error of the mean

[5] Saturated- saturated fatty acids

[6] MUFA- monounsaturated fatty acids

[7] PUFA- polyunsaturated fatty acids

[8] n-6- omega 6 fatty acids

[9] n-3- omega 3 fatty acids

[10] n-6:n-3-omega 6 fatty acid: omega 3 fatty acid ratio

[a,b,c] Means with different superscripts within a row are different ($P<0.05$)

5.4.6.2 Liver tissue

There was a significant interactive effect between oil type and energy regimen on the fatty acid composition of piglet liver tissue at weaning (Table 5.9). Piglets at weaning from sows offered a diet containing soya oil and the phased energy regimen had an increased proportion of C18:2c ($P<0.001$) and C22:0 ($P<0.05$) in liver tissue compared to piglets from sows offered diets containing salmon oil. The total proportions of PUFA and n-6 fatty acids (both $P<0.01$) were greatest in the liver tissue of piglets from sows offered diets containing soya oil and phased dietary regimen compared to all other treatment groups ($P<0.05$). Piglets from sows offered diets containing salmon oil and the phased energy regimen had greater proportions of C20:1c, C24:0, C24:1c (all $P<0.001$), C22:5cn3 ($P<0.01$) and total MUFA ($P<0.01$) in liver tissue compared to all other treatment groups. Total MUFA which was not different for piglets from sows offered salmon oil and flat energy regimen in lactation ($P>0.05$).

Table 5. 9. Fatty acid composition (g/100g total fatty acids) of piglet liver tissue collected at weaning after offering sows diets containing soya or salmon oil and a flat or phased dietary regimen during lactation.

	Soya oil		Salmon oil			Oil	Energy	Oil × Energy
Fatty acid[1]	Flat[2]	Phased[3]	Flat	Phased	SEM[4]	*P-value*	*P-value*	*P-value*
C12:0	0.02	0.02	0.01	0.02	0.002	0.686	0.316	0.284
C14:0	0.49	0.46	0.47	0.53	0.042	0.590	0.637	0.273
C15:0	0.06	0.05	0.06	0.06	0.003	0.057	0.900	0.410
C16:0	18.9	17.9	19.3	19.1	0.367	0.034	0.102	0.329
C16:1c	2.22	1.68	2.14	1.88	0.126	0.623	0.004	0.279
C17:0	0.18	0.17	0.18	0.17	0.009	0.803	0.130	0.643
C17:1c	0.18	0.16	0.17	0.16	0.005	0.368	<0.001	0.129
C18:0	21.0	20.5	21.3	20.4	0.504	0.920	0.184	0.719
C18:1t	0.18	0.16	0.16	0.16	0.014	0.503	0.649	0.462
C18:1c9	8.91	8.76	7.92	8.76	0.393	0.219	0.381	0.212
C18:1c11	1.86	1.50	1.79	1.47	0.069	0.447	<0.001	0.793
C18:2t	0.04	0.04	0.04	0.04	0.002	<0.001	0.888	0.669
C18:2c	19.5^{a}	23.1^{b}	16.5^{c}	16.4^{c}	0.507	<0.001	0.002	<0.001
C20:0	0.09	0.09	0.09	0.08	0.003	0.409	0.618	0.198
C18:3cn6	0.12	0.25	0.10	0.11	0.029	0.009	0.022	0.060
C20:1c	0.11^{ab}	0.09^{a}	0.12^{b}	0.21^{c}	0.010	<0.001	0.003	<0.001
C18:3cn3	0.68	0.99	0.54	0.78	0.066	0.010	<0.001	0.578
C20:2c	0.47	0.57	0.41	0.48	0.023	<0.001	<0.001	0.555
C22:0	0.08^{ab}	0.09^{a}	0.08^{b}	0.06^{c}	0.004	<0.001	0.328	0.046
C20:3c8	0.74	0.83	1.00	0.87	0.059	0.017	0.785	0.069
C22:1c	0.08	0.08	0.08	0.09	0.004	0.171	0.238	0.068
C20:3c11	0.12	0.15	0.12	0.16	0.007	0.880	<0.001	0.474
C20:4c5	14.7	14.6	12.6	10.7	0.606	<0.001	0.111	0.146
C23:0	0.05	0.05	0.04	0.04	0.003	0.005	0.534	0.284

C22:2c	0.01	0.01	0.01	0.02	0.001	0.053	<0.001	0.085
C24:0	0.87^{ab}	0.49^{a}	1.49^{b}	3.22^{c}	0.274	<0.001	0.018	<0.001
C24:1c	0.15^{ab}	0.12^{a}	0.19^{b}	0.26^{c}	0.014	<0.001	0.273	<0.001
C22:5cn3	2.39^{ab}	2.15^{a}	2.55^{b}	2.84^{c}	0.094	<0.001	0.737	0.008
C22:6c	5.61	4.90	10.6	10.9	0.662	<0.001	0.758	0.449
Total:								
Saturated[5]	41.8^{a}	39.8^{b}	42.9^{ac}	43.6^{c}	0.484	<0.001	0.205	0.009
MUFA[6]	13.5	12.4	12.4	12.8	0.493	0.534	0.487	0.133
PUFA[7]	44.4^{a}	47.5^{b}	44.4^{a}	43.3^{c}	0.368	<0.001	0.011	<0.001
n-3[8]	8.81	8.15	13.7	14.6	0.693	<0.001	0.874	0.263
n-6[9]	35.5^{a}	39.3^{b}	30.6^{c}	28.6^{c}	0.878	<0.001	0.308	<0.001
n6:n3[10]	4.37	4.88	2.25	2.17	0.274	<0.001	0.424	0.277

---

[1] Liver fatty acids are reported as g/100g of total fatty acids with a reporting limit of 0.01 g/100g.

[2] 14.5 MJ/kg DE diet offered for 28 days of lactation

[3] 14.5 MJ DE/kg diet offered from day 1 to 14 of lactation and 15.5 MJ/kg DE diet offered from day 15 to 28 of lactation

[4] SEM- standard error of the mean

[5] Saturated- saturated fatty acids

[6] MUFA- monounsaturated fatty acids

[7] PUFA- polyunsaturated fatty acids

[8] n-6- omega 6 fatty acids

[9] n-3- omega 3 fatty acids

[10] n-6:n-3-omega 6 fatty acid: omega 3 fatty acid ratio

[a,b,c] Means with different superscripts within a row are different (P<0.05)

5.4.6.3 Muscle tissue

There was a significant interactive effect between sow dietary oil type and energy regimen on the fatty acid profile of piglet muscle tissue collected at weaning (Table 5.10). Similar to adipose and liver tissue, muscle of piglets from sows offered a diet containing soya oil and a phased energy regimen had a greater proportion of C18:2c than all other treatment groups ($P<0.05$). The total proportion of the fatty acids C18:1t ($P<0.05$), C20:1c ($P<0.001$), C20:3c11, C22:2c, C24:0, C24:1c, C22:6c and total n-6 (all $P<0.05$) were greatest in the muscle of piglets from sow offered diets containing salmon oil and the phased energy regimen. The total proportions of saturated, MUFA, PUFA, n-3 and n6:n3 ratio in piglet muscle were unaffected ($P>0.05$).

5.4.7 Piglet serum IgG concentration and body composition at weaning

There was no effect of maternal lactation dietary treatment on IgG concentrations in piglet serum collected at weaning ($P>0.05$). The average IgG concentration of piglet serum was 66.4 mg/ml (SEM=10.5), with IgG concentrations ranging from 11.9 to 289.3 mg/ml. There was no interactive effect of oil type or energy regimen offered to sows on piglet bone or body composition measures ($P>0.05$). Piglets born to sows offered the phased energy regimen had greater total bone area than piglet born to sows offered the flat energy regimen (420.3 vs. 402.9 cm^2, respectively). There was no direct effect of dietary oil type or energy regimen offered to sows during lactation on any other piglet bone or body composition measures recorded i.e. bone mineral density, body fat, lean mass ($P>0.05$).

Table 5. 10. Fatty acid composition (g/100g total fatty acids) of piglet muscle tissue collected at weaning after offering sows diets containing soya or salmon oil and a flat or phased dietary regimen during lactation

	Soya oil		Salmon oil			Oil	Energy	Oil × Energy
Fatty acid[1]	Flat[2]	Phased[3]	Flat	Phased	SEM[4]	*P-value*	*P-value*	*P-value*
C12:0	0.05	0.04	0.06	0.05	0.002	<0.001	0.095	0.593
C14:0	1.63	1.49	1.89	1.91	0.061	<0.001	0.339	0.194
C14:1c	0.04	0.04	0.06	0.05	0.003	<0.001	0.078	0.582
C15:0	0.06	0.06	0.06	0.07	0.005	0.089	0.594	0.625
C16:0	26.4	26.1	27.4	26.9	0.507	0.083	0.422	0.764
C16:1c	5.66	5.06	6.36	5.68	0.222	0.005	0.007	0.851
C17:0	0.15	0.15	0.16	0.14	0.010	0.588	0.365	0.513
C17:1c	0.35	0.34	0.34	0.35	0.020	0.780	0.913	0.531
C18:0	8.14	8.05	8.16	7.91	0.266	0.821	0.528	0.755
C18:1t	0.18^{a}	0.16^{a}	0.19^{a}	0.27^{b}	0.023	0.008	0.171	0.033
C18:1c9	27.6	25.0	27.9	27.0	0.757	0.118	0.037	0.264
C18:1c11	2.95	2.58	3.16	2.82	0.125	0.075	0.008	0.878
C18:2c	20.4^{a}	24.7^{b}	17.5^{c}	18.6^{c}	0.463	<0.001	<0.001	0.001
C20:0	0.10	0.09	0.09	0.09	0.005	0.293	0.099	0.663
C18:3cn6	0.07	0.07	0.06	0.06	0.004	0.010	0.797	0.698
C20:1c	0.44^{a}	0.30^{b}	0.52^{a}	0.63^{c}	0.030	<0.001	0.772	<0.001
C18:3cn3	1.52	1.90	1.48	1.71	0.044	0.010	<0.001	0.096
C20:2c	0.61	0.59	0.57	0.64	0.023	0.961	0.327	0.056
C22:0	0.02	0.02	0.01	0.01	0.002	0.010	0.123	0.447
C20:3c8	0.26	0.24	0.27	0.27	0.014	0.274	0.684	0.336
C22:1c	0.03	0.03	0.04	0.05	0.005	0.015	0.109	0.146
C20:3c11	0.15^{ab}	0.14^{a}	0.17^{b}	0.19^{c}	0.007	<0.001	0.398	0.038
C20:4c5	1.88	1.96	1.50	1.62	0.148	0.018	0.519	0.911
C22:2c	0.02^{a}	0.02^{a}	0.03^{a}	0.03^{b}	0.002	0.005	0.379	0.039

C24:0	0.20^{ab}	0.14^{a}	0.33^{b}	0.62^{c}	0.063	<0.001	0.078	0.010
C24:1c	0.03^{a}	0.03^{a}	0.03^{a}	0.05^{b}	0.005	0.024	0.251	0.049
C22:5cn3	0.59	0.52	0.76	0.99	0.075	<0.001	0.269	0.061
C22:6c	0.41^{a}	0.30^{a}	0.80^{b}	1.25^{c}	0.129	<0.001	0.192	0.036
Total:								
Saturated[5]	36.7	36.1	38.2	37.6	0.589	0.014	0.331	0.954
MUFA[6]	37.1	33.4	38.4	36.7	0.865	0.010	0.005	0.263
PUFA[7]	26.0	30.5	23.3	25.5	0.592	<0.001	<0.001	0.060
n-3[8]	2.65	2.85	3.19	4.12	0.224	<0.001	0.016	0.113
n-6[9]	23.3^{a}	27.7^{b}	20.0^{c}	21.3^{c}	0.582	<0.001	<0.001	0.012
n6:n3[10]	9.34	9.73	6.25	5.46	0.463	<0.001	0.663	0.212

[1] Muscle fatty acids are reported as g/100g of total fatty acids with a reporting limit of 0.01 g/100g.

[2] 14.5 MJ/kg DE diet offered for 28 days of lactation

[3] 14.5 MJ DE/kg diet offered from day 1 to 14 of lactation and 15.5 MJ/kg DE diet offered from day 15 to 28 of lactation

[4] SEM- standard error of the mean

[5] Saturated- saturated fatty acids

[6] MUFA- monounsaturated fatty acids

[7] PUFA- polyunsaturated fatty acids

[8] n-6- omega 6 fatty acids

[9] n-3- omega 3 fatty acids

[10] n-6:n-3-omega 6 fatty acid: omega 3 fatty acid ratio

[a,b,c] Means with different superscripts within a row are different ($P<0.05$)

5.5 Discussion

The benefits of increasing sow lactation energy intake and fish oil inclusion in lactation diets have been reported separately, but this is the first time that both been investigated simultaneously. The aim of the present study was to examine the effect of dietary salmon oil compared to soya oil during lactation and increasing dietary energy density in late lactation on production measures in sows and progeny. Furthermore, their effect on the fatty acid status of colostrum, milk, piglet blood and piglet tissues at weaning.

5.5.1 Oil type and energy level interactive effects

There was no interactive effect between oil type and energy regimen on sow or piglet performance measures. This result disagrees with the hypothesis as it was expected that increasing the proportion of n-3 fatty acids in the lactation diet and increasing the energy density in late lactation would better support piglet growth through improved milk yield (Mateo et al., 2009, Pedersen et al., 2016). There were interactive effects observed which affected the proportion of fatty acids in piglet tissues and blood plasma collected at weaning as well as sow colostrum and milk samples. These results were expected as the energy density of the diet was increased by increasing the oil inclusion in the diet. Although the proportion of fatty acids increased with increasing oil inclusion in the salmon oil phased energy diet, this was not the case for soya oil which is likely due to the contribution of fatty acids from the cereal ingredients. Therefore, this is likely the key driver for the interactive effects seen in this study rather than a change in energy balance causing sows to mobilise body reserves.

5.5.2 Dietary oil type in sow lactation diet

Whilst sows offered the diet containing salmon oil had a greater feed intake in the 3rd week of lactation, overall feed intake or energy intake did not differ between oil treatments in this study. Salmon oil could have reduced feed intake as oils high in unsaturated fatty acids can be prone to lipids peroxidation, but regular analyses of the peroxidation status of oil confirmed that peroxidation was minimal in the trial diets (<10 mEq/kg). In the current study diets were offered from day 105 of gestation and therefore effects on litter size and number born alive were not expected. However, effects during lactation were expected.

The present study found that salmon oil in sow lactation diets tended to decrease pre-weaning mortality rate compared to soya oil (9.9 % vs. 13.4 %, respectively). Similarly, Rooke et al. (2001a) reported that although salmon oil reduced piglet birth weight it also reduced pre-weaning mortality from 11.7 % to 10.2 % by reducing the number of piglet deaths due to crushing by the sow. On the contrary, Smit et al. (2015) found that supplementing sows with an n-3 LCPUFA marine oil did not reduce the pre-weaning mortality rate of low birth weight litters. It was hypothesised that salmon oil inclusion would increase piglet survivability to weaning however; oil type in this study did not affect piglet birth weight, litter suckling duration or frequency, piglet body composition or blood serum IgG at weaning. This suggests that improvements in piglet pre-weaning mortality were not mediated through increases in piglet vigour at birth, fat deposition or immunity at weaning; however, as piglet colostrum intake and cause of death were not explored in this study, further investigation is required to understand fully the potential effect of salmon oil on piglet mortality.

