Management and nutritional strategies to improve the postnatal performance of light weight pigs

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ABSTRACT

During the production period from birth to slaughter there are some pigs that grow markedly slower, despite conditions that seem to support the rapid growth of their contemporaries. This reduction in growth inevitably leads to weight variation within a group and results in system inefficiencies. The aim of this thesis was to identify risk factors involved in poor growth and to develop management and nutritional treatments to enable light pigs to maximise their growth at different stages of production.

Risk factor analysis for a large dataset showed that, in particular, low birth and weaning weight result in poor growth to finishing. Some light pigs do, however, have the capacity to compensate for low weight at earlier stages of production. Preweaning intervention demonstrated that low birth weight pigs cross fostered into litters with similar weight littermates had a significantly higher weaning weight than those in mixed litters with heavier pigs; however the provision of supplementary milk to such litters had no further beneficial effect. A post weaning feeding regime formulated for low birth weight pigs, with a higher nutrient specification diet based on more digestible ingredients, not only showed improved performance to 10 weeks of age, but also enabled low birth weight pigs to meet the BW of heavier birth weight pigs. In contrast, a high specification diet (higher in amino acid: energy content) had no effect on the growth of low birth weight pigs when offered from 9 weeks of age, suggesting a critical window for intervention.

Overall, the crucial stages of postnatal growth for light pigs have been identified, and preweaning and early post weaning treatments have been developed. These not only improve the performance of low birth weight pigs but also allow them to catch up with heavier birth weight pigs.

Declaration

This thesis has been composed by myself and has not been submitted as part of any previous application for a degree. All sources of information have been specifically acknowledged by means of referencing.

Sadie Louise Douglas

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Publications and conference abstracts

Peer-reviewed publications

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List of abbreviations

ADG	Daily live weight gain
ADFI	Average daily feed intake
ADMI	Average daily milk intake
BiW	Birth weight
BW	Body weight
CP	Crude Protein
CRL	Crown rump length
CV	Coefficient of variation
d	Day
DE	Digestible Energy
FW	Final weight
H	Hour
FCE	Feed conversion efficiency
FI	Feed intake
IW	Intermediate body weight
kg	Kilogram
LBiW	Low birth weight
m	Metre
mo	Month
NBiW	Normal birth weight
NE	Net energy
OR	Odds ratio
PI	Ponderal index
SD	Standard deviation
SDG	Scaled ADG
SFI	Scaled FI

wk	Week
WW	Weaning weight

Contents

List of tables

List of figures

Chapter 1. Introduction

1.1 What are light pigs?

Within an animal population there will always be natural variation in growth performance, and pigs are no exception to this. Differences in growth inevitably give rise to variation in body weight (BW), with the poor performers or light weight pigs presenting producers with a problem which has significant financial, welfare and environmental implications (Patience et al., 2004). Whilst the economic impact of light pigs has resulted in renewed interest in improving their performance, consumer demand for leaner more consistent meat products has also led to retailers requiring uniform carcasses. Producers are given tight contract specifications to adhere to with regards to BW at the abattoir and failure to adhere to these contracts will result in financial penalties (McCutcheon, 2002). This pressure to produce carcasses within a narrow weight range means that the industry is very keen to look at ways of increasing the uniformity of all pigs within a group. Rather than slowing the growth of larger pigs, increasing the uniformity by increasing the growth of light pigs through, for example, exploitation of their ability to compensate for previous growth retardation (Handel and Stickland, 1988) is a preferable approach.

Light pigs can be defined as pigs that, at a certain age, have a BW which is significantly below the average of the group. They grow markedly slower than their counterparts, despite the presence of freely available, good quality food that seems to support the fast growth of their counterparts. This reduction of growth can occur at any stage of production from birth through to finishing. Whilst this variability in postnatal growth may arise from management deficiencies, it can also be the result of pigs born with low birth weight (LBiW) (Quiniou et al., 2002). Often these initial deficits in BW are exacerbated by the postnatal environment, with access to inferior teats, competition from heavier littermates and unsuitable nutrition, meaning these pigs are simply unable to catch up. These LBiW pigs have a significant number of implications for the pig industry, especially because they may be associated with poor feed conversion efficiency (FCE) (Powell and Aberle, 1980; Gondret et al., 2006) and increased days to slaughter (Beaulieu et al., 2010). In recent years selection for sow prolificacy has resulted in increased litter size, which ultimately causes a decrease in the overall mean piglet birth weight (BiW) and increased within-litter variability (Roehe, 1999; Quiniou et al., 2002). Consequently, it is likely that as the number of LBiW pigs continues to increase, the problems faced by producers will worsen. Despite being recognised by the pig industry as a significant problem, there is a scarcity of literature which investigates the lifetime performance of light pigs, rather focusing on their growth over shorter periods such as birth to weaning. It is therefore important to identify the risk factors associated with poor lifetime performance in pigs, and determine which factors, BiW or otherwise, contribute significantly to light pigs at slaughter age.