Previous research has suggested supplementing sows with fish oil during lactation may accelerate the maturation of the piglet immune system (Luo et al., 2009). It was hypothesised that salmon oil would increase IgG levels in piglet serum at weaning however, in agreement with Leonard et al. (2010), the present study observed no effect of oil type on piglet IgG blood serum concentrations at weaning. On the contrary, Rooke et al. (2003) reported piglet IgG at weaning tended to be greater for progeny from sows with tuna oil included in the maternal diet. However, the authors concluded that IgG on day 28 is positively related to passively acquired IgG levels at day 7. Indeed, as piglet IgG concentration in the present study varied greatly between individuals, it is likely a reflection of maternal IgG levels and resulting colostrum intake.

In this study, salmon oil inclusion in the sow lactation diet increased litter ADG in the second and fourth week of lactation, but overall there was no effect on litter weaning weight. This is consistent with the results of Fritsche et al. (1993) and Taugbøl et al. (1993) who reported no effect of n-3 LCPUFA supplementation from day 107 of gestation to weaning on piglet or litter weaning weight. However, some studies have reported increased piglet growth until the end of the nursery period when sows are supplemented with n-3 oils in gestation and lactation (Rooke et al., 2001b, Mateo et al., 2009, Smit et al., 2013). Therefore, longer periods of n-3 supplementation may have positive effect on growth by further increasing n-3 fatty acid content of piglet tissues or improving piglet gut development. Unfortunately, this study terminated at weaning, so any positive effect post-weaning may have been overlooked.

With current increases in litter size it is important to maximise sow milk yield as it a limiting factor in the growth of suckling piglets (Quesnel et al., 2015). However, nutritional strategies to improve sow milk yield have had varying success. Lauridsen and Danielsen (2004) reported no effect of oil inclusion or dietary oil type on sow milk production. Contrary to this, the present study found that diets containing salmon oil increased sow milk yield on day 14 by 7.5 % and day 28 by 11.6 % with overall milk yield being 10 % greater compared sows offered diets containing soya oil, with no negative effect on sow body reserves. Indeed Lee et al. (2014) found that supplementing sows with CLA increased sow milk yield by 10 % compared to soya oil fed sows. Although the exact mechanism of how oils influence sow milk yield is unclear, previous research with lactating cows suggest there may be shift in energy partitioning as milk yield increased, milk fat decreased with no significant effect on cow body reserves and net energy balance (Bernal-Santos et al., 2003).

As expected, the fatty acid profile of sow colostrum and milk can be attributed to sow dietary oil treatment. In agreement with the findings of Lauridsen and Danielsen (2004), this study found that DHA, DPA and EPA were greater in milk from sows fed salmon oil, reducing the overall ratio of n6:n3 fatty acids. Similarly, Arbuckle and Innis (1993) reported fish oil inclusion increased milk DHA and EPA but no difference in ARA (C20:4c5) was detected, while in the present study salmon oil, decreased ARA in sows’ milk. In the current study, EPA levels increased as lactation progressed and initially

DPA and DHA decreased from colostrum to day 14 but increased again on day 21. In this study, sows were offered a phased energy regimen, which increased the energy density of the diet through an increase in the oil content and this is likely to have been a key driver in the increase proportion of fatty acids in day 21 milk compared to day 14 milk samples.

As maternal dietary fats alter the fatty acid profile of milk, this subsequently influences the proportion of fatty acids in the plasma of suckling piglets. Fritsche et al. (1993) reported EPA and total n-3 fatty acids in piglet plasma increased with increasing age when sows were supplemented with fish oil from day 107 until weaning, suggesting piglets efficiently absorbed n-3 fatty acids from the sows’ milk. Although in the current study no difference was detected between the levels of EPA in piglet plasma, as hypothesised the current study found that DHA levels and the proportion of n-3 fatty acids were higher, reducing the ratio of n6:n3 fatty acids in piglet blood plasma at weaning from sows offered salmon oil diets. Also, in the present study, salmon oil inclusion increased the level of DHA in piglet adipose, liver and muscle tissue at weaning but C18:3cn3 was greater in the tissues of piglet from sows offered lactation diets containing soya oil. On the contrary, Bazinet et al. (2003) reported increasing α-linoleic acid (ALA) a precursor to DHA increased the proportion of C18:3cn3 and DHA in the carcass, liver and brain of suckling piglets. As the conversion of ALA to EPA and DHA in the human liver, is estimated to only be 10-15 % efficient (Holub, 2002) this may explain the higher ALA in piglet tissues from sows fed soya oil.

There is little information in the literature regarding how n-3 fatty acids in sow diets influences body composition in offspring. In a review by

Muhlhausler et al. (2011), n-3 long chain PUFA supplementation of rodents resulted in lower body fat mass of progeny, while there are conflicting results of n-6 supplementation and fat deposition in pigs (Dugan et al., 1997, Ostrowska et al., 1999, Cordero et al., 2010). In the present study piglet total body fat and lean mass as well as estimated visceral and subcutaneous tissue area at weaning were unaffected by maternal dietary oil treatment during lactation. This may be a result comparing n-6 and n-3 oils, both of which can influence body composition of the pig. Piglet bone mineral content and density were also unaffected by sow dietary treatment in this study. Mollard et al. (2005) reported elevated bone mass with an ARA:DHA ratio of 0.5:0.1 g/100g total fat. Although the exact mechanism is unclear, it is thought long chain PUFAs may affect prostaglandin E_2 production, which is important in bone metabolism.

Overall the inclusion of salmon oil in sow lactation diets increased the proportion of n-3 fatty acids in colostrum and milk as well as piglet blood plasma and tissues collected at weaning; but this did not translate to an improvement in sow or piglet performance to weaning when compared to soya oil. However dietary salmon oil did reduce piglet mortality and increase sow milk yield and therefore its use in sow lactation diets warrants further investigation.

5.5.3 Phased energy regimen

Oils are often used to increase the energy density of lactation diets. Dietary fat can increase the palatability of diets (Rossi et al., 2010). Although sow lactation feed intake was not affected by dietary energy regimen in this study, as expected energy intake in late lactation and overall lactation energy intake were greater for sows offered the phased energy regimen. The energy requirements for the lactation diets used in this study were calculated using the requirement tables in the British Society of Animal Science (BSAS) *Nutrient Requirements Standards for Pigs* (Whittemore et al., 2003). From this the energy requirements for a sow to rear 14 pigs to 8.5 kg at weaning would be 112.8 MJ DE/day. Although the number of piglets weaned in the present study were lower than expected (average. 12.2), sows offered the phased energy regimen were able to achieve an intake of 116.1 MJ DE per day which enabled sows to rear piglets to the target weight (8.6 kg). However overall total litter weight weaned did not differ between treatment groups. Total lactation energy intake between phased and flat energy regimens only differed by 7 % and this may not have been sufficient to see any treatment effects on sow milk yield or piglet growth. Indeed, in the present study, regardless of sow dietary treatment sow feed intake was greater than commercial herds (Kruse et al., 2011), with an average sow lactation feed intake of 7.1 kg/day, overall nutrient intake increases, improving subsequent piglet growth (Eissen et al., 2003).

Sow back-fat depth and BCS in this study were not affected by sow dietary treatment but by day of sampling, decreasing as lactation progressed. It was hypothesised that sow weight and body condition loss would be minimised with increased energy intake in lactation (Smits et al., 2013) but they did not differ between treatments. These findings are supported by Eissen et al. (2003) who report that additional feed intake in lactation was not used efficiently by sows nursing larger litters (≥ 11 pigs) as neither sow body condition loss or piglet weight gain was improved. Although with a lactation weigh loss of <10 %, subsequent reproductive performance should not have been compromised in the present study (Thaker and Bilkei, 2005).

As mentioned, sow milk yield is a limiting factor in the growth of nursing pigs and piglet milk intake increases with increasing body weight as maintenance energy requirements increase (Theil et al., 2002). Therefore, the influence of maternal diet on milk production, increases as lactation progresses (Tokach et al., 1992). Previous research attempting to increase sow milk yield through an increase in sow dietary energy has been unsuccessful (Craig et al., 2016). In disagreement with the hypothesis, the present study found that increasing sow energy intake in late lactation did not increase sow milk yield measured through piglet growth. On the other hand, Pedersen et al. (2016) reported sows fed a 2 diet-regimen produced more milk in week 4 of lactation even with a lower feed intake than sows fed a single diet throughout lactation. The authors concluded that a diet formulated to provide optimal nutrient supply is a more important determinant for sow milk yield than the energy density of the diet. In this study sow milk yield appeared to plateau on day 14, which agrees with previous research (Craig et al., 2016).

In the present study, sow dietary energy regimen did change the fatty acid composition of milk collected on day 21 of lactation, as well as piglet plasma and tissues at weaning. In the present study, Oleic acid (C18:1c9) levels in day 21 milk did not differ between energy regimen but as oleic acid is found in high concentrations in sow fat (Tilton et al., 1999), this finding suggests sows offered the flat energy regimen for the duration of lactation may have mobilised stored fats. Reducing energy level in lactation can cause some fatty acids to be selectively stored in fat deposits. Indeed Beyer et al. (2007)

reported decreased C16:0 levels in milk of sow fed 80 % ME. However, in this study, C12:0, C14:1c, C16:0 and C17:0 acids were higher in the day 21 milk of sows offered the flat energy regimen. Although the exact mechanism in not eluded, as sow back-fat depth did not differ between sow energy treatments it is likely the fatty acids were directly incorporated from blood lipids which are directly influenced by diet (Bee, 2000). In the present study total bone area was found to be greater for piglets from sows offered the phased dietary regimen which may be a result of reduced n6:n3 ratio in sows milk. Previous research has suggested that increasing dietary n-3 fatty acids and reducing the ratio of n6:n3 fatty acids can enhance the bone formation in rats and piglets (Watkins et al., 2000, Weiler and Fitzpatrick-Wong, 2002).

Offering sows a phased dietary regimen to increase energy intake in lactation did influence the fatty acid profile of milk, piglet plasma and tissues but sow body condition and piglet growth to weaning was not improved. This suggests that improving sow lactation feed intake and offering sows a flat feeding regimen with 15.0 MJ DE/kg is sufficient to improve the performance of lactating multiparous sows.

5.5.4 Sow body temperature

Infrared thermography is a popular diagnostic and monitoring tool in both human and animal health. Sow body temperature was investigated in the current study as a potential tool to detect metabolic activity i.e. milk production in the mammary gland. In a review by Soerensen and Pedersen (2015), pig body temperature is highly correlated to measurements at ear, eye and udder areas. In this study, both sow rectal and eye temperature were measured to try to establish body temperature. However, in the present study eye and udder temperatures measured using infrared camera were consistently lower than rectal temperature measured with a digital thermometer. Similarly, Schmidt et al. (2013), reported that sow body temperatures measured with an infrared camera or an infrared thermometer were lower than those measured with the rectal thermometer. The current study found that sow udder temperature increased significantly from day 114 of gestation to the first day of lactation, which may indicate increased metabolic activity and colostrum production. Although heat stress can also increase sow udder temperature as blood flow is increased to the skin (Renaudeau et al., 2003, Muns et al., 2016a). In the present study the farrowing pen is designed with metal slats under the sow to provide a cooler surface than the surrounding plastic slats and the ambient temperature is set at 19 °C until 1-week post farrowing to minimise heat stress. Indeed, all sow body temperatures recorded before farrowing were below normal sow body temperature (38.8 °C). Sow body temperature did increase significantly the first day of lactation and may be a result of stress or infection from parturition. Although sow body temperatures were not recorded during lactation, the reduced room temperature and farrowing pen design may have encouraged higher sow feed intake, increasing sow output through litter growth. This may in part explain the lack of any treatment effects seen in this study.

5.6 Conclusion

Overall, there was no synergistic effects of dietary oil type and energy regimen on sow or piglet productivity. The inclusion of salmon oil in sow lactation diets did not improve sow body condition, or piglet growth performance to weaning when compared to soya oil. However, salmon oil did tend to decrease piglet mortality and increase sow milk yield. Therefore, salmon oil in sow lactation diets should be investigated further as they could increase piglet survivability and growth to weaning through an increase in sow milk yield. In addition, offering sows a phased feeding regimen did not provide any additional benefits to piglet growth to weaning over a flat feeding regimen. The lack of treatment effect seen in this study may have been a result of high sow lactation feed intake. For that reason, the findings from this study suggests improving sow lactation feed intake to ~7.1 kg/day and a single diet with a digestible energy level of ~15.0 MJ DE/kg will support modern multiparous sows and a litter gain of 84.4 kg during lactation (i.e. 12 piglets weaned at. 8.5 kg at 28 days old).

Chapter 6

General Discussion

Increasing litter size has allowed pig producers to increase production without an increase in sow herd size, but larger litters are associated with an increase in the proportion of low-birth weight piglets and a concurrent rise in pre-weaning mortality rates (Quiniou et al., 2002, Wolf et al., 2008). Indeed, as global pork consumption continues to grow, key production measures such as numbers born alive, pre-weaning mortality and piglet growth to weaning are target areas for improvement within the pig industry. However, the sows' ability to rear a litter to a good weaning weight over a number of parities is influenced by many factors. Maternal nutrition offers a considerable opportunity to improve foetal and piglet growth (Kim et al., 2013, Rekiel et al., 2014). As a result, recent research has focused on determining nutritional requirements for contemporary sows and identifying potential nutritional supplements for on farm use in sows (Moehn and Ball, 2013). Therefore, the two main aims of this PhD thesis were to 1) identify sow and dietary characteristics affecting sow productivity in pig herds and 2) to investigate the use of salmon oil, vitamin D_3 level and energy level in sow diets as nutritional strategies to improve piglet survivability and growth performance to weaning.

6.1 Meta-analysis to identify sow and dietary characteristics during gestation affecting reproductive performance

A meta-analysis of data representing 12 studies from 2 research sites found that sow live-weight and back-fat depth at service and during early gestation (day 25 to 50) were less critical to sow reproductive success than previously thought. However greater sow live-weight and back-fat depth in late gestation (day 110) were associated with increased litter size and numbers born alive, which supports the findings of Maes et al. (2004). In this research, heavier, fatter sows in late gestation had heavier piglets at weaning, and did so with a lower feed intake during lactation, which is not surprising as sows often mobilise body reserves to make up for a deficiency in energy intake.

Previous studies have proposed using biological measures of sow metabolic status such as changes in body protein mass and energy balance to manage sow reproduction (Clowes et al., 2003b, Willis et al., 2003), but these are complex and currently not easily exploitable for on farm use. However, exploring sow live-weight and back-fat depth as indicators of reproductive performance exploits practical on farm measures. As such the findings from this study are promising and suggest that although modern sows are of a leaner genotype, if producers focus on recovering and improving sow body condition and weight gain during gestation they can be confident that reproductive ability, as measured by total number of piglets born and reared to a good weaning weight, is not compromised. This work involved sow records collected between 2005 and 2015 and demonstrates the influence of sow characteristics on the reproductive performance of a more modern animal than sows 20 years ago. However, with continual improvements in sow productivity due to genetic gain, the use of such sow characteristics as predictors of reproductive performance in sows should be re-assessed on a continual basis. Furthermore, this conclusion would benefit from the collection and validation of large scale on farm data.

Further meta-analysis of the above data supports the current recommended digestible energy levels for gestating sows (NRC, 2012) and suggests that 30.4-36.3 MJ DE/day throughout gestation is appropriate for modern sows. In contrast, the provision of lysine in sow gestation diets needs to be re-considered. Moehn et al. (2011) and Samuel et al. (2012) highlight that the amino acid requirement of sows increases dramatically in late gestation to meet the demand for foetal growth and mammary development. The current study found a lysine intake of 21.5-32.3 g/day total lysine in late gestation was associated with improved reproductive performance. Also, in this study, the lysine levels identified as being optimal in early, mid and late gestation were higher than the current recommendation of 8.9 to 14.7 g/day total lysine for gestating sows (NRC, 2012). These findings demonstrate the need to re-evaluate the lysine requirements and recommendations for gestating sows and support previous research that a one-diet approach during gestation is no longer sufficient for the modern sow (Kim et al., 2009).

6.2 Nutritional strategies in gestation and lactation to improve piglet survivability and growth performance to weaning

In this research, salmon oil and vitamin D_3 inclusion levels in gestation diets for sows and salmon oil and dietary energy level in sow lactation diets were investigated. No biologically important interactive effects were found and therefore the direct effects of oil, vitamin D_3 and energy level are the focus here.

6.2.1 Salmon oil effect in gestation and lactation

Performance benefits observed in response to n-3 oils in sows are thought to be mediated through an increase in the n-3 fatty acid status of both sows and piglets. The current research demonstrates that maternal nutrition can influence the proportion of fatty acids in piglet blood and tissues at birth through placental transfer and at weaning through milk intake (Rooke et al., 1998, De Quelen et al., 2010, Sampels et al., 2011). Corroborating the findings of Fritsche et al. (1993) and Taugbøl et al. (1993) salmon oil inclusion in sow diets in the current study did not improve overall piglet growth performance to weaning. On the contrary, studies that supplemented sows' diets with fish oil during both gestation and lactation did result in increased post-weaning piglet growth (Rooke et al., 2001b, Mateo et al., 2009, Smit et al., 2013).

Of the studies that have measured piglet vitality at birth, most suggest that salmon oil has a detrimental effect on piglet vitality as a result of an increase in the natural gestation length of sows (Fritsche et al., 1993, Edwards and Pike, 1997, Rooke et al., 1998). Indeed n-3 fatty acids can affect prostaglandin production (Allen and Harris, 2001, Gulliver et al., 2012). However, in the current study when salmon oil was included in the gestation diet and sows farrowed naturally, dietary oil type had no influence on gestation length or piglet vitality at birth. In contrast, when salmon oil was included in the lactation diet in this work and all sows were induced to farrow, salmon oil inclusion tended to reduce piglet pre-weaning mortality. The findings from both studies appear to have conflicting results, but on closer examination, even though piglet BMI and Ponderal indices (an indication of survivability (Baxter et al., 2008)) were reduced when salmon oil was used in the gestation study, pre-weaning mortality rates were unaffected. Overall it is concluded that salmon oil may have merit as a nutritional solution to reduce pre-weaning piglet mortality when offered in the sow lactation diet.

Offering sows a lactation diet containing salmon oil increased sow milk yield and litter growth during week 2 and 4 of lactation. Salmon oil contains a greater proportion of unsaturated fatty acids, that are more efficiently digested due to increased solubility (Rosero et al., 2015). Therefore, fatty acids from salmon oil were most likely more available for use to support milk production. However, n-3 fatty acids have also been found to be preferentially stored in adipose tissue and metabolised for milk production when required, which was demonstrated in the current study with greater DPA and DHA levels in the day 14 milk of sows fed salmon oil during gestation. Sow body condition was unaffected indicating that salmon oil inclusion in lactation may improve milk yield without a detrimental effect on sow body condition. As demonstrated from the meta-analysis, maintaining good sow body condition and weight is important. Therefore, maximising sow productivity without a negative effect on sow body condition is important when sows are now capable of producing up to 15.8 L/day of milk at peak lactation (Craig et al., 2017).

Contrary to the findings of Rooke et al. (2003), Bontempo et al. (2004) and Mitre et al. (2005), but in agreement with Leonard et al. (2010) and Eastwood et al. (2014), this current study observed no effect of oil type fed during gestation on sow colostrum and milk IgG or oil type fed during lactation on piglet serum IgG at weaning. These inconsistencies in the literature are not surprising since the exact underlying mechanisms of how oils influence immunoglobulin production are yet to be elucidated. N-6 and n-3 fatty acids may affect interleukins and prostaglandin E_2 production, impacting the regulation and production of immunoglobulins (Rossi et al., 2010, Yao et al., 2012). The lack of oil effect on milk and piglet IgG levels may due to the fact that colostrum and milk IgG levels can also vary as a result of transfer of IgG from sow blood serum (Mitre et al., 2005) while piglet serum IgG levels at weaning are likely to be influenced by colostrum intake (Rooke et al., 2003). Therefore, in the future it would be interesting to repeat these studies to ascertain how n-3 and n-6 fatty acids affect immunoglobulin production and also establish the influence of sow IgG levels and piglet colostrum intake.

In this research, sow udder and eye temperature were continually lower than rectal temperature which agrees with Schmidt et al. (2013). Interestingly sows offered a lactation diet containing soya oil had increased rectal temperature in late gestation compared to salmon oil. This finding also warrants further examination as an increased sow rectal temperature due to a high n-6:n-3 ratio may be attributed to a pro-inflammatory response to n-6 fatty acids (Papadopoulos et al., 2008).

6.2.2 Vitamin D_3 effect in sow gestation diet

Since pig production is principally conducted indoors, the need for dietary vitamin D_3 supplementation is well established (Lauridsen and Jensen, 2013). Contrary to the findings of Lauridsen et al. (2010), the current study found that a higher level of dietary vitamin D_3 did not increase number born alive but piglet birth weight was increased. Weber et al. (2014) reported heavier piglets at birth as result of 25(OH)D3 supplementation compared to 2000 IU vitamin D_3 supplementation. Discrepancies in the findings from this work and that of

Weber et al. (2014) may be explained by 25(OH)D3 levels in the plasma of sows, as levels of 25(OH)D3 of sows offered the high vitamin D_3 level in this study were similar to the levels of those sows offered 25(OH)D3 supplement in Weber et al. (2014). In the current study, a lower level of vitamin D_3 improved piglet growth in late lactation, which agrees with Lauridsen et al. (2010) and suggests that lower level of vitamin D_3 (~800 to 1000 IU/kg) maximise the body gain of piglets.

In the current study, increasing dietary vitamin D_3 level for sows during gestation increased the concentration of IgG in sow colostrum. Although this finding is contrary to much of the literature which suggests that vitamin D_3 suppresses immunoglobulin expression in humans (Baeke et al., 2010), 1, $25(OH)_2D_3$ has been reported to be important for human immunoglobulin homeostasis (Chen et al., 2007). The finding of this study should be investigated further to better understand the elemental mechanisms of dietary vitamin D_3 in pigs and its relationship with IgG levels in sow colostrum. Interestingly, irrespective of dietary treatment, the average IgG concentration of sow colostrum in the current study was much greater (242.7 mg/ml) than previously reported (64.4 mg/ml) (Hurley, 2015). As piglets are born immunologically naïve, they rely on solely on maternal immunoglobulins in colostrum and milk until their immune system is fully developed at 3-4 weeks old (Rooke and Bland, 2002). Therefore, sows with increased IgG levels in colostrum should be further studied to gain a comprehensive understanding of the key mechanisms that result in this advantageous trait with the aim to improve piglet immunity.

The actual vitamin D_3 levels were greater than the expected values (‘High’; 2755 IU/kg and ‘Low’ 1195 IU/kg), but this study demonstrates that doubling the vitamin D_3 inclusion level in gestation diets, provides no significant benefits for pig production. This is pertinent, as since commencing this work the price of vitamin D_3 has increased by ~900 % from €8.50/kg in 2017 to €85.00/kg in 2018 due to reduced supply in the market (*personal communication*). A strong conclusion from this study is that a vitamin D_3 level ~1000 IU/kg in sow gestation diets is sufficient to optimise performance in the modern prolific sow and her progeny.

6.2.3 Energy level effect in late lactation

It was hypothesised that increasing the dietary energy density of the lactation diet through increased dietary oil content would better support milk production by compensating for plateauing feed intake in late lactation (Park et al., 2008, Pedersen et al., 2016). The energy content of lactation diets were determined using the assumptions that: milk yield = 4.2 × piglet growth (Van der Peet-Schwering et al., 1998), the maintenance requirement for a 250 kg sow is 28.9 MJ ME (Noblet et al., 1998) and the energy requirement for milk yield is 5.4 MJ ME/kg (Whittemore et al., 2003). It was estimated that a diet would need to provide 112.79 DE/day for a sow to rear 14 piglets to 8.5 kg at 28 days old. This could be achieved with a diet containing 14.5 MJ DE/kg at a mean lactation intake of 7.7 kg/day or 15.5 MJ DE/kg at a mean lactation intake of 7.3 kg/day. In agreement with Craig et al. (2016), a key finding of the current study was that the phase feeding approach adopted here was not successful in increasing sow milk yield and subsequently there was no improvement in piglet growth to weaning.

It is important to note that sows in this current study and that of Craig et al. (2016) had a high feed intake (7.2 kg/day) relative to their commercial counterparts (5.9 kg/day) (Kruse et al., 2011). Therefore, the phased energy regimen in this study only equated to ~7 % increase in total energy intake over the 28-day lactation, which may not have been sufficient to observe a treatment effect. Sows used in this work were F1 cross (Large White × Landrace), which is a common commercial breed in the UK and Ireland, thus increasing sow lactation intake on farm to increase sow lactation energy intake is conceivable. The current study does acknowledge the conclusions of Eissen et al. (2003) and Craig et al. (2017) that increasing sow lactation feed intake and consequently nutrient intake will better support sow metabolic status and milk production. In the current study, average litter size was lower than expected but the findings from this study still support the BSAS recommended energy requirements for lactating sows, as sows with an intake of 105 MJ DE/day weaned 12 pigs at an average weight of 8.5 kg at weaning. In addition, as no improvement in piglet growth performance to weaning or a reduction in sow body condition loss during lactation was observed with the phase feeding regimen, this study suggests a single diet for the duration of lactation with a DE level of ~15.0 MJ DE/kg is appropriate for modern multiparous sows.

6.3 Recommendations for future study

It is clear from the findings of this study that sow body condition during gestation can influence reproductive performance. Unfortunately, optimal target live-weight and back-fat depth of sows during gestation could not be identified and also sow genotype could not be analysed, therefore these should be the focus of future meta-analyses of experimental studies and on farm data. Efforts should also focus on confirming the optimal lysine levels for each stage of gestation identified in this work. As amino acid requirements are recommended in relation to lysine, identifying appropriate lysine levels and therefore the requirements for other amino acids during each stage of gestation will optimise the reproductive potential of the modern sow.

Previous studies have documented n-3 oils increasing subsequent litter size (Smits et al., 2011) but due to time constraints in this work, it was not possible to observe sows in subsequent parities. There are also potential benefits for piglet growth if sows are supplemented with n-3 oils for longer periods of time (e.g. during gestation and lactation). Therefore, it would be of interest to conduct further research into the use of salmon oil in both sow gestation and lactation diets with a view to increasing piglet growth. It was hypothesised that salmon oil inclusion in the gestation diet would increase gestation length, but this was not the case in the current study. It would be interesting to repeat the gestation study but induce sows allowing for a more robust cross fostering programme. This may better assess the effect of oil treatment on piglet survivability and vitality at birth, under normal commercial conditions.

Although the findings of this research support the recommendation of a lower level of vitamin D_3 for gestating sows (~800 to 1000 IU/kg), it may be of merit to investigate different vitamin D_3 levels during lactation. In this current study, all sows were offered the same lactation diet containing 2000 IU/kg vitamin D_3 and this may also have masked any subsequent effect of low vitamin D_3 level during gestation. As milk production is the major nutritional demand for lactating sows, it would be advantageous to assess dietary vitamin D_3 levels and the influence on calcium metabolism for milk production and subsequent litter growth. Sow lactation feed intake in the current study was greater than found on commercial farms and so may have masked any effect of increasing dietary energy density in late lactation, as energy intake was very high. It would be interesting to repeat this study and restrict sow feed intake level to mimic commercial sow intake levels.

6.4 Conclusions

This research aimed to identify factors affecting sow herd productivity and investigate nutritional strategies in gestation and lactation to find solutions to improve sow productivity through increased piglet survivability and growth to weaning. This research demonstrated that sow live-weight and back-fat depth during gestation are associated with subsequent reproductive performance and should be monitored and managed to improve sow output. While current recommended digestible energy intakes for modern gestating sows are appropriate, increased lysine levels during gestation were associated with improved sow reproductive performance. These results support the current view that nutrient requirements should be re-evaluated for the modern prolific sow and suggest that a phased dietary regimen in gestation may better support the nutritional needs of gestating sows.

Several studies have found it to be difficult to influence piglet vitality through gestation nutrition, however based on the findings of this work there may be merit in focusing on lactation nutrition. There were some indications in this work and that of others that piglet pre-weaning mortality could be reduced through salmon oil inclusion in sow diets. To address the inconsistencies in the literature, further work should aim to gain a better understanding of the underlying mechanism by which salmon oil improves piglet survivability, as it was clear that fatty acids from salmon oil were transferred effectively from the maternal diet to the blood and tissues of piglets. In addition, it would be interesting to further investigate phased feeding during lactation on a commercial farm setting as benefits may be detectable with lower sow feed intake. With increasing vitamin D_3 price, the findings of this research should give commercial producers and feed companies the confidence to reduce vitamin D_3 inclusion levels to ~1000 IU/kg in sow gestation diets. This research highlights the potential of modern prolific sows and therefore findings from this study should be exploited by the industry to maximise sow output and piglet productivity.

List of References

Agostini, P., Fahey, A., Manzanilla, E., O’Doherty, J., De Blas, C. & Gasa, J. 2014. Management factors affecting mortality, feed intake and feed conversion ratio of grow-finishing pigs. *Animal,* 8, 1312-1318.

Agriculture and Horticulture Development Board (AHDB). 2016. *Indoor breeding herd key performance indicators (KPI's)* [Online]. [Accessed on 29 November 2016]. Available from: http://pork.ahdb.org.uk/prices-stats/costings-herd-performance/indoor-breeding-herd/?performanceMeasure=Total+pigs+born+per+litter.

Agriculture and Horticulture Development Board (AHDB). 2017. *2016 Pig cost of production in selected countries* [Online]. [Accessed on 31 May 2018]. Available from: https://pork.ahdb.org.uk/media/274535/2016-pig-cost-of-production-in-selected-countries.pdf.

Agriculture and Horticulture Development Board (AHDB). 2018. *UK Pig Meat Supplies Forcast* [Online]. [Accessed on 31 May 2018]. Available from: https://pork.ahdb.org.uk/prices-stats/production/uk-pig-meat-supplies-forecast/.

Allan, P. & Bilkei, G. 2005. Oregano improves reproductive performance of sows. *Theriogenology,* 63, 716-721.

Allen, K. G. & Harris, M. A. 2001. The role of n-3 fatty acids in gestation and parturition. *Experimental biology and medicine,* 226, 498-506.

Almeida, F., Kirkwood, R., Aherne, F. & Foxcroft, G. 2000. Consequences of different patterns of feed intake during the estrous cycle in gilts on subsequent fertility. *Journal of Animal Science,* 78, 1556-1563.

Alonso-Spilsbury, M., Mota-Rojas, D., Martínez-Burnes, J., Arch, E., Mayagoitia, A. L., Ramírez-Necoechea, R., Olmos, A. & Trujillo, M. a. E. 2004. Use of oxytocin in penned sows and its effect on fetal intra-partum asphyxia. *Animal Reproduction Science,* 84, 157-167.