1.2 Problems associated with light pigs

Management of a population of pigs with large differences in BW can be problematic and result in system inefficiencies. Often, at different stages of production, pigs will be sorted by BW with the aim of managing the variation. This inevitably requires both staff and possible sorting equipment (such as automatic sorters) and profitability can be impacted by sorting and regrouping pigs because of the resultant effect of increased aggression on performance. Light pigs increase the variability within a group and this can be associated with inefficient pen utilisation in batch systems and/or financial penalties at the abattoir for poor grading specification. Farmers are required to produce pigs within an ideal weight range, with financial penalties at the abattoir if pigs fall above or below this (Brumm et al., 2002). In a continuous flow system light pigs can be held back until they reach market weight, but this results in losses by the producer due to inefficient pen utilisation and additional feed costs. In contrast, in an all in all out system, light pigs may dictate when the whole shed can be emptied, resulting in a slower barn throughput. However, holding the main population of pigs too long may result in the larger pigs exceeding contract limits and having deteriorating FCE.

Light pigs not only pose management difficulties and potential financial losses for producers, but they also represent a welfare issue for the animals. The highest risk of mortality for pigs is during the preweaning period (Roehe and Kalm, 2000), with piglet BiW an important factor for survival (Kerr and Cameron, 1995; Roehe and Kalm, 2000). Wu et al (2006) have reported that the likelihood of survival decreases from 95 to 15% as BiW decreases from 1.80 to 0.61 kg, meaning that light pigs require additional attention from producers. Whilst there is limited research on the effect of low BW on post weaning mortality, Larriestra et al (2006) found pigs weighing less than 3.6 kg at weaning (at d 17) had a significantly higher risk of mortality during the nursery period than heavier pigs. However the effects may vary in pigs which have a higher age at weaning.

For this reason, as well as possible effects on lifetime performance, some producers may eliminate light pigs from production at birth (Rehfeldt and Kuhn, 2006); however public perception of this practice is negative. Whilst preweaning and early post weaning mortality is increased in light pigs, the greatest effect is only seen in those with extremely low BW, and it is therefore possible that many of these disadvantaged pigs can benefit from additional care. Not only does this raise welfare questions about the necessity of euthanasia of a larger number of piglets, but also indicates unnecessary loss of profits for producers.

1.3 How has the industry attempted to deal with light pigs?

Whilst it is now well established that light pigs are problematic, attempts to deal with them thus far have had a limited effect. Most commonly, on-farm techniques are employed to attempt to manage the variation rather than reduce it. As previously discussed, in more extreme cases, culling piglets under a certain weight at birth has been tried, but with limited success and negative public perception. Most commonly, the industry attempts to deal with such animals by regrouping pigs on the basis of live weight. Regrouping based on live weight can occur at all stages of production, from cross-fostering in the farrowing house right through to mixing pens in the finisher house. The current approach does not seem to confer any benefits on the growth of the light pigs and for this reason the practice can be perceived as disruptive by farmers. Whilst this process may remove some of the barriers that are imposed on the performance of lighter pigs, such as issues of competition, sorting by weight appears to have limited to no beneficial effect (Gonyou and Peterson, 1998; O'Quinn et al., 2001); despite this it is still common practice on many UK farms. The absence of benefits from the regrouping of pigs according to their BW may be due the fact that, whilst regrouping based on live weight may remove competition from heavier littermates, light pigs are still fed the same feed and kept in the same environmental conditions which may not be optimal for their reduced BW.

More recently, nutritional interventions at different stages of production have been the focus of attempts to improve the performance of light pigs. Weaning weight (WW) has a significant effect on subsequent growth performance, with lighter pigs at weaning performing less well (Kavanagh et al., 1997; Mahan et al., 1998). Manipulation of preweaning nutrition is therefore one possible approach to improve WW. Wolter et al (2002) reported that the provision of supplementary milk improved WW; however since BiW had a greater impact on post weaning performance it was not an effective strategy to improve the long term performance of light pigs. In a similar study by Morise et al (2011), provision of a high protein milk replacer to LBiW pigs benefitted their preweaning growth although the effect only persisted in males post weaning. This suggests that providing additional nutrition preweaning may not always result in long term benefits for light pigs or in reduced overall weight variation.

In contrast, the use of specialised starter regimes to improve the nursery performance of light pigs at weaning has provided more positive results. Most recently, Beaulieu et al (2012) reported that LBiW pigs responded positively to a complex diet, incorporating a range of more digestible ingredients rather than a simple diet formulation, with an improvement in the immediate post weaning performance; however the effects were only observed for 1 week (wk) post treatment. A study by Magowan et al (2011) which followed pigs to finishing found that pigs with light WW benefitted from a high allowance of starter diets, which gave an improved 15 wk weight. This is similar to Mahan et al (1998) who reported that feeding a phase 1 diet for a longer period was beneficial, however it was found that WW had a greater influence on post weaning growth than any dietary regime. So whilst it seems apparent that light pigs may benefit from specialised nutrition, often these benefits are not present in the longer term or of great enough magnitude to enable pigs to catch up with the weight for age of heavier littermates; however this remains an area that requires more research.

As discussed, although light pigs are recognised by the pig industry as a significant problem, attempts to improve their performance have thus far had a limited effect. Identifying and understanding the factors which contribute to poor performance and light pigs is vital in developing treatments to reduce weight variation. It is also important to establish at what age, or stage of production, light pigs can benefit from interventions, as it appears that treatments given at some stages are more effective than at others.

1.4 Thesis aims

The aim of this thesis was to provide understanding of risk factors that are associated with the occurrence of light weight pigs and, by providing such understanding, to develop nutritional and management treatments that might enable these pigs to decrease the deficit in their body weight.

The specific objectives of this thesis were:

To identify the risk factors associated with occurrence of light pigs through a detailed literature review; this will include both pre and postnatal factors which may affect postnatal performance (Chapter 2).

To conduct a detailed epidemiological study to identify the risk factors which contribute towards poor performance in pigs and determine whether light pigs can exhibit catch up growth and at which stages of production (Chapter 3).

To determine if the provision of a high nutrient specification diet will improve the growth performance of pigs which are light at 9 weeks of age as a result of different causal factors (chapter 4).

To determine whether management and nutritional treatments preweaning can increase the WW and performance to slaughter of LBiW pigs (Chapter 5).

To investigate whether a high specification starter regime and the provision of an extra amount of feed can improve the nursery exit weight of pigs which were light at weaning as a result of LBiW (Chapter 6).

Chapter 2. The risk factors associated with poor growth performance in pigs

An understanding of the risk factors for poor growth which are inherent in the pig or present in its environment is critical in reducing variability. Whilst some factors will be hereditary, many will be the result of the animals' interactions with the pre- and postnatal environment. It is important to consider that it is rarely one factor acting independently which results in suboptimal growth, but several acting simultaneously in an additive or interactive way (Black et al., 2001).

2.1 Animal characteristics

The homogeneity of growth of pigs can be influenced by genetics, with average daily live weight gain (ADG) being a moderately heritable trait in pigs at approximately 20 to 40% (van Wijk et al., 2005; Hoque et al., 2007; Rothschild et al., 2011). As the main aim of pig production is to produce quality lean meat in the most efficient way, the objectives of breeding programmes commonly include improved leanness, ADG and FCE (Rothschild et al., 2011). The UK relies on relatively few breeds in commercial production, with the Large White, Landrace, Duroc and Meishan breeds usually being cross-bred to produce dam lines with desirable traits. These are then crossed with purebred or synthetic sire lines to produce the slaughter generation. This crossing of different breeds, favoured for different production traits, can generate variation in size and performance in the crossbred slaughter population.

Furthermore in pigs, as well as other animals, males tend to grow faster than females and are usually heavier when mature (Comstock et al., 1944), although this is not necessarily supported by literature with conflicting evidence on the effect gender has on the performance of modern commercial pigs during different stages of production. In the majority of cases, the effect of sex on performance is not the sole cause of investigation, but rather how sex interacts with other factors. Looking specifically at pre weaning growth, Skorjanc et al (2007) investigated the effect of both BiW and sex, with no effect of sex being reported. Dunshea et al (2003) reported very few effects of sex on the lifetime growth of pigs, with the exception of the initial period post weaning where light weight gilts outperformed their male counterparts (this applied only to light weight animals) (Dunshea et al., 2002). In the nursery period, Hill et al (2007) found no effect of sex (gilts and barrows). However focusing on pigs in the grower and finisher, O'Connell (2006) found that boars grew both faster and more efficiently than gilts from 60 kg to 100 kg, with an even greater difference in performance noted when dietary lysine concentrations were increased. Whilst in the UK it is not common practice to castrate pigs like elsewhere in Europe, as there may be differences in growth between boars and barrows (Quiniou et al., 2010) this is important to consider when comparing literature. Focusing on the later stages of production, Quiniou et al (2010) found no difference in the growth performance of boars, gilts or barrows post weaning from day (d) 28 to 63; however in the later part of the finisher period from d 105 to 152, gilts and barrows had significantly lower ADG than boars as well as a poorer FCE. In contrast, Wolter and Ellis (2001) reported differences in the performance of gilts and barrows in the finisher stage, with barrows requiring fewer days to reach market weight (Wolter and Ellis, 2001). Given the lack of clarity, it is important to establish the role sex has on the effect of lifetime growth performance.