Alonso-Spilsbury, M., Mota-Rojas, D., Villanueva-García, D., Martínez-Burnes, J., Orozco, H., Ramírez-Necoechea, R., Mayagoitia, A. L. & Trujillo, M. E. 2005. Perinatal asphyxia pathophysiology in pig and human: a review. *Animal Reproduction Science,* 90, 1-30.

Alvarenga, A., Chiarini-Garcia, H., Cardeal, P., Moreira, L., Foxcroft, G., Fontes, D. & Almeida, F. 2013. Intra-uterine growth retardation affects birthweight and postnatal development in pigs, impairing muscle accretion, duodenal mucosa morphology and carcass traits. *Reproduction, Fertility and Development,* 25, 387-395.

Amdi, C., Krogh, U., Flummer, C., Oksbjerg, N., Hansen, C. & Theil, P. K. 2013a. Intrauterine growth restricted piglets defined by their head shape ingest insufficient amounts of colostrum. *Journal of Animal Science,* 91, 5605-5613.

Amdi, C., Giblin, L., Hennessy, A. A., Ryan, T., Stanton, C., Stickland, N. C. & Lawlor, P. G. 2013b. Feed allowance and maternal backfat levels during gestation influence maternal cortisol levels, milk fat composition and offspring growth. *Journal of Nutritional Science,* 2, e1.

Amdi, C., Giblin, L., Ryan, T., Stickland, N. C. & Lawlor, P. G. 2014. Maternal backfat depth in gestating sows has a greater influence on offspring growth and carcass lean yield than maternal feed allocation during gestation. *Animal,* 8, 236-244.

Amusquivar, E., Laws, J., Clarke, L. & Herrera, E. 2010. Fatty acid composition of the maternal diet during the first or the second half of gestation influences the fatty acid composition of sows’ milk and plasma, and plasma of their piglets. *Lipids,* 45, 409-418.

Andersen, I. L., Berg, S. & Bøe, K. E. 2005. Crushing of piglets by the mother sow (Sus scrofa)—purely accidental or a poor mother? *Applied Animal Behaviour Science,* 93, 229-243.

Andersen, I. L., Nævdal, E. & Bøe, K. E. 2011. Maternal investment, sibling competition, and offspring survival with increasing litter size and parity in pigs (Sus scrofa). *Behavioral Ecology and Eociobiology,* 65, 1159-1167.

Aranow, C. 2011. Vitamin D and the immune system. *Journal of investigative medicine,* 59, 881-886.

Arbuckle, L. D. & Innis, S. M. 1993. Docosahexaenoic acid is transferred through maternal diet to milk and to tissues of natural milk-fed piglets. *The Journal of Nutrition,* 123, 1668-1675.

Auldist, D., Morrish, L., Eason, P. & King, R. 1998. The influence of litter size on milk production of sows. *Animal Science,* 67, 333-337.

Auldist, D., Carlson, D., Morrish, L., Wakeford, C. & King, R. 2000. The influence of suckling interval on milk production of sows. *Journal of Animal Science,* 78, 2026-2031.

Baeke, F., Takiishi, T., Korf, H., Gysemans, C. & Mathieu, C. 2010. Vitamin D: modulator of the immune system. *Current opinion in pharmacology,* 10, 482-496.

Ball, R. O., Samuel, R. & Moehn, S. 2008. Nutrient requirements of prolific sows. *Advances in Pork Production,* 19, 223-236.

Barb, C., Hausman, G. & Czaja, K. 2005. Leptin: a metabolic signal affecting central regulation of reproduction in the pig. *Domestic Animal Endocrinology,* 29, 186-192.

Baxter, E., Jarvis, S., D'eath, R., Ross, D., Robson, S., Farish, M., Nevison, I., Lawrence, A. & Edwards, S. 2008. Investigating the behavioural and physiological indicators of neonatal survival in pigs. *Theriogenology,* 69, 773-783.

Bazinet, R. P., McMillan, E. G. & Cunnane, S. C. 2003. Dietary α-linolenic acid increases the n− 3 PUFA content of sow's milk and the tissues of the suckling piglet. *Lipids,* 38, 1045.

Bee, G. 2000. Dietary conjugated linoleic acids alter adipose tissue and milk lipids of pregnant and lactating sows. *The Journal of Nutrition,* 130, 2292-2298.

Bee, G. 2004. Effect of early gestation feeding, birth weight, and gender of progeny on muscle fiber characteristics of pigs at slaughter. *Journal of Animal Science,* 82, 826-836.

Bergsma, R., Kanis, E., Verstegen, M. & Knol, E. 2008. Genetic parameters and predicted selection results for maternal traits related to lactation efficiency in sows. *Journal of Animal Science,* 86, 1067-1080.

Bergsma, R., Kanis, E., Verstegen, M., van der Peet–Schwering, C. & Knol, E. 2009. Lactation efficiency as a result of body composition dynamics and feed intake in sows. *Livestock Science,* 125, 208-222.

Berkeveld, M., Langendijk, P., Soede, N. M., Kemp, B., Taverne, M. A., Verheijden, J. H., Kuijken, N. & Koets, A. P. 2009. Improving adaptation to weaning: effect of intermittent suckling regimens on piglet feed intake, growth, and gut characteristics. *Journal of Animal Science,* 87, 3156-3166.

Bernal-Santos, G., Perfield II, J., Barbano, D., Bauman, D. & Overton, T. 2003. Production Responses of Dairy Cows to Dietary Supplementation with Conjugated Linoleic Acid (CLA) During the Transition Period and Early Lactation. *Journal of Dairy Science,* 86, 3218-3228.

Beyer, M., Jentsch, W., Kuhla, S., Wittenburg, H., Kreienbring, F., Scholze, H., Rudolph, P. E. & Metges, C. C. 2007. Effects of dietary energy intake during gestation and lactation on milk yield and composition of first, second and fourth parity sows. *Archives of Animal Nutrition,* 61, 452-468.

Beyga, K. & Rekiel, A. 2009. Effect of the backfat thickness of sows in late pregnancy on the composition of colostrum and milk. *Archives Animal Breeding,* 52, 593-602.

Bichard, M. & David, P. 1984. Effectiveness of genetic selection for prolificacy in pigs. *Journal of Reproduction and Fertility.* Supplement, 33, 127-138.

Bligh, E. G. & Dyer, W. J. 1959. A rapid method of total lipid extraction and purification. *Canadian journal of Biochemistry and Physiology,* 37, 911-917.

Bontempo, V., Sciannimanico, D., Pastorelli, G., Rossi, R., Rosi, F. & Corino, C. 2004. Dietary conjugated linoleic acid positively affects immunologic variables in lactating sows and piglets. *The Journal of Nutrition,* 134, 817-824.

Bord Bia. 2016. *Meat and Livestock Review and Outlook 2015/16.* [Online]. [Accessed on 31 May 2018]. Available from: https://www.bordbia.ie/industry/buyers/industryinfo/meat/Documents/Meat-and-Livestock-Review-and-Outlook-2015-2016.pdf.

Bourne, F. & Curtis, J. 1973. The transfer of immunoglobulins IgG, IgA and IgM from serum to colostrum and milk in the sow. *Immunology,* 24, 157.

Bruininx, E., Binnendijk, G., Van der Peet-Schwering, C., Schrama, J., Den Hartog, L., Everts, H. & Beynen, A. 2002. Effect of creep feed consumption on individual feed intake characteristics and performance of group-housed weanling pigs. *Journal of Animal Science,* 80, 1413-1418.

Buitrago, J., Walker, E., Snyder, W. & Pond, W. 1974. Blood and tissue traits in pigs at birth and at 3 weeks from gilts fed low or high energy diets during gestation. *Journal of Animal Science,* 38, 766-771.

Burne, T. H., McGrath, J. J., Eyles, D. W. & Mackay-Sim, A. 2005. Behavioural characterization of vitamin D receptor knockout mice. *Behavioural Brain Research,* 157, 299-308.

Buzoianu, S. G., Walsh, M. C., Rea, M. C., O'Donovan, O., Gelencsér, E., Ujhelyi, G., Szabó, E., Nagy, A., Ross, R. P. & Gardiner, G. E. 2012. Effects of feeding Bt maize to sows during gestation and lactation on maternal and offspring immunity and fate of transgenic material. *PLoS One,* 7, e47851.

Cabrera, R., Boyd, R., Jungst, S., Wilson, E., Johnston, M., Vignes, J. & Odle, J. 2010. Impact of lactation length and piglet weaning weight on long-term growth and viability of progeny. *Journal of Animal Science,* 88, 2265-2276.

Campbell, R., Taverner, M. & Curic, D. 1985. The influence of feeding level on the protein requirement of pigs between 20 and 45 kg live weight. *Animal Science,* 40, 489-496.

Campos, P., Silva, B., Donzele, J., Oliveira, R. & Knol, E. 2012. Effects of sow nutrition during gestation on within-litter birth weight variation: a review. *Animal,* 6, 797-806.

Carr, J. 1998. *Garth pig stockmanship standards*. Sheffield, UK. 5M Enterprises Limited.

Casellas, J., Casas, X., Piedrafita, J. & Manteca, X. 2005. Effect of medium- and long-chain triglyceride supplementation on small newborn-pig survival. *Preventive Veterinary Medicine,* 67, 213-221.

Castren, H., Algers, B., Jensen, P. & Saloniemi, H. 1989. Suckling behaviour and milk consumption in newborn piglets as a response to sow grunting. *Applied Animal Behaviour Science,* 24, 227-238.

Ceglia, L. 2008. Vitamin D and skeletal muscle tissue and function. *Molecular Aspects of Medicine,* 29, 407-414.

Cerisuelo, A., Baucells, M., Gasa, J., Coma, J., Carrion, D., Chapinal, N. & Sala, R. 2009. Increased sow nutrition during midgestation affects muscle fiber development and meat quality, with no consequences on growth performance. *Journal of Animal Science,* 87, 729-739.

Chen, S., Sims, G. P., Chen, X. X., Gu, Y. Y., Chen, S. & Lipsky, P. E. 2007. Modulatory effects of 1, 25-dihydroxyvitamin D3 on human B cell differentiation. *The Journal of Immunology,* 179, 1634-1647.

Cheng, L., Yu, Y., Zhang, Q., Szabo, A., Wang, H. & Huang, X.-F. 2015. Arachidonic acid impairs hypothalamic leptin signaling and hepatic energy homeostasis in mice. *Molecular and Cellular Endocrinology,* 412, 12-18.

Clements, M. R. & Fraser, D. R. 1988. Vitamin D supply to the rat fetus and neonate. *The Journal of Clinical Investigation,* 81, 1768-1773.

Close, W. & Cole, D. 2000. *Nutrition of sows and boars.* Nottingham: Nottingham University Press.

Clowes, E., Aherne, F. & Foxcroft, G. 1994. Effect of delayed breeding on the endocrinology and fecundity of sows. *Journal of Animal Science,* 72, 283-291.

Clowes, E., Aherne, F., Foxcroft, G. & Baracos, V. 2003a. Selective protein loss in lactating sows is associated with reduced litter growth and ovarian function. *Journal of Animal Science,* 81, 753-764.

Clowes, E., Aherne, F., Schaefer, A., Foxcroft, G. & Baracos, V. 2003b. Parturition body size and body protein loss during lactation influence performance during lactation and ovarian function at weaning in first-parity sows. *Journal of Animal Science,* 81, 1517-1528.

Coffey, J., Hines, E., Starkey, J., Starkey, C. & Chung, T. 2012. Feeding 25-hydroxycholecalciferol improves gilt reproductive performance and fetal vitamin D status. *Journal of Animal Science,* 90, 3783-3788.

Collins, C. L., Pluske, J. R., Morrison, R. S., McDonald, T. N., Smits, R. J., Henman, D. J., Stensland, I. & Dunshea, F. R. 2017. Post-weaning and whole-of-life performance of pigs is determined by live weight at weaning and the complexity of the diet fed after weaning. *Animal Nutrition,* 3, 372-379.

Cooper, D., Patience, J., Zijlstra, R. & Rademacher, M. 2001. Effect of energy and lysine intake in gestation on sow performance. *Journal of Animal Science,* 79, 2367-2377.

Cordero, G., Isabel, B., Menoyo, D., Daza, A., Morales, J., Pineiro, C. & Lopez-Bote, C. 2010. Dietary CLA alters intramuscular fat and fatty acid composition of pig skeletal muscle and subcutaneous adipose tissue. *Meat Science,* 85, 235-239.

Cordero, G., Isabel, B., Morales, J., Menoyo, D., Pineiro, C., Daza, A. & Lopez-Bote, C. 2011. Conjugated linoleic acid (CLA) during last week of gestation and lactation alters colostrum and milk fat composition and performance of reproductive sows. *Animal Feed Science and Technology,* 168, 232-240.

Corino, C., Pastorelli, G., Rosi, F., Bontempo, V. & Rossi, R. 2009. Effect of dietary conjugated linoleic acid supplementation in sows on performance and immunoglobulin concentration in piglets. *Journal of Animal Science,* 87, 2299-2305.

Corson, A., Laws, J., Litten, J. C., Dodds, P., Lean, I. & Clarke, L. 2008. Effect of dietary supplementation of different oils during the first or second half of pregnancy on the glucose tolerance of the sow. *Animal,* 2, 1045-1054.

Cottney, P. D., Magowan, E., Ball, M. E. E. & Gordon, A. 2012. Effect of oestrus number of nulliparous sows at first service on first litter and lifetime performance. *Livestock Science,* 146, 5-12.

Cottney, P. D. 2012. *Improving the productivity of the breeding sow herd in Northern Ireland.* Ph.D. thesis, Queen's University Belfast.

Craig, A., Henry, W. & Magowan, E. 2016. Effect of phase feeding and valine-to-lysine ratio during lactation on sow and piglet performance. *Journal of Animal Science,* 94, 3835-3843.

Craig, A., Gordon, A. & Magowan, E. 2017. Understanding the drivers of improved pig weaning weight by investigation of colostrum intake, sow lactation feed intake, or lactation diet specification. *Journal of Animal Science,* 95, 4499-4509.

Cromwell, G., Hall, D., Clawson, A., Combs, G., Knabe, D., Maxwell, C., Noland, P., Orr, D. & Prince, T. 1989. Effects of additional feed during late gestation on reproductive performance of sows: a cooperative study. *Journal of Animal Science,* 67, 3-14.

De Greeff, A., Resink, J., van Hees, H., Ruuls, L., Klaassen, G., Rouwers, S. & Stockhofe-Zurwieden, N. 2016. Supplementation of piglets with nutrient-dense complex milk replacer improves intestinal development and microbial fermentation. *Journal of Animal Science,* 94, 1012-1019.

De Quelen, F., Boudry, G. & Mourot, J. 2010. Linseed oil in the maternal diet increases long chain-PUFA status of the foetus and the newborn during the suckling period in pigs. *British Journal of Nutrition,* 104, 533-543.

De Rensis, F., Gherpelli, M., Superchi, P. & Kirkwood, R. 2005. Relationships between backfat depth and plasma leptin during lactation and sow reproductive performance after weaning. *Animal Reproduction Science,* 90, 95-100.

Decaluwé, R., Maes, D., Declerck, I., Cools, A., Wuyts, B., De Smet, S. & Janssens, G. 2013. Changes in back fat thickness during late gestation predict colostrum yield in sows. *Animal,* 7, 1999-2007.

Decaluwé, R., Maes, D., Wuyts, B., Cools, A., Piepers, S. & Janssens, G. 2014. Piglets′ colostrum intake associates with daily weight gain and survival until weaning. *Livestock Science,* 162, 185-192.

Declerck, I., Sarrazin, S., Dewulf, J. & Maes, D. 2017. Sow and piglet factors determining variation of colostrum intake between and within litters. *Animal,* 11, 1336-1343.