2.2 The prenatal environment

As a polytocous species, the sow uterus must support the growth of a large number of embryos, development of which requires delivery of vital nutrients and oxygen from the dam via the placental vascularisation. It is well established that uterine capacity and insufficient vascularisation (Wu et al., 2008; Oksbjerg et al., 2013; Pardo et al., 2013a) can become limiting factors for embryo growth and development and result in intrauterine growth restriction (IUGR) in pigs. IUGR is defined as impaired growth of the mammalian embryo/foetus, with pigs exhibiting more severe naturally occurring IUGR than any other domestic species (Wang et al., 2008). Historically, IUGR pigs have been identified on the basis of their BiW (Bauer et al., 1998), for example 1.5 to 2.0 standard deviation (SD) units below the average BiW (Wang et al., 2009; D'Inca et al., 2010a; D'Inca et al., 2010b), however it is important to realise that not every LBiW pig has experienced IUGR; they may be constitutionally small as a result of genetics. This is an important distinction to make, as IUGR is associated with a greater range of morbidities and mortalities than occur in piglets which are just small at birth (Baxter et al., 2008). Therefore it is important to consider both IUGR and BiW separately, as it is possible that they have differential effects on postnatal piglet performance. However, as the majority of literature uses the two terms interchangeably, it is often difficult to disentangle which morbidities are associated with either condition. For this reason, the ponderal index (PI) is often used as an indicator of IUGR. Ponderal index is the ratio of BW to length (weight/length^3), with a low PI (disproportionally long and thin) possibly indicating IUGR (Chellani et al., 1990).

2.2.1 Intrauterine growth restriction

In the case of unaffected offspring with 'normal' prenatal growth, intrauterine space restriction is minimal which allows normal placental development and consequently an improved nutrient exchange between foetus and the dam (Pardo et al., 2013a). The severity of restriction in utero is likely to vary between pigs and therefore not all are similarly affected, giving rise to varying degrees of IUGR. More recently head morphology (Chevaux et al., 2010) rather than BiW has been used to identify IUGR. In particular the ratio of the BW to head size (Baxter et al., 2008) has been used to indicate a 'dolphin-like' head shape (Hales et al., 2013), which is due to the 'brain sparing' effect (Bauer et al., 2003) as the body directs nutrients preferentially to the brain to ensure development of important organs.

At birth the proteomes of the small intestine, liver and skeletal muscles are altered in IUGR neonates, which may contribute to reductions in immune function, protein synthesis and cellular signalling (Wang et al., 2008). Pardo et al (2013) also found that IUGR can affect both the development of internal organs as well as myogenesis. Inevitably, as a result of altered physiology, IUGR pigs may not respond as well to the postnatal environment as non-affected pigs. For example, it has been demonstrated that new born piglets with IUGR have been shown to ingest insufficient amounts of colostrum compared to normal littermates (Amdi et al., 2013), which may be one possible cause of increased mortality associated with IUGR pigs.

Prevention of IUGR is a topic with increasing popularity. As most gestating sows are fed restrictedly, it has been hypothesized by numerous authors that increasing feed allowance may rectify the problem by reducing nutrient restriction of embryos. Dwyer et al (1994) found no difference in the BiW of piglets whose mothers had been fed different diets during early gestation (ranging from d 25 to 80), which is not surprising as Noblet et al (1985) showed no effect of maternal nutrition on foetal BiW before d 80 of gestation. Although Dwyer et al (1994) found that increasing sows feed intake (FI) at targeted points in gestation can increase the ration of secondary to primary muscle fibres in piglets (but no increase in total muscle fibre number), more recent work has found no such effect (Nissen et al., 2003; Bee, 2004), with no benefits observed in postnatal performance of piglets (Cerisuelo et al., 2009; McNamara et al., 2011; Rehfeldt et al., 2011). Given the lack of effect of maternal nutrition during gestation, current thinking indicates that causal factors occur earlier, even prior to ovulation (Foxcroft et al., 2006). Increasing the period in between weaning and the next pregnancy in sows has been shown to reduce the coefficient of variation (CV) and increase the total litter weight at birth, likely related to follicular development (Wientjes et al., 2013). However at present there are no strategies to successfully prevent IUGR, especially in more prolific sow lines, so ultimately management of these pigs is required. Despite all of the deficiencies associated with IUGR, it has been suggested that pigs may be able to compensate if given special attention and a postnatal environment adapted to their altered requirements (Wu et al., 2006).