Devillers, N., Van Milgen, J., Prunier, A. & Le Dividich, J. 2004. Estimation of colostrum intake in the neonatal pig. *Animal Science,* 78, 305-313.

Devillers, N., Farmer, C., Le Dividich, J. & Prunier, A. 2007. Variability of colostrum yield and colostrum intake in pigs. *Animal,* 1, 1033-1041.

Ding, S., Schoenmakers, I., Jones, K., Koulman, A., Prentice, A. & Volmer, D. A. 2010. Quantitative determination of vitamin D metabolites in plasma using UHPLC-MS/MS. *Analytical and Bioanalytical Chemistry,* 398, 779-789.

Douglas, S., Szyszka, O., Stoddart, K., Edwards, S. & Kyriazakis, I. 2014. A meta-analysis to identify animal and management factors influencing gestating sow efficiency. *Journal of Animal Science,* 92, 5716-5726.

Dourmad, J. 1991. Effect of feeding level in the gilt during pregnancy on voluntary feed intake during lactation and changes in body composition during gestation and lactation. *Livestock Production Science,* 27, 309-319.

Dourmad, J., Etienne, M. & Noblet, J. 1996. Reconstitution of body reserves in multiparous sows during pregnancy: effect of energy intake during pregnancy and mobilization during the previous lactation. *Journal of Animal Science,* 74, 2211-2219.

Dourmad, J., Quiniou, N., Heugebaert, S., Paboeuf, F. & Ngo, T. 2012. Effect of parity and number of suckling piglets on milk production of sows. In: *Book of Abstracts of the 63rd Annual Meeting of the European Federation of Animal Science, 27-31 August 2012, Bratislava, Slovakia.* The Netherlands: Wageningen Academic Publishers, 44.

Dugan, M., Aalhus, J., Schaefer, A. & Kramer, J. 1997. The effect of conjugated linoleic acid on fat to lean repartitioning and feed conversion in pigs. *Canadian Journal of Animal Science,* 77, 723-725.

Dwyer, C. M., Stickland, N. & Fletcher, J. 1994. The influence of maternal nutrition on muscle fiber number development in the porcine fetus and on subsequent postnatal growth. *Journal of Animal Science,* 72, 911-917.

Eastham, P., Smith, W., Whittemore, C. & Phillips, P. 1988. Responses of lactating sows to food level. *Animal Production,* 46, 71-77.

Eastwood, L., Leterme, P. & Beaulieu, A. 2014. Changing the omega-6 to omega-3 fatty acid ratio in sow diets alters serum, colostrum, and milk fatty acid profiles, but has minimal impact on reproductive performance. *Journal of Animal Science,* 92, 5567-5582.

Edwards, S. & Pike, I. 1997. Effect of fishmeal on sow reproductive performance. *Animal Science*, 55-55.

Edwards, S. 2002. Perinatal mortality in the pig: environmental or physiological solutions? *Livestock Production Science,* 78, 3-12.

Eissen, J., Kanis, E. & Kemp, B. 2000. Sow factors affecting voluntary feed intake during lactation. *Livestock Production Science,* 64, 147-165.

Eissen, J., Apeldoorn, E., Kanis, E., Verstegen, M. & De Greef, K. 2003. The importance of a high feed intake during lactation of primiparous sows nursing large litters. *Journal of Animal Science,* 81, 594-603.

Engblom, L., Lundeheim, N., Dalin, A.-M. & Andersson, K. 2007. Sow removal in Swedish commercial herds. *Livestock Science,* 106, 76-86.

Estienne, M., Harper, A., Barb, C. & Azain, M. 2000. Concentrations of leptin in serum and milk collected from lactating sows differing in body condition. *Domestic Animal Endocrinology,* 19, 275-280.

European Commission directive 2008/120/EC of 18 December 2008 on the Minimum standards for the protection of pigs [Online]. [Accessed on 3 August 2018]. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008L0120.

Farmer, C., Devillers, N., Rooke, J. A. & Dividich, J. L. 2006. Colostrum production in swine: from the mammary glands to the piglets. *Pig News and Information,* 27.

Farmer, C. & Petit, H. 2009. Effects of dietary supplementation with different forms of flax in late-gestation and lactation on fatty acid profiles in sows and their piglets. *Journal of Animal Science,* 87, 2600-2613.

Farmer, C., Palin, M.-F., Theil, P. K., Sorensen, M. & Devillers, N. 2012. Milk production in sows from a teat in second parity is influenced by whether it was suckled in first parity. *Journal of Animal Science,* 90, 3743-3751.

Feyera, T. & Theil, P. K. 2014. Nutrient balances of energy, lysine and nitrogen in late gestating and early lactating sows. In: *Book of Abstracts of the 65st Annual Meeting of the European Federation for Animal Science, 25-28 August 2014, Copenhagen, Denmark.* The Netherlands: Wageningen Academic Publishers*,* 342.

Filha, W. A., Bernardi, M., Wentz, I. & Bortolozzo, F. 2010. Reproductive performance of gilts according to growth rate and backfat thickness at mating. *Animal Reproduction Science,* 121, 139-144.

Fix, J., Cassady, J., Herring, W., Holl, J., Culbertson, M. & See, M. 2010. Effect of piglet birth weight on body weight, growth, backfat, and longissimus muscle area of commercial market swine. *Livestock Science,* 127, 51-59.

Flohr, J. R., Tokach, M. D., Dritz, S. S., DeRouchey, J. M., Goodband, R., Nelssen, J. & Bergstrom, J. 2014. An evaluation of the effects of added vitamin D in maternal diets on sow and pig performance. *Journal of Animal Science,* 92, 594-603.

Foisnet, A., Farmer, C., David, C. & Quesnel, H. 2010. Relationships between colostrum production by primiparous sows and sow physiology around parturition. *Journal of Animal Science,* 88, 1672-1683.

Ford, S., Vonnahme, K. & Wilson, M. 2002. Uterine capacity in the pig reflects a combination of uterine environment and conceptus genotype effects. *Journal of Animal Science,* 80, supplement 1, 66-73.

Foxcroft, G., Dixon, W., Novak, S., Putman, C., Town, S. & Vinsky, M. 2006. The biological basis for prenatal programming of postnatal performance in pigs. *Journal of Animal Science,* 84, supplement 13, 105-112.

Fritsche, K. L., Huang, S.-C. & Cassity, N. A. 1993. Enrichment of omega-3 fatty acids in suckling pigs by maternal dietary fish oil supplementation. *Journal of Animal Science,* 71, 1841-1847.

Gao, K., Jiang, Z., Lin, Y., Zheng, C., Zhou, G., Chen, F., Yang, L. & Wu, G. 2012. Dietary L-arginine supplementation enhances placental growth and reproductive performance in sows. *Amino Acids,* 42, 2207-2214.

Gerritsen, R., Soede, N., Langendijk, P., Hazeleger, W. & Kemp, B. 2008. The intermittent suckling regimen in pigs: consequences for reproductive performance of sows. *Reproduction in Domestic Animals,* 43, 29-35.

Goff, J. P., Horst, R. L. & Littledike, E. T. 1984. Effect of sow vitamin D status at parturition on the vitamin D status of neonatal piglets. *The Journal of Nutrition,* 114, 163-169.

Gómez-Carballar, F., Lara, L., Nieto, R. & Aguilera, J. 2013. Effect of increasing lysine supply during last third of gestation on reproductive performance of Iberian sows. *Spanish Journal of Agricultural Research,* 11, 798-807.

Gonçalves, M., Gourley, K., Dritz, S. S., Tokach, M. D., Bello, N. M., DeRouchey, J. M., Woodworth, J. C. & Goodband, R. D. 2016. Effects of amino acids and energy intake during late gestation of high-performing gilts and sows on litter and reproductive performance under commercial conditions. *Journal of Animal Science,* 94, 1993-2003.

Goodband, R., Tokach, M., Goncalves, M., Woodworth, J., Dritz, S. & DeRouchey, J. 2013. Nutritional enhancement during pregnancy and its effects on reproduction in swine. *Animal Frontiers,* 3, 68-75.

Guesnet, P. & Alessandri, J.-M. 2011. Docosahexaenoic acid (DHA) and the developing central nervous system (CNS)–implications for dietary recommendations. *Biochimie,* 93, 7-12.

Gugjoo, M., Ahmad, R., Bhat, S. & Wani, M. 2012. Stillbirth in pigs. *Journal of Advanced Veterinary Research,* 2, 218-231.

Gulliver, C., Friend, M., King, B. & Clayton, E. 2012. The role of omega-3 polyunsaturated fatty acids in reproduction of sheep and cattle. *Animal Reproduction Science,* 131, 9-22.

Gunnarsson, S., Pickova, J., Högberg, A., Neil, M., Wichman, A., Wigren, I., Uvnäs-Moberg, K. & Rydhmer, L. 2009. Influence of sow dietary fatty acid composition on the behaviour of the piglets. *Livestock Science,* 123, 306-313.

Haggarty, P., Page, K., Abramovich, D., Ashton, J. & Brown, D. 1997. Long-chain polyunsaturated fatty acid transport across the perfused human placenta. *Placenta,* 18, 635-642.

Hales, J., Moustsen, V. A., Nielsen, M. B. F. & Hansen, C. F. 2013. Individual physical characteristics of neonatal piglets affect preweaning survival of piglets born in a noncrated system. *Journal of Animal Science,* 91, 4991-5003.

Handel, S. & Stickland, N. 1987. The growth and differentiation of porcine skeletal muscle fibre types and the influence of birthweight. *Journal of Anatomy,* 152, 107.

Hansen, A., Strathe, A., Kebreab, E., France, J. & Theil, P. 2012. Predicting milk yield and composition in lactating sows: A Bayesian approach. *Journal of Animal Science,* 90, 2285-2298.

Head, R. & Williams, I. 1995. Potential milk production in gilts. *In:* Hennessy, D. & Cranwell, P. eds. *Manipulating pig production V, 26-29 Novemember 1995, Canberra.* Werribee: Australasian Pig Science Association, 134.

Heo, S., Yang, Y., Jin, Z., Park, M., Yang, B. & Chae, B. 2008. Effects of dietary energy and lysine intake during late gestation and lactation on blood metabolites, hormones, milk compositions and reproductive performance in primiparous sows. *Canadian Journal of Animal Science,* 88, 247-255.

Herpin, P., Le Dividich, J., Hulin, J. C., Fillaut, M., De Marco, F. & Bertin, R. 1996. Effects of the level of asphyxia during delivery on viability at birth and early postnatal vitality of newborn pigs. *Journal of Animal Science,* 74, 2067-2075.

Herpin, P., Damon, M. & Le Dividich, J. 2002. Development of thermoregulation and neonatal survival in pigs. *Livestock Production Science,* 78, 25-45.

Heyer, A., Andersson, H., Lindberg, J. & Lundström, K. 2004. Effect of extra maternal feed supply in early gestation on sow and piglet performance and production and meat quality of growing/finishing pigs. *Acta Agriculturae Scandinavica, Section A-Animal Science,* 54, 44-55.

Hines, E., Coffey, J., Starkey, C., Chung, T. & Starkey, J. 2013. Improvement of maternal vitamin D status with 25-hydroxycholecalciferol positively impacts porcine fetal skeletal muscle development and myoblast activity. *Journal of Animal Science,* 91, 4116-4122.

Holick, M.F. 2006. Resurrection of vitamin D deficiency and rickets. *Journal of Clincial Investigation*, 116, 2062-2072.

Holub, B. J. 2002. Clinical nutrition: 4. Omega-3 fatty acids in cardiovascular care. *Canadian Medical Association Journal,* 166, 608-615.

Horst, R., Goff, J. & Reinhardt, T. 1994. Calcium and Vitamin D Metabolism in the Dairy Cow. *Journal of Dairy Science,* 77, 1936-1951.

Hoving, L., Soede, N., Van der Peet-Schwering, C., Graat, E., Feitsma, H. & Kemp, B. 2011. An increased feed intake during early pregnancy improves sow body weight recovery and increases litter size in young sows. *Journal of Animal Science,* 89, 3542-3550.

Hurley, W. 2015. Composition of sow colostrum and milk. In: Farmer, C. ed. *The gestating and lactating sow.* The Netherlands: Wageningen Academic Publishers, 193-229.

Illmann, G., Neuhauserová, K., Pokorná, Z., Chaloupková, H. & Šimečková, M. 2008. Maternal responsiveness of sows towards piglet's screams during the first 24h postpartum. *Applied Animal Behaviour Science,* 112, 248-259.

Innis, S. M., Sprecher, H., Hachey, D., Edmond, J. & Anderson, R. E. 1999. Neonatal polyunsaturated fatty acid metabolism. *Lipids,* 34, 139-149.

Innis, S. M. 2007. Dietary (n-3) fatty acids and brain development. *The Journal of Nutrition,* 137, 855-859.

Jayaraman, B. & Nyachoti, C. M. 2017. Husbandry practices and gut health outcomes in weaned piglets: A review. *Animal Nutrition,* 3, 205-211.

Jean, K.-B. & Chiang, S.H. 1999. Increased survival of neonatal pigs by supplementing medium-chain triglycerides in late-gestating sow diets. *Animal Feed Science and Technology,* 76, 241-250.

Johnson, R., Zimmerman, D., Lamberson, W. & Sasaki, S. 1984. Influencing prolificacy of sows by selection for physiological factors. *Journal of Reproduction and Fertility.* Supplement, 33, 139-149.

Jones, D. & Stahly, T. 1999. Impact of amino acid nutrition during lactation on body nutrient mobilization and milk nutrient output in primiparous sows. *Journal of Animal Science,* 77, 1513-1522.

Kemp, B. 1998. Lactational effects on the endocrinology of reproduction. In: Verstegen, M.W.A., Moughan, P.J. & Schrama, J.W. eds. *The Lactating Sow*. The Netherlands: Wageningen Pers, 241-257.

Kemp, B. & Soede, N. 2012. Should weaning be the start of the reproductive cycle in hyper-prolific sows? a physiological view. *Reproduction in Domestic Animals,* 47, 320-326.

Kilbride, A. L., Mendl, M., Statham, P., Held, S., Harris, M., Cooper, S. & Green, L. E. 2012. A cohort study of preweaning piglet mortality and farrowing accommodation on 112 commercial pig farms in England. *Preventive Veterinary Medicine,* 104, 281-291.

Kim, S.W., Hurley, W.L., Han, I.K. & Easter, R.A. 1999. Changes in tissue composition associated with mammary gland growth during lactation in sows. *Journal of Animal Science,* 77, 2510-2516.

Kim, S. W., Mateo, R. D., Yin, Y.-L. & Wu, G. 2007. Functional amino acids and fatty acids for enhancing production performance of sows and piglets. *Asian Australasian Journal of Animal Sciences,* 20, 295.

Kim, S. W., Hurley, W. L., Wu, G. & Ji, F. 2009. Ideal amino acid balance for sows during gestation and lactation. *Journal of Animal Science,* 87, supplement 14, 123-132.

Kim, S. W., Weaver, A. C., Shen, Y. B. & Zhao, Y. 2013. Improving efficiency of sow productivity: nutrition and health. *Journal of Animal Science and Biotechnology,* 4, 26.

King, R., Mullan, B., Dunshea, F. & Dove, H. 1997. The influence of piglet body weight on milk production of sows. *Livestock Production Science,* 47, 169-174.

King, R., Campbell, R., Smits, R., Morley, W., Ronnfeldt, K., Butler, K. & Dunshea, F. 2000. Interrelationships between dietary lysine, sex, and porcine somatotropin administration on growth performance and protein deposition in pigs between 80 and 120 kg live weight. *Journal of Animal Science,* 78, 2639-2651.