2.2.2 Birth weight

The majority of swine literature suggests an established relationship between BiW and postnatal growth, with piglets born underweight more likely to underperform throughout life (Rehfeldt and Kuhn, 2006; Rehfeldt et al., 2008; Beaulieu et al., 2010). Consequently, BiW has long been considered an important trait in pig production (Rehfeldt and Kuhn, 2006). Whilst it is inevitable that a number of LBiW pigs in studies will have been exposed to a certain degree of IUGR, when comparing them to pigs with classic IUGR symptoms (such as the ‘dolphin head’), it seems that that they do not exhibit such a wide range of morbidities and mortalities. However, they do have poor postnatal growth rates when compared to heavier littermates and it has been suggested that they may remain stunted throughout their life (Gondret et al., 2005; Rehfeldt and Kuhn, 2006; Wang et al., 2008). For this reason, piglets with significantly LBiW may be excluded from rearing by producers (Rehfeldt and Kuhn, 2006), especially as survival rates decrease from 95% to 15% as BiW decreases from 1.80 to 0.61 kg (Wu et al., 2006). The lower growth potential has been attributed to the fact that pigs born with LBiW may have a lower number of muscle fibres formed prenatally (Nissen et al., 2004; Gondret et al., 2005; Gondret et al., 2006; Rehfeldt and Kuhn, 2006; Paredes et al., 2013). As the number of fibres is set at birth, and subsequent growth is only by hypertrophy, this may limit growth performance. Low birth weight has also been shown to result in retardation of the digestive tract both at birth (Wang et al., 2005) and weaning (Michiels et al., 2013), which is likely to affect how they respond to nutrition.

The perceived impact of BiW on postnatal performance is variable in literature, with some papers suggesting a negative influence and others less so. It is possible that the variability in the results is due to the definition of LBiW pigs, which can vary between studies, with more extreme effects on performance only observed in the lowest weight pigs. Identification of subpopulations which may have the capacity for higher subsequent growth, versus pigs that are likely to remain stunted, is therefore important.

2.3 The postnatal environment

2.3.1 Lactation

The initial period following parturition, when the piglet is suckling from the sow, is not only critical for piglet survival but also for subsequent performance because WW is likely to influence ADG in later stages (Klindt, 2003). It has been reported by Tokach (1992) that each additional 0.5 kg at weaning corresponds to an additional 2 kg in BW by slaughter, emphasising the importance of maximising preweaning growth.

In the first few days following parturition, the new born piglet is extremely vulnerable. Colostrum intake after parturition is considered one of the major determinants of piglet survival (Devillers et al., 2011), with insufficient intake a major cause of neonatal mortality (Edwards, 2002). Whilst colostrum allows the transfer of maternal antibodies to the piglets, it also contains vital growth factors which promote development of the gut (Wang and Xu, 1996; Dunshea and Van Barneveld, 2003). It has recently been shown that IUGR piglets consume an insufficient amount of colostrum (Amdi et al., 2013), which may therefore hinder gut development and could affect digestion and absorption of food. Once the available colostrum has been consumed, piglets rely on sows' milk for their sole source of energy and nutrients. Weaning weight is closely related to consumption of sow's milk during lactation (Lewis et al., 1978) and therefore high intake is vital to maximise preweaning growth. Low birth weight pigs have been shown to consume less milk per suckling than heavier littermates (Campbell and Dunkin, 1982). Since the suckling frequency is fixed for the litter as a whole, this may affect the total amount they consume. As sows' milk production capacity is limited, inevitably there will be competition between littermates. During lactation, sibling competition has a major effect on survival and growth; this includes primary competition, where piglets fight to establish teat ownership, as well as indirect competition where heavier pigs may be able to better stimulate their teats to access a disproportionate share of available nutrients (Milligan et al., 2001b). A fixed teat order is established soon after birth, with the larger or more dominant piglets usually accessing the anterior teats (Skok et al., 2007). These teats are the more productive, so that pigs suckling from the posterior teats would consume less milk and subsequently exhibit lower daily weight gains (Skok et al., 2007).

Cross fostering is a strategy which is commonly employed on UK farms, with the aim of manipulating litter size, either reducing or increasing the number of piglets usually to approximately 10 to 12 piglets. Litter size has a significant effect on piglet performance, with smaller litter sizes having a positive effect on WW (Stewart and Diekman, 1989; Deen and Bilkei, 2004; English and Bilkei, 2004). This improvement in weight is likely due to decreased competition for access to a functional teat as there are fewer pigs (Bilkei and Biro, 1999; Tuchscherer et al., 2000). This is supported by English and Bilkei (2004) who noted that piglet behaviour varies in larger litters, with smaller pigs more likely to miss nursing episodes and spend more time in teat disputes.

Cross fostering can also be undertaken to create homogenous litters composed of piglets with similar BW. This is done on the assumption that LBiW pigs are at a competitive disadvantage when raised with heavier littermates. Therefore they would be expected to perform better in litters with smaller pigs and less weight variability, as there is less competition for access to the best teats, as the biggest pigs are likely to suckle from the most productive teats (Fraser and Jones, 1975). In support of this, English and Bilkei (2004) reported a decrease in the 21 d WW of LBiW pigs when grouped with heavier littermates. However, a series of studies by Milligan et al (Milligan et al., 2001a; Milligan et al., 2001b; Milligan et al., 2002a; Milligan et al., 2002b) found no difference in the ADG of LBiW piglets when grouped with heavier pigs, questioning whether they are indeed disadvantaged. This was supported by Fix et al (2010), who reported no difference in ADG resulting from within-litter variation. It is important to consider that while creating homogenous litters will benefit small pigs, which are out competed for the most productive anterior teats, there will still be a hierarchy in litters composed of all LBiW or all normal birth weight (NBiW) pigs.

2.3.2 Weaning

Natural weaning is a process that occurs gradually, with pigs becoming less reliant on sow milk and more reliant on other food sources; this usually occurs from 8 to 9 weeks post-partum and can last for 3 to 4 weeks (Whittemore and Kyriazakis, 2006). However in today's commercial farms, weaning is an abrupt and often stressful process which usually occurs between 21 and 28 d of age, this coincides with milk production reaching a plateau in the sow at approximately 21 d. Weaning may involve a significant number of changes to the pigs environment, including change in feed (liquid to solid), transport, mixing with unfamiliar pigs and new housing (Berkeveld et al., 2007). Many will experience a post weaning 'growth check', where they exhibit loss of weight or a reduction in weight gain, due to a reduction in FI (Cooper et al., 2009). This is a widespread problem experienced on farms and results in economic losses for the producer. This growth check can lead to delays in reaching market weight (Wiseman, 1998), so to ensure minimal growth loss there needs to be high FI of a nutrient dense diet almost immediately following weaning (Lawlor et al., 2002). Post weaning FI is likely to be influenced by a number of factors such as the use of creep feed, stress, temperature, water availability, as well as the nature of feed itself. Ideally starter regimes need to be highly palatable and digestible, as well as dense in nutrients to account for the low FI by newly weaned pigs. Both increased allowance and more complex starter diets including a range of highly digestible ingredients can result in improved performance (Mahan et al., 1998; Mahan et al., 2004; Magowan et al., 2011b) as well as a reduction in the numbers of days to slaughter (Mahan et al., 1998).

There has been a gradual decrease in the age at which pigs are weaned over the years mainly facilitated by the drive to improve sow output through greater farrowing frequency. More recently, a further driver to reduce weaning age has been an approach to improve the health of piglets by reducing the transfer of growth depressing pathogens from sow to piglet in segregated early weaning (SEW) systems (Main et al., 2004). Whilst individual producers will make a decision about what age is best to wean their piglets based on sow performance, herd health, pig performance as well as costs and other factors (Smith et al., 2006), significantly reducing the age may have a negative effect on both short term and long term pig performance (Edwards, 2010). This is supported by the results of Leibbrandt et al (1975) who demonstrated that increased weaning age from two to four weeks resulted in greater adaptation to the post weaning environment and a decrease in growth check. When considering long term effects, Main et al (2004) found that every one day increase in weaning age from d 12 to 21.5 resulted in a 1.8 kg increase in weight per pig sold, with differences in performance noted not only in the initial period after weaning but also long term. It is therefore important for producers to consider the increased benefits that arise from weaning at an earlier age in comparison to the negative effects on piglet lifetime performance that it may cause.