King, R., Eason, P., Smits, R., Morley, W. & Henman, D. 2006. The response of sows to increased nutrient intake during mid to late gestation. *Crop and Pasture Science,* 57, 33-39.

Kirk, R. K., Svensmark, B., Ellegaard, L. & Jensen, H. 2005. Locomotive disorders associated with sow mortality in Danish pig herds. *Journal of Veterinary Medicine Series A,* 52, 423-428.

Klindt, J. 2003. Influence of litter size and creep feeding on preweaning gain and influence of preweaning growth on growth to slaughter in barrows. *Journal of Animal Science,* 81, 2434-2439.

Knap, P. & Rauw, W. 2008. Selection for high production in pigs. In: Rauw, W.M. ed. *Resource allocation theory applied to farm animal production*. CABI Publishing, 210-229.

Knox, R. & Zas, S. R. 2001. Factors influencing estrus and ovulation in weaned sows as determined by transrectal ultrasound. *Journal of Animal Science,* 79, 2957.

Koketsu, Y., Dial, G. D., Pettigrew, J. E. & Marsh, W. E. 1996. Characterization of feed intake patterns during lactation in commercial swine herds. *Journal of Animal Science,* 74, 1202-1210.

Koketsu, Y., Takenobu, S. & Nakamura, R. 2006. Preweaning mortality risks and recorded causes of death associated with production factors in swine breeding herds in Japan. *Journal of Veterinary Medical Science,* 68, 821-826.

Koketsu, Y. 2007. Longevity and efficiency associated with age structures of female pigs and herd management in commercial breeding herds. *Journal of Animal Science,* 85, 1086-1091.

Koketsu, Y., Tani, S. & Iida, R. 2017. Factors for improving reproductive perfromance of sows and herd productivity in commerical breeding herds. *Porcine Health Management*, 3, 1.

Kongsted, A. G. 2005. A review of the effect of energy intake on pregnancy rate and litter size–discussed in relation to group-housed non-lactating sows. *Livestock Production Science,* 97, 13-26.

Krogh, U., Flummer, C., Jensen, S. K. & Theil, P. K. 2012. Colostrum and milk production of sows is affected by dietary conjugated linoleic acid. *Journal of Animal Science,* 90, 366-368.

Kruse, S., Traulsen, I. & Krieter, J. 2011. Analysis of water, feed intake and performance of lactating sows. *Livestock Science,* 135, 177-183.

Kusina, J., Pettigrew, J., Sower, A., White, M., Crooker, B. & Hathaway, M. 1999. Effect of protein intake during gestation and lactation on the lactational performance of primiparous sows. *Journal of Animal Science,* 77, 931-941.

Lauridsen, C. & Danielsen, V. 2004. Lactational dietary fat levels and sources influence milk composition and performance of sows and their progeny. *Livestock Production Science,* 91, 95-105.

Lauridsen, C., Halekoh, U., Larsen, T. & Jensen, S. K. 2010. Reproductive performance and bone status markers of gilts and lactating sows supplemented with two different forms of vitamin D. *Journal of Animal Science,* 88, 202-213.

Lauridsen, C. & Jensen, S. K. 2013. Vitamin nutrition. In: Bach Knudsen, K.E., Kjeldsen, N.J., Poulsen, H.D. & Jensen, B.B. eds. *Nutritional Physiology of Pigs-Online Publication.* Foulum: Videncenter for Svineproduktion, 1-28.

Lawlor, P. & Lynch, P. 2005. Management interventions to help keep piglets alive in large litters. *Irish Veterinary Journal,* 58, 640-645.

Lawlor, P. G. & Lynch, P. B. 2007. A review of factors influencing litter size in Irish sows. *Irish Veterinary Journal,* 60, 359.

Lawlor, P. G., Lynch, P. B., O connell, M. K., Mcnamara, L., Reid, P. & Stickland, N. C. 2007a. The influence of over feeding sows during gestation on reproductive performance and pig growth to slaughter. *Archiv Fur Tierzucht,* 50, 82.

Lawlor, P. G., Lynch, P. B., O'Connell, M. K., Heit, C. & Mattras, D. 2007b. Manipulation of liquid feed curves during lactation to increase sow feed intake and its impact on sow weight and back-fat and piglet performance to weaning. In: *Proceedings of the Agricultural Research Forum, 12 March 2007, Tullamore, Ireland*, 116.

Lawlor, P. G., Ryan, T., O'connell, K. & Lynch, P. B. 2012. Manipulation of liquid feeding curves for sows to increase lactation feed intake. In: *Proceedings of Pig Research to Improve Sustainability*, 1 November 2012, *Agri-food and Bioscience Institute (AFBI), Hillsborough*. AFBI, 35-52.

Laws, J., Laws, A., Lean, I., Dodds, P. & Clarke, L. 2007a. Growth and development of offspring following supplementation of sow diets with oil during early to mid gestation. *Animal*, 1, 1482-1489.

Laws, J., Laws, A., Lean, I., Dodds, P. & Clarke, L. 2007b. Growth and development of offspring following supplementation of sow diets with oil during mid to late gestation. *Animal*, 1, 1490-1496.

Laws, J., Litten, J. C., Laws, A., Lean, I. J., Dodds, P. F. & Clarke, L. 2009. Effect of type and timing of oil supplements to sows during pregnancy on the growth performance and endocrine profile of low and normal birth weight offspring. *British Journal of Nutrition,* 101, 240-249.

Le Dividich, J. & Noblet, J. 1983. Thermoregulation and energy metabolism in the neonatal pig. In: INRA ed. *Annales de recherches vétérinaires*, 14, 375-381.

Le Dividich, J., Rooke, J. & Herpin, P. 2005. Nutritional and immunological importance of colostrum for the new-born pig. *The Journal of Agricultural Science,* 143, 469-485.

Lee, S.-H., Joo, Y.-K., Lee, J.-W., Ha, Y.-J., Yeo, J.-M. & Kim, W.-Y. 2014. Dietary Conjugated Linoleic Acid (CLA) increases milk yield without losing body weight in lactating sows. *Journal of Animal Science and Technology,* 56, 11.

Leenhouwers, J., Knol, E., De Groot, P., Vos, H. & Van der Lende, T. 2002. Fetal development in the pig in relation to genetic merit for piglet survival. *Journal of Animal Science,* 80, 1759-1770.

Legault, C. 1984. Selection of breeds, strains and individual pigs for prolificacy. *Journal of Reproduction and Fertility.* Supplement, 33, 151-166.

Leliveld, L., Riemensperger, A., Gardiner, G., O'Doherty, J., Lynch, P. & Lawlor, P. 2013. Effect of weaning age and postweaning feeding programme on the growth performance of pigs to 10 weeks of age. *Livestock Science,* 157, 225-233.

Leonard, S., Sweeney, T., Bahar, B., Lynch, B. & O'doherty, J. 2010. Effect of maternal fish oil and seaweed extract supplementation on colostrum and milk composition, humoral immune response, and performance of suckled piglets. *Journal of Animal Science,* 88, 2988-2997.

Leroy, J., Van Soom, A., Opsomer, G., Goovaerts, I. & Bols, P. 2008. Reduced Fertility in High-yielding Dairy Cows: Are the Oocyte and Embryo in Danger? Part II Mechanisms Linking Nutrition and Reduced Oocyte and Embryo Quality in High-yielding Dairy Cows. *Reproduction in Domestic Animals,* 43, 623-632.

Li, P., Kim, S. W., Li, X., Datta, S., Pond, W. G. & Wu, G. 2009. Dietary supplementation with cholesterol and docosahexaenoic acid affects concentrations of amino acids in tissues of young pigs. *Amino Acids,* 37, 709-716.

Liao, S.F., Wang, T. & Regmi, N. 2015. Lysine nutrition in swine and the related monogastric animals:muscle protein biosynthesis and beyond. *SpringerPlus*, 41, 147.

Lin, C., Chiang, S. & Lee, H. 1995. Causes of reduced survival of neonatal pigs by medium-chain triglycerides: blood metabolite and behavioral activity approaches. *Journal of Animal Science,* 73, 2019-2025.

Liu, H.-Q., Qiu, Y., Mu, Y., Zhang, X.-J., Liu, L., Hou, X.-H., Zhang, L., Xu, X.-N., Ji, A.-L. & Cao, R. 2013. A high ratio of dietary n-3/n-6 polyunsaturated fatty acids improves obesity-linked inflammation and insulin resistance through suppressing activation of TLR4 in SD rats. *Nutrition Research,* 33, 849-858.

Lodge, G. 1969. The effects of pattern of feed distribution during the reproductive cycle on the performance of sows. *Animal Production,* 11, 133-143.

Loisel, F., Farmer, C., Ramaekers, P. & Quesnel, H. 2013. Effects of high fiber intake during late pregnancy on sow physiology, colostrum production, and piglet performance. *Journal of Animal Science,* 91, 5269-5279.

Lucia, J., Dial, G. & Marsh, W. 1999. Estimation of lifetime productivity of female swine. *Journal of the American Veterinary Medical Association,* 214, 1056-1059.

Lucia, T., Dial, G. D. & Marsh, W. E. 2000. Lifetime reproductive performance in female pigs having distinct reasons for removal. *Livestock Production Science,* 63, 213-222.

Luo, J., Huang, F., Xiao, C., Chen, W., Jiang, S. & Peng, J. 2009. Effect of dietary supplementation of fish oil for lactating sows and weaned piglets on piglet Th polarization. *Livestock Science,* 126, 286-291.

Madsen, J. & Bee, G. 2015. Compensatory growth feeding strategy does not overcome negative effects on growth and carcass composition of low birth weight pigs. *Animal,* 9, 427-436.

Maes, D., Janssens, G., Delputte, P., Lammertyn, A. & de Kruif, A. 2004. Back fat measurements in sows from three commercial pig herds: relationship with reproductive efficiency and correlation with visual body condition scores. *Livestock Production Science,* 91, 57-67.

Magowan, E., Ball, M., McCracken, K., Beattie, V., Bradford, R., Robinson, M., Scott, M., Gordon, F. & Mayne, C. 2011. The performance response of pigs of different wean weights to ‘high’or ‘low’input dietary regimes between weaning and 20 weeks of age. *Livestock Science,* 136, 232-239.

Mahan, D. & Lepine, A. 1991. Effect of pig weaning weight and associated nursery feeding programs on subsequent performance to 105 kilograms body weight. *Journal of Animal Science,* 69, 1370-1378.

Main, D., Clegg, J., Spatz, A. & Green, L. 2000. Repeatability of a lameness scoring system for finishing pigs. *Veterinary Record,* 147, 574-576.

Main, R. G., Dritz, S. S., Tokach, M. D., Goodband, R. & Nelssen, J. L. 2005. Effects of weaning age on growing-pig costs and revenue in a multi-site production system. *Journal of Swine Health and Production,* 13, 189.

Markham, T., Latorre, R., Lawlor, P., Ashton, C., McNamara, L., Natter, R., Rowlerson, A. & Stickland, N. 2009. Developmental programming of skeletal muscle phenotype/metabolism. *Animal,* 3, 1001-1012.

Mateo, R. D., Wu, G., Bazer, F. W., Park, J. C., Shinzato, I. & Kim, S. W. 2007. Dietary L-arginine supplementation enhances the reproductive performance of gilts. *The Journal of Nutrition,* 137, 652-656.

Mateo, R. D., Wu, G., Moon, H. K., Carroll, J.A. & Kim, S.W. 2008. Effects of dietary arginine supplementation during gestation and lactation on the performance of lactating primiparous sows and nursing piglets. *Journal of Animal Science,* 86, 827-835.

Mateo, R. D., Carroll, J.A., Hyun, Y., Smith, S. & Kim, S.W. 2009. Effect of dietary supplementation of n-3 fatty acids and elevated concentrations of dietary protein on the performance of sows. *Journal of Animal Science,* 87, 948-959.

Matte, J. J., Guay, F. & Girard, C. L. 2006. Folic acid and vitamin B-12 in reproducing sows: New concepts. *Canadian Journal of Animal Science,* 86, 197-205.

McNamara, L., Giblin, L., Markham, T., Stickland, N., Berry, D. P., O'Reilly, J. J., Lynch, P. B., Kerry, J. & Lawlor, P. G. 2011. Nutritional intervention during gestation alters growth, body composition and gene expression patterns in skeletal muscle of pig offspring. *Animal,* 5, 1195-1206.

McNeil, C. J., Finch, A. M., Page, K. R., Clarke, S. D., Ashworth, C. J. & McArdle, H. J. 2005. The effect of fetal pig size and stage of gestation on tissue fatty acid metabolism and profile. *Reproduction,* 129, 757-763.

McPherson, R., Ji, F., Wu, G., Blanton, J. & Kim, S. 2004. Growth and compositional changes of fetal tissues in pigs. *Journal of Animal Science,* 82, 2534-2540.

Mejia-Guadarrama, C., Pasquier, A., Dourmad, J., Prunier, A. & Quesnel, H. 2002. Protein (lysine) restriction in primiparous lactating sows: effects on metabolic state, somatotropic axis, and reproductive performance after weaning. *Journal of Animal Science,* 80, 3286-3300.

Miller, Y., Collins, A., Smits, R., Thomson, P. & Holyoake, P. 2012. Providing supplemental milk to piglets preweaning improves the growth but not survival of gilt progeny compared with sow progeny. *Journal of Animal Science,* 90, 5078-5085.

Milligan, B. N., Fraser, D. & Kramer, D. L. 2001. Birth weight variation in the domestic pig: effects on offspring survival, weight gain and suckling behaviour. *Applied Animal Behaviour Science,* 73, 179-191.

Milligan, B. N., Fraser, D. & Kramer, D. L. 2002. Within-litter birth weight variation in the domestic pig and its relation to pre-weaning survival, weight gain, and variation in weaning weights. *Livestock Production Science,* 76, 181-191.

Mitre, R., Etienne, M., Martinais, S., Salmon, H., Allaume, P., Legrand, P. & Legrand, A. B. 2005. Humoral defence improvement and haematopoiesis stimulation in sows and offspring by oral supply of shark-liver oil to mothers during gestation and lactation. *British Journal of Nutrition,* 94, 753-762.

Moehn, S., Franco, D., Levesque, C., Samuel, R. & Ball, R. O. 2011. New energy and amino acid requirements for gestating sows. *Advances in Pork Production,* 22, 157-166.

Moehn, S. & Ball, R. O. 2013. Nutrition of pregnant sows. In: Smith, J.H. ed. *Proceedings of the 2013 London Swine Conference, Managing for Production, 27-28 March 2013, London, Ontario*: London Swine Confrence, 55-63.

Mollard, R. C., Kovacs, H. R., Fitzpatrick-Wong, S. C. & Weiler, H. A. 2005. Low levels of dietary arachidonic and docosahexaenoic acids improve bone mass in neonatal piglets, but higher levels provide no benefit. *The Journal of Nutrition,* 135, 505-512.

Morgan, C., Whittemore, C., Phillips, P. & Crooks, P. 1987. The prediction of the energy value of compounded pig foods from chemical analysis. *Animal Feed Science and Technology,* 17, 81-107.

Mota-Rojas, D., Martínez-Burnes, J., Trujillo, M. E., López, A., Rosales, A. M., Ramírez, R., Orozco, H., Merino, A. & Alonso-Spilsbury, M. 2005. Uterine and fetal asphyxia monitoring in parturient sows treated with oxytocin. *Animal Reproduction Science,* 86, 131-141.

Muhlhausler, B., Gibson, R. & Makrides, M. 2011. The effect of maternal omega-3 long-chain polyunsaturated fatty acid (n-3 LCPUFA) supplementation during pregnancy and/or lactation on body fat mass in the offspring: a systematic review of animal studies. *Prostaglandins, Leukotrienes and Essential Fatty Acids,* 85, 83-88.

Mullan, B. & Williams, I. 1989. The effect of body reserves at farrowing on the reproductive performance of first-litter sows. *Animal Science,* 48, 449-457.

Muns, R., Malmkvist, J., Larsen, M., Sørensen, D. & Pedersen, L. 2016a. High environmental temperature around farrowing induced heat stress in crated sows. *Journal of Animal Science,* 94, 377-384.

Muns, R., Nuntapaitoon, M. & Tummaruk, P. 2016b. Non-infectious causes of pre-weaning mortality in piglets. *Livestock Science,* 184, 46-57.

Muns, R. & Magowan, E. 2018. The effect of creep feed intake and starter diet allowance on piglets' gut structure and growth performance after weaning. *Journal of Animal Science,* 96, 3815-3823.

Murthi, P., Yong, H. E., Ngyuen, T. P., Ellery, S., Singh, H., Rahman, R., Dickinson, H., Walker, D. W., Davies-Tuck, M. & Wallace, E. M. 2016. Role of the placental vitamin D receptor in modulating feto-placental growth in fetal growth restriction and preeclampsia-affected pregnancies. *Frontiers in Physiology,* 7, 43.

Nielsen, B., Su, G., Lund, M. S. & Madsen, P. 2013. Selection for increased number of piglets at d 5 after farrowing has increased litter size and reduced piglet mortality. *Journal of Animal Science,* 91, 2575-2582.

Noblet, J., Dourmad, J. Y. & Etienne, M. 1990. Energy utilization in pregnant and lactating sows: modeling of energy requirements. *Journal of Animal Science,* 68, 562-572.

Noblet, J., Etienne, M. & Dourmad, J. 1998. Energetic efficiency of milk production. In: Verstegen, M.W.A., Moughan, P.J. & Schrama, J.W. eds. *The Lactating Sow.* The Netherlands: Wageningen Pers, 113-130.

NRC (National Research Council). 1998. *Nutrient requirements of swine*. 10th rev. ed. Washingtion, D.C: The National Academies Press.

NRC (National Research Council). 2012. *Nutrient Requirements of Swine.* 11th rev. ed. Washington, D.C:The National Academies Press.

O'Brien, M. A. & Jackson, M. W. 2012. Vitamin D and the immune system: beyond rickets. *The Veterinary Journal,* 194, 27-33.

O’fallon, J., Busboom, J., Nelson, M. & Gaskins, C. 2007. A direct method for fatty acid methyl ester synthesis: application to wet meat tissues, oils, and feedstuffs. *Journal of Animal Science,* 85, 1511-1521.

Oliviero, C., Heinonen, M., Valros, A. & Peltoniemi, O. 2010. Environmental and sow-related factors affecting the duration of farrowing. *Animal Reproduction Science,* 119, 85-91.

Ostrowska, E., Muralitharan, M., Cross, R. F., Bauman, D. E. & Dunshea, F. R. 1999. Dietary conjugated linoleic acids increase lean tissue and decrease fat deposition in growing pigs. *The Journal of Nutrition,* 129, 2037-2042.

Panzardi, A., Bernardi, M., Mellagi, A., Bierhals, T., Bortolozzo, F. & Wentz, I. 2013. Newborn piglet traits associated with survival and growth performance until weaning. *Preventive Veterinary Medicine,* 110, 206-213.

Papadopoulos, G. A., Maes, D. G., Van Weyenberg, S., van Kempen, T. A., Buyse, J. & Janssens, G. P. 2008. Peripartal feeding strategy with different n-6: n-3 ratios in sows: effects on sows' performance, inflammatory and periparturient metabolic parameters. *British Journal of Nutrition,* 101, 348-357.

Parfet, K. & Gonyou, H. 1991. Attraction of newborn piglets to auditory, visual, olfactory and tactile stimuli. *Journal of Animal Science,* 69, 125-133.

Park, M., Yang, Y., Choi, J., Yoon, S., Ahn, S., Lee, S., Yang, B., Lee, J. & Chae, B. 2008. Effects of dietary fat inclusion at two energy levels on reproductive performance, milk compositions and blood profiles in lactating sows. *Acta Agriculturae Scandinavica, Section A-Animal Science,* 58, 121-128.

Pedersen, T. F., Bruun, T. S., Feyera, T., Larsen, U. K. & Theil, P. K. 2016. A two-diet feeding regime for lactating sows reduced nutrient deficiency in early lactation and improved milk yield. *Livestock Science,* 191, 165-173.

Pettigrew, J. E. 1981. Supplemental dietary fat for peripartal sows: a review. *Journal of Animal Science,* 53, 107-117.

Pettigrew, J. E. & Yang, H. 1997. Protein nutrition of gestating sows. *Journal of Animal Science,* 75, 2723-2730.

PIC, 2017. Gilt and sow management guidelines, 2017 ed. [Online]. [Accessed 12 March 2019]. Available from: http://gb.pic.com/sites/gb_picgenus_com/Uploads/files/Downloads/Other/GiltandSowManagementGuidelines_2017_Metric_A4_UK.pdf.

Pinelli-Saavedra, A. & Scaife, J. 2005. Pre-and postnatal transfer of vitamins E and C to piglets in sows supplemented with vitamin E and vitamin C. *Livestock Science,* 97, 231-240.

Pluske, J. R., Williams, I. H., Zak, L. J., Clowes, E. J., Cegielski, A. C. & Aherne, F. X. 1998. Feeding lactating primiparous sows to establish three divergent metabolic states: III. Milk production and pig growth. *Journal of Animal Science,* 76, 1165-1171.

Prunier, A., Quesnel, H., de Bragança, M. M. & Kermabon, A. 1996. Environmental and seasonal influences on the return-to-oestrus after weaning in primiparous sows: a review. *Livestock Production Science,* 45, 103-110.

Quesnel, H., Pasquier, A., Jan, N. & Prunier, A. 2000. Influence of insulin treatment and feed restriction on follicular development in cyclic gilts. *Animal Reproduction Science,* 64, 77-87.

Quesnel, H., Brossard, L., Valancogne, A. & Quiniou, N. 2008. Influence of some sow characteristics on within-litter variation of piglet birth weight. *Animal,* 2, 1842-1849.

Quesnel, H. 2011. Colostrum production by sows: variability of colostrum yield and immunoglobulin G concentrations. *Animal,* 5, 1546-1553.

Quesnel, H., Farmer, C. & Devillers, N. 2012. Colostrum intake: Influence on piglet performance and factors of variation. *Livestock Science,* 146, 105-114.

Quesnel, H., Ramaekers, P., Hees, H. v. & Farmer, C. 2013. Relations between peripartum concentrations of prolactin and progesterone in sows and piglet growth in early lactation. *Canadian Journal of Animal Science,* 93, 109-112.

Quesnel, H., Farmer, C. & Theil, P. 2015. Colostrum and milk production. In: Farmer, C. ed. *The gestating and lactating sow.* The Netherlands: Wageningen Academic Publishers, 173-192.

Quiniou, N., Dagorn, J. & Gaudré, D. 2002. Variation of piglets' birth weight and consequences on subsequent performance. *Livestock Production Science,* 78, 63-70.

Quiniou, N., Richard, S., Mourot, J. & Etienne, M. 2008. Effect of dietary fat or starch supply during gestation and/or lactation on the performance of sows, piglets' survival and on the performance of progeny after weaning. *Animal*, 2, 1633-1644.

Raclot, T. 2003. Selective mobilization of fatty acids from adipose tissue triacylglycerols. *Progress in Lipid Research,* 42, 257-288.

Ramanau, A., Kluge, H., Spilke, J. & Eder, K. 2004. Supplementation of sows with L-carnitine during pregnancy and lactation improves growth of the piglets during the suckling period through increased milk production. *The Journal of Nutrition,* 134, 86-92.

Rehfeldt, C., Tuchscherer, A., Hartung, M. & Kuhn, G. 2008. A second look at the influence of birth weight on carcass and meat quality in pigs. *Meat Science,* 78, 170-175.

Rekiel, A., Więcek, J., Batorska, M. & Kulisiewicz, J. 2014. Effect of sow prolificacy and nutrition on preand postnatal growth of progeny–a review. *Annals of Animal Science,* 14, 3-15.

Renaudeau, D., Noblet, J. & Dourmad, J. 2003. Effect of ambient temperature on mammary gland metabolism in lactating sows. *Journal of Animal Science,* 81, 217-231.

Revell, D., Williams, I., Mullan, B., Ranford, J. & Smits, R. 1998. Body composition at farrowing and nutrition during lactation affect the performance of primiparous sows: II. Milk composition, milk yield, and pig growth. *Journal of Animal Science,* 76, 1738-1743.

Rooke, J., Bland, I. & Edwards, S. 1998. Effect of feeding tuna oil or soyabean oil as supplements to sows in late pregnancy on piglet tissue composition and viability. *British Journal of Nutrition,* 80, 273-280.

Rooke, J., Bland, I. & Edwards, S. 1999. Relationships between fatty acid status of sow plasma and that of umbilical cord, plasma and tissues of newborn piglets when sows were fed on diets containing tuna oil or soyabean oil in late pregnancy. *British Journal of Nutrition,* 82, 213-221.

Rooke, J., Shanks, M. & Edwards, S. 2000. Effect of offering maize, linseed or tuna oils throughout pregnancy and lactation on sow and piglet tissue composition and piglet performance. *Animal Science,* 71, 289-299.

Rooke, J., Sinclair, A., Edwards, S., Cordoba, R., Pkiyach, S., Penny, P., Penny, P., Finch, A. & Horgan, G. 2001a. The effect of feeding salmon oil to sows throughout pregnancy on pre-weaning mortality of piglets. *Animal Science,* 73, 489-500.

Rooke, J., Sinclair, A. & Edwards, S. 2001b. Feeding tuna oil to the sow at different times during pregnancy has different effects on piglet long-chain polyunsaturated fatty acid composition at birth and subsequent growth. *British Journal of Nutrition,* 86, 21-30.

Rooke, J., Sinclair, A. & Ewen, M. 2001c. Changes in piglet tissue composition at birth in response to increasing maternal intake of long-chain n-3 polyunsaturated fatty acids are non-linear. *British Journal of Nutrition,* 86, 461-470.

Rooke, J. & Bland, I. 2002. The acquisition of passive immunity in the new-born piglet. *Livestock Production Science,* 78, 13-23.

Rooke, J., Carranca, C., Bland, I., Sinclair, A., Ewen, M., Bland, V. & Edwards, S. 2003. Relationships between passive absorption of immunoglobulin G by the piglet and plasma concentrations of immunoglobulin G at weaning. *Livestock Production Science,* 81, 223-234.

Roongsitthichai, A. & Tummaruk, P. 2014. Importance of Backfat Thickness to Reproductive Performance in Female Pigs. *The Thai Journal of Veterinary Medicine,* 44, 171.

Rortvedt, L. & Crenshaw, T. 2012. Expression of kyphosis in young pigs is induced by a reduction of supplemental vitamin D in maternal diets and vitamin D, Ca, and P concentrations in nursery diets. *Journal of Animal Science,* 90, 4905-4915.

Rosero, D., Odle, J., Arellano, C., Boyd, R. & van Heugten, E. 2015. Development of prediction equations to estimate the apparent digestible energy content of lipids when fed to lactating sows. *Journal of Animal Science,* 93, 1165-1176.

Rossi, R., Pastorelli, G., Cannata, S. & Corino, C. 2010. Recent advances in the use of fatty acids as supplements in pig diets: a review. *Animal Feed Science and Technology,* 162, 1-11.

Rutherford, K., Baxter, E., D'Eath, R., Turner, S., Arnott, G., Roehe, R., Ask, B., Sandøe, P., Moustsen, V. & Thorup, F. 2013. The welfare implications of large litter size in the domestic pig I: biological factors. *Animal Welfare,* 22, 199-218.

Ryan, T., Lynch, P. B. & Lawlor, P. G. 2009. Comparison between computerised liquid feeding and ad libitum dry feeding for sows during lactation. In: *Book of Abstracts of the 60th Annual Meeting of the European Federation of Animal Science, 24-27 August 2009, Barcelona, Spain*. The Netherlands: Wageningen Academic Publishers, 451.

Špinka, M., Illmann, G., Algers, B. & Štetkova, Z. 1997. The role of nursing frequency in milk production in domestic pigs. *Journal of Animal Science,* 75, 1223-1228.

Sampels, S., Pickova, J., Högberg, A. & Neil, M. 2011. Fatty acid transfer from sow to piglet differs for different polyunsaturated fatty acids (PUFA). *Physiological Research,* 60, 113.

Samuel, R., Moehn, S., Pencharz, P. & Ball, R. 2012. Dietary lysine requirement of sows increases in late gestation. *Journal of Animal Science,* 90, 4896-4904.

Sangild, P., Fowden, A. & Trahair, J. 2000. How does the foetal gastrointestinal tract develop in preparation for enteral nutrition after birth? *Livestock Science,* 66, 141-150.

Sasaki, Y. & Koketsu, Y. 2008. Sows having high lifetime efficiency and high longevity associated with herd productivity in commercial herds. *Livestock Science,* 118, 140-146.

Schenkel, A., Bernardi, M., Bortolozzo, F. & Wentz, I. 2010. Body reserve mobilization during lactation in first parity sows and its effect on second litter size. *Livestock Science,* 132, 165-172.

Schmidt, M., Lahrmann, K.-H., Ammon, C., Berg, W., Schön, P. & Hoffmann, G. 2013. Assessment of body temperature in sows by two infrared thermography methods at various body surface locations. *Journal of Swine Health and Production,* 21, 203-209.

Skok, J. & Škorjanc, D. 2014. Group suckling cohesion as a prelude to the formation of teat order in piglets. *Applied Animal Behaviour Science,* 154, 15-21.

Smit, M., Patterson, J. L., Webel, S., Spencer, J., Cameron, A., Dyck, M., Dixon, W. & Foxcroft, G. 2013. Responses to n-3 fatty acid (LCPUFA) supplementation of gestating gilts, and lactating and weaned sows. *Animal,* 7, 784-792.

Smit, M., Spencer, J., Patterson, J., Dyck, M., Dixon, W. & Foxcroft, G. 2015. Effects of dietary enrichment with a marine oil-based n-3 LCPUFA supplement in sows with predicted birth weight phenotypes on birth litter quality and growth performance to weaning. *Animal,* 9, 471-480.

Smith, A. L., Stalder, K. J., Serenius, T. V., Baas, T. J. & Mabry, J. W. 2008. Effect of weaning age on nursery pig and sow reproductive performance. *Journal of Swine Health and Production,* 16, 131.

Smits, R., Luxford, B., Mitchell, M. & Nottle, M. 2011. Sow litter size is increased in the subsequent parity when lactating sows are fed diets containing n-3 fatty acids from fish oil. *Journal of Animal Science,* 89, 2731-2738.

Smits, R., Henman, D. & King, R. 2013. Increasing the energy content of lactation diets fed to first-litter sows reduces weight loss and improves productivity over two parities. *Animal Production Science,* 53, 23-29.

Soede, N., Laurenssen, B., Abrahamse-Berkeveld, M., Gerritsen, R., Dirx-Kuijken, N., Langendijk, P. & Kemp, B. 2012. Timing of lactational oestrus in intermittent suckling regimes: consequences for sow fertility. *Animal Reproduction Science,* 130, 74-81.