2.3.3 Post weaning

Inevitably management strategies vary between farms and the producer is likely to try and maintain an environment which is suitable for their livestock. However, there are a number of known environmental factors that can hinder growth performance and, while the extent of each will vary between holdings, the basic principles remain.

Nutrition is one of the most important factors in growth performance and, as feed accounts for approximately 60% of the total cost of production (BPEX, 2013b), it is important that producers get it right. Poor feeding regimes such as incorrect diets, dramatic changes in diets and inadequate access to feed can all result in reduced FI or utilisation and a drop in performance. Provision of a diet which does not meet the nutritional requirements of pigs is likely to affect all pigs, but inevitably will have a greater effect on some than others. Pigs with reduced growth rates can also find the problem exacerbated due to competition from dominant pen mates; the more dominant (often heavier) pigs will take a higher proportion of the food (Baldwin and Meese, 1979), thereby increasing their own growth at the expense of others which will further increase within pen variation. Any problems in the diet are more likely to have a pronounced effect in those younger pigs such as weaners, who are at a critical stage in their digestive maturity, rather than finisher pigs (Whittemore and Kyriazakis, 2006). Formulation of dietary regimes needs to consider the stage of growth (or BW), genetic potential as well as the environment of the pig to prevent insufficient or excessive feeding of nutrients which can be costly. Diets are formulated for the ‘average’ pig in a population, meaning pigs which fall considerably below this weight are likely to be disadvantaged. For example, LBiW pigs may have a reduced FI post weaning (Nissen and Oksbjerg, 2011) and therefore when given the same feed as heavier pigs will consume less and as a result consume fewer nutrients. These pigs may also have immature digestive systems, including reduced secretion of digestive enzymes (Xu et al., 1994; Wang et al., 2008; D'Inca et al., 2010b) and a less developed digestive tract

(Michiels et al., 2013) which can hinder digestion and absorption of nutrients. Low birth weight pigs may also have altered body composition in relation to heavier littermates both at birth and slaughter, with a higher percentage of adipose tissue (Bee, 2004; Rehfeldt and Kuhn, 2006; Rehfeldt et al., 2008), which may alter their amino acid: energy requirements. The effect of feeding light weight pigs a feed which is not formulated for their requirements means they are unlikely to be able to grow to their full potential and will perpetuate poor ADG.

Pigs will experience their optimum growth performance when in their thermoneutral zone (Baker, 2004); therefore in indoor pig rearing environmental temperature is tightly controlled during each stage of production to optimise growth (Straw et al., 2006). Pigs do not have the ability to sweat sufficiently, so are susceptible to overheating as they rely on panting to dissipate heat (Dewey et al., 2009). When exposed to higher ambient temperatures, a decrease in their FI is observed as the pigs try to reduce heat production (Renaudeau et al., 2008); subsequently this reduction in nutrients will detrimentally affect the growth of the pig. A decrease in the ambient temperature below the thermoneutral zone means pigs require more energy to maintain body temperature. This will result in an increase in their FI, but no increase in their growth as they metabolise food to generate heat. The BW and FI of the animal will determine their upper and lower critical temperatures (Baker, 2004), with lower environmental temperatures for pigs required as they progress from birth to finishing. As smaller pigs will have a larger surface area: volume ratio (Stanton and Carroll, 1974) as well as a lower FI, they are more vulnerable than a larger pig to lower temperature because they will have a greater lower critical temperature. In weaners, the critical period (0 to 2 weeks post weaning) is a time where a higher ambient temperature is needed to counteract the thermal challenge experienced by the pigs due to the reduced FI and metabolism (Le Dividich and Herpin, 1994). Le Dividich et al (1980) also reported a high incidence of post weaning diarrhoea with fluctuations of ambient temperature at weaning. Following this period the temperature can be gradually reduced by 2 to 3°C as the pigs adjust to the changes imposed at weaning.

The stocking density of pig units can have a significant effect on growth performance, whilst correct manipulation may be beneficial to pig performance. Under stocking in colder months can give rise to cold stress if housing has poor ambient temperature control, whilst decreasing stocking density in warmer months can be useful in reducing heat stress (Jones et al., 2011), which is likely to affect smaller pigs as their lower critical temperature is greater than larger counterparts. Below a critical threshold, reducing space allowance reduces FI and growth rate (Gonyou et al., 2006). The reasons for this may include the fact that overstocking can quickly result in problems with pigs such as aggression (Jones et al., 2011) and unequal levels of FI, with the submissive (often smaller) pigs at a disadvantage in accessing resource. As a result there is a legal minimum space allowance in the EU to prevent overstocking, with the minimum allowance increasing as the BW of the pig increase.