Soede, N. & Kemp, B. 2015. Best practices in the lactating and weaned sow to optimize reproductive physiology and performance. In: Farmer, C.

ed. *The gestating and lactating sow.* The Netherlands: Wageningen Academic Publishers, 377-407.

Soerensen, D. D. & Pedersen, L. J. 2015. Infrared skin temperature measurements for monitoring health in pigs: a review. *Acta Veterinaria Scandinavica,* 57, 5.

Stalder, K. J., Lacy, R. C., Cross, T. L. & Conatser, G. E. 2003. Financial impact of average parity of culled females in a breed-to-wean swine operation using replacement gilt net present value analysis. *Journal of Swine Health and Production,* 11, 69-74.

Statista. 2018. *Projected pig meat consumption worldwide from 2014 to 2026 (in metric kilotons)** [Online]. [Accessed on 31 May 2018]. Available from: https://www.statista.com/statistics/739879/pork-consumption-worldwide/.

Stavrakakis, S., Guy, J., Syranidis, I., Johnson, G. & Edwards, S. 2015. Pre-clinical and clinical walking kinematics in female breeding pigs with lameness: A nested case-control cohort study. *The Veterinary Journal,* 205, 38-43.

Strathe, A., Bruun, T. & Hansen, C. 2017. Sows with high milk production had both a high feed intake and high body mobilization. *Animal,* 11, 1913-1921.

Strobel, N., Buddhadasa, S., Adorno, P., Stockham, K. & Greenfield, H. 2013. Vitamin D and 25-hydroxyvitamin D determination in meats by LC–IT-MS. *Food Chemistry,* 138, 1042-1047.

Su, G., Sorensen, D. & Lund, M. 2008. Variance and covariance components for liability of piglet survival during different periods. *Animal,* 2, 184-189.

Sulabo, R., Jacela, J., Tokach, M., Dritz, S., Goodband, R., DeRouchey, J. M. & Nelssen, J. 2010. Effects of lactation feed intake and creep feeding on sow and piglet performance. *Journal of Animal Science,* 88, 3145-3153.

Tang, M., Laarveld, B., Van Kessel, A., Hamilton, D., Estrada, A. & Patience, J. 1999. Effect of segregated early weaning on postweaning small intestinal development in pigs. *Journal of Animal Science,* 77, 3191-3200.

Tanghe, S., Millet, S. & De Smet, S. 2013. Echium oil and linseed oil as alternatives for fish oil in the maternal diet: Blood fatty acids profiles and oxidative status of sows and piglets. *Journal of Animal Science,* 91, 3253-3264.

Tanghe, S., Missotten, J., Raes, K., Vangeyte, J. & De Smet, S. 2014. Diverse effects of linseed oil and fish oil in diets for sows on reproductive performance and pre-weaning growth of piglets. *Livestock Science,* 164, 109-118.

Taugbøl, O., Framstad, T. & Saarem, K. 1993. Supplements of cod liver oil to lactating sows. Influence on milk fatty acid composition and growth performance of piglets. *Journal of Veterinary Medicine Series A,* 40, 437-443.

Thaker, M. & Bilkei, G. 2005. Lactation weight loss influences subsequent reproductive performance of sows. *Animal Reproduction Science,* 88, 309-318.

Theil, P. K., Nielsen, T. T., Kristensen, N. B., Labouriau, R., Danielsen, V., Lauridsen, C. & Jakobsen, K. 2002. Estimation of milk production in lactating sows by determination of deuterated water turnover in three piglets per litter. *Acta Agriculturae Scandinavica, Section A-Animal Science,* 52, 221-232.

Theil, P. K., Flummer, C., Hurley, W., Kristensen, N. B., Labouriau, R. & Sørensen, M. T. 2014a. Mechanistic model to predict colostrum intake based on deuterium oxide dilution technique data and impact of gestation and prefarrowing diets on piglet intake and sow yield of colostrum. *Journal of Animal Science,* 92, 5507-5519.

Theil, P. K., Lauridsen, C. & Quesnel, H. 2014b. Neonatal piglet survival: impact of sow nutrition around parturition on fetal glycogen deposition and production and composition of colostrum and transient milk. *Animal,* 8, 1021-1030.

Theil, P. K. 2015. Transition feeding of sows. In: Farmer, C. ed. *The gestating and lactating sow.* The Netherlands: Wageningen Academic Publishers, 147-172.

Thodberg, K. & Sørensen, M. T. 2006. Mammary development and milk production in the sow: Effects of udder massage, genotype and feeding in late gestation. *Livestock Science,* 101, 116-125.

Tilton, S., Miller, P., Lewis, A., Reese, D. & Ermer, P. 1999. Addition of fat to the diets of lactating sows: I. Effects on milk production and composition and carcass composition of the litter at weaning. *Journal of Animal Science,* 77, 2491-2500.

Tokach, M., Pettigrew, J., Crooker, B., Dial, G. & Sower, A. 1992. Quantitative influence of lysine and energy intake on yield of milk components in the primiparous sow. *Journal of Animal Science,* 70, 1864-1872.

Topigs Norsvin, 2016. Manual Topigs 20: Rearing gilts and sows, 23 May 2016. [Online]. [Accessed 12 March 2019]. Available from: https://topigsnorsvin.be/wp-content/uploads/2017/12/Manual-Topigs-20-ENG.pdf.

Town, S., Putman, C., Turchinsky, N., Dixon, W. & Foxcroft, G. 2004. Number of conceptuses in utero affects porcine fetal muscle development. *Reproduction,* 128, 443-454.

Town, S., Patterson, J., Pereira, C., Gourley, G. & Foxcroft, G. 2005. Embryonic and fetal development in a commercial dam-line genotype. *Animal Reproduction Science,* 85, 301-316.

Trenerry, V. C., Plozza, T., Caridi, D. & Murphy, S. 2011. The determination of vitamin D3 in bovine milk by liquid chromatography mass spectrometry. *Food Chemistry,* 125, 1314-1319.

Tuchscherer, M., Puppe, B., Tuchscherer, A. & Tiemann, U. 2000. Early identification of neonates at risk: traits of newborn piglets with respect to survival. *Theriogenology,* 54, 371-388.

Vadmand, C. N., Krogh, U., Hansen, C. F. & Theil, P. K. 2015. Impact of sow and litter characteristics on colostrum yield, time for onset of lactation, and milk yield of sows. *Journal of Animal Science,* 93, 2488-2500.

Van den Brand, H., Langendijk, P., Soede, N. & Kemp, B. 2001. Effects of postweaning dietary energy source on reproductive traits in primiparous sows. *Journal of Animal Science,* 79, 420-426.

Van den Brand, H., Soede, N. & Kemp, B. 2006. Supplementation of dextrose to the diet during the weaning to estrus interval affects subsequent variation in within-litter piglet birth weight. *Animal Reproduction Science,* 91, 353-358.

Van der Peet-Schwering, C.M.C., Swinkels, J.W.G.M. & Den Hartog, L.A. 1998. Nutritional strategy and reproduction. In: Verstegen, M.W.A., Moughan, J.W. & Schrama, J.W. eds. *The Lactating Sow.* The Netherlands: Wageningen Pers, 221-240.

Van Leeuwen, J., Williams, S., Martens, M., Jourquin, J., Driancourt, M., Kemp, B. & Soede, N. 2011. The effect of different postweaning altrenogest treatments of primiparous sows on follicular development, pregnancy rates, and litter sizes. *Journal of Animal Science,* 89, 397-403.

Van Til, L. D., Dohoo, I. R., Spangler, E. & Ogilvie, T. H. 1991. A survey of biological productivity of Prince Edward Island swine herds. *Canadian Journal of Veterinary Research,* 55, 174.

Vasdal, G. & Andersen, I. L. 2012. A note on teat accessibility and sow parity: consequences for newborn piglets. *Livestock Science,* 146, 91-94.

Vigano, P., Mangioni, S., Pompei, F. & Chiodo, I. 2003. Maternal-conceptus cross talk: a review. *Placenta,* 24, S56-S61.

Voillet, V., SanCristobal, M., Lippi, Y., Martin, P. G., Iannuccelli, N., Lascor, C., Vignoles, F., Billon, Y., Canario, L. & Liaubet, L. 2014. Muscle transcriptomic investigation of late fetal development identifies candidate genes for piglet maturity. *BMC Genomics,* 15, 797.

Walsh, M., Geraert, P., Maillard, R., Kluess, J. & Lawlor, P. 2012. The effect of a non-starch polysaccharide-hydrolysing enzyme (Rovabio® Excel) on feed intake and body condition of sows during lactation and on progeny growth performance. *Animal,* 6, 1627-1633.

Watkins, B. A., Li, Y., Allen, K. G., Hoffmann, W. E. & Seifert, M. F. 2000. Dietary ratio of (n-6)/(n-3) polyunsaturated fatty acids alters the fatty acid composition of bone compartments and biomarkers of bone formation in rats. *The Journal of Nutrition,* 130, 2274-2284.

Weary, D. M., Phillips, P. A., Pajor, E. A., Fraser, D. & Thompson, B. K. 1998. Crushing of piglets by sows: effects of litter features, pen features and sow behaviour. *Applied Animal Behaviour Science,* 61, 103-111.

Weber, G., Witschi, A., Wenk, C. & Mertens, H. 2014. Effects of dietary 25-hydroxycholecalciferol and cholecalciferol on blood and vitamin D and mineral status, bone turnover, milk composition and reproductive performance of sows. *Journal of Animal Science,* 92, 899-909.

Weiler, H. A. & Fitzpatrick-Wong, S. C. 2002. Modulation of essential (n-6):(n-3) fatty acid ratios alters fatty acid status but not bone mass in piglets. *The Journal of Nutrition,* 132, 2667-2672.

Whittemore, C. & Yang, H. 1989. Physical and chemical composition of the body of breeding sows with differing body subcutaneous fat depth at parturition, differing nutrition during lactation and differing litter size. *Animal Science,* 48, 203-212.

Whittemore, C. T., Hazzledine, M. J. & Close, W. H. 2003. *Nutrient Requirement Standards for Pigs*. Penicuik: BSAS.

Whittemore, C. T. & Kyriazakis, I. eds. 2006. *Whittemore's Science and Practice of Pig Production*. 3rd edition. Oxford: Blackwell Publishing.

Wientjes, J., Soede, N., Van der Peet-Schwering, C., Van den Brand, H. & Kemp, B. 2012. Piglet uniformity and mortality in large organic litters: Effects of parity and pre-mating diet composition. *Livestock Science,* 144, 218-229.

Wientjes, J., Soede, N., Knol, E., Van den Brand, H. & Kemp, B. 2013. Piglet birth weight and litter uniformity: Effects of weaning-to-pregnancy interval and body condition changes in sows of different parities and crossbred lines. *Journal of Animal Science,* 91, 2099-2107.

Williams, I. H., Close, W.H. & Cole, D.J.A. 1993. Strategies for sow nutrition: predicting the response of pregnant animals to protein and energy intake. In Cole, D.J.A. eds. *Recent Advances in Animal Nutrition*. Nottingham: Nottingham University Press, 133-147.

Williams, P., Marten, N., Wilson, V., Litten-Brown, J., Corson, A., Clarke, L., Symonds, M. & Mostyn, A. 2009. Influence of birth weight on gene regulators of lipid metabolism and utilization in subcutaneous adipose tissue and skeletal muscle of neonatal pigs. *Reproduction,* 138, 609-617.

Willis, H., Zak, L. & Foxcroft, G. 2003. Duration of lactation, endocrine and metabolic state, and fertility of primiparous sows. *Journal of Animal Science,* 81, 2088-2102.

Witschi, A.-K., Liesegang, A., Gebert, S., Weber, G. & Wenk, C. 2011. Effect of source and quantity of dietary vitamin D in maternal and creep diets on bone metabolism and growth in piglets. *Journal of Animal Science,* 89, 1844-1852.

Wolf, J., Žáková, E. & Groeneveld, E. 2008. Within-litter variation of birth weight in hyperprolific Czech Large White sows and its relation to litter size traits, stillborn piglets and losses until weaning. *Livestock Science,* 115, 195-205.

Wolter, B. & Ellis, M. 2001. The effects of weaning weight and rate of growth immediately after weaning on subsequent pig growth performance and carcass characteristics. *Canadian Journal of Animal Science,* 81, 363-369.

Wolter, B., Ellis, M., Corrigan, B. & DeDecker, J. 2002. The effect of birth weight and feeding of supplemental milk replacer to piglets during lactation on preweaning and postweaning growth performance and carcass characteristics. *Journal of Animal Science,* 80, 301-308.

Worobec, E., Duncan, I. & Widowski, T. 1999. The effects of weaning at 7, 14 and 28 days on piglet behaviour. *Applied Animal Behaviour Science,* 62, 173-182.

Wu, G., Pond, W. G., Flynn, S. P., Ott, T. L. & Bazer, F. W. 1998. Maternal dietary protein deficiency decreases nitric oxide synthase and ornithine decarboxylase activities in placenta and endometrium of pigs during early gestation. *The Journal of Nutrition,* 128, 2395-2402.

Yang, H., Eastham, P., Phillips, P. & Whittemore, C. 1989. Reproductive performance, body weight and body condition of breeding sows with differing body fatness at parturition, differing nutrition during lactation, and differing litter size. *Animal Production,* 48, 181-201.

Yang, H., Foxcroft, G., Pettigrew, J., Johnston, L., Shurson, G., Costa, A. & Zak, L. 2000. Impact of dietary lysine intake during lactation on follicular development and oocyte maturation after weaning in primiparous sows. *Journal of Animal Science,* 78, 993-1000.

Yang, Y., Heo, S., Jin, Z., Yun, J., Choi, J., Yoon, S., Park, M., Yang, B. & Chae, B. 2009. Effects of lysine intake during late gestation and lactation on blood metabolites, hormones, milk composition and reproductive performance in primiparous and multiparous sows. *Animal Reproduction Science,* 112, 199-214.

Yao, W., Li, J., jun Wang, J., Zhou, W., Wang, Q., Zhu, R., Wang, F. & Thacker, P. 2012. Effects of dietary ratio of n-6 to n-3 polyunsaturated fatty acids on immunoglobulins, cytokines, fatty acid composition, and performance of lactating sows and suckling piglets. *Journal of Animal Science and Biotechnology,* 3, 43.

Young, M., Tokach, M., Aherne, F., Main, R., Dritz, S., Goodband, R. & Nelssen, J. 2005. Effect of sow parity and weight at service on target maternal weight and energy for gain in gestation. *Journal of Animal Science,* 83, 255-261.

Young, M. & Aherne, F. 2005. Monitoring and maintaining sow condition. *Advances in Pork Production,* 16, 299-313.

Zaleski, H. M. & Hacker, R. R. 1993. Variables related to the progress of parturition and probability of stillbirth in swine. *The Canadian Veterinary Journal,* 34, 109.

Zehnder, D., Evans, K. N., Kilby, M. D., Bulmer, J. N., Innes, B. A., Stewart, P. M. & Hewison, M. 2002. The ontogeny of 25-hydroxyvitamin D3 1α-hydroxylase expression in human placenta and decidua. *The American Journal of Pathology,* 161, 105-114.

Zhang, R., Hu, Q., Li, P., Xue, L., Piao, X. & Li, D. 2011. Effects of lysine intake during middle to late gestation (day 30 to 110) on reproductive performance, colostrum composition, blood metabolites and hormones of multiparous sows. *Asian-Australasian Journal of Animal Sciences,* 24, 1142-1147.

Zhu, J. & DeLuca, H. F. 2012. Vitamin D 25-hydroxylase–Four decades of searching, are we there yet? *Archives of Biochemistry and Biophysics,* 523, 30-36.