It is commonplace in pig production for unfamiliar pigs to be mixed; this can occur from birth to finishing. Mixing can take place for a number of reasons such as preweaning cross fostering, evening up BW within groups or improving pen utilisation. For example, at finishing heavier pigs in a pen may be sent to slaughter whilst lighter pigs that are not a suitable weight for slaughter are held back, and subsequently mixed with other pigs to clear pens. As there is a social hierarchy present from birth, mixing pigs will disrupt this leading to the need for pigs to establish a new hierarchy (Puppe et al., 2008). Whilst mixing can be considered a stressor in pigs, the effect on performance reported in the literature is variable. Whilst no effect of removing and remixing light weight pigs post weaning on performance to slaughter was reported by Brumm al (2002), Spooder et al (2000) concluded that mixing pigs in the finisher stage led to increased aggression and detrimental effects in the immediate post mixing period. The adverse effect of mixing on the behaviour of pigs was supported by D'Eath et al (2010), who reported increased aggression in finisher pigs, although this was in pigs already classified as having above average aggressive temperament. So, while the aim of mixing pigs at different stages is usually to reduce the variation in BW, the possible effect on performance needs to be considered.

2.4 Conclusions

At different stages of production there are a number of different factors which can affect performance. Not all pigs are born with the same growth potential or experience the same in utero environment. As such, some pigs may be disadvantaged from birth and early stages of production with subsequent interactions with the environment likely to have a significant impact on performance. In particular, the lactation period may inhibit optimal growth as piglets compete for limited resources. The nutrition of pigs is also likely to have a major impact on performance and pigs with lower BW at different stages of production may have altered requirements.

Whilst swine literature has identified many risk factors which can negatively affect the growth performance of pigs, there is a scarcity of data which has taken into account the effect of these risk factors on the lifetime performance of pigs. Such understanding is necessary to improve light pig performance, as it is likely that whether light pigs will benefit from intervention treatments will depend on the reasons that have led to their lighter weight.

Chapter 3: Identification of risk factors associated with poor lifetime growth performance in pigs

3.1 Introduction

Variation in BW is a common problem in the pig industry and has financial, welfare and environmental implications (Patience et al., 2004). Variability in postnatal growth may arise from management deficiencies but can also be a result of pigs born small or growing markedly slower despite suitable environments. Rather than slowing the growth of larger pigs, increasing the uniformity by increasing the growth of smaller pigs, through for example exploitation of their ability to compensate (Handel and Stickland, 1988), is a preferable approach.

Although research has suggested that numerous factors affect lifetime performance (De Grau et al., 2005; Larriestra et al., 2006), it is important to consider at what point, or under what circumstances, a deficit in growth can be considered permanent and intervention ineffective. Birth weight is considered to be a critical indicator of postnatal performance, with piglets born underweight often remaining stunted throughout their life (Gondret et al., 2005; Rehfeldt et al., 2008; Fix et al., 2010). Initial deficits are often exacerbated by access to inferior teats, stress at weaning, and competition from heavier littermates, meaning these piglets are simply unable to catch up. However literature also suggests that WW may be a better predictor of future growth and the number of days it takes to reach slaughter weight (Wolter and Ellis, 2001; Smith et al., 2007).

There is a distinct lack of data available on lifetime performance of low BW pigs. As a result, research on how to manage weight variation is limited, with few practical suggestions that have been proven to be effective (O'Quinn et al., 2001; Brumm et al., 2002). The aim of this paper was to identify risk factors associated with poor lifetime performance in pigs, paying particular attention to the effect BiW and WW have on subsequent performance. Understanding such factors would lead to effective interventions that may reduce BW variability within a group.

3.2 Materials and Method

Two production databases were obtained from commercial breeding companies operating internationally. The datasets for breeding companies 1 and 2 contained records for approximately 40,000 and 90,000 pigs respectively, and a range of variables used for analyses (Table 3.1). Databases included only pigs that survived from birth to finishing.

Breeding company 1 provided data for 10,181 litters produced in the same unit over the period January 2000 to June 2010. Only a subset of pigs from each litter was followed, with 69% of those being gilts and the rest intact males. These data were from pigs produced in the United Kingdom in a conventional health unit (Enzootic Pneumonia and Porcine Reproductive Respiratory Syndrome positive) and consisted of 3 different genotypes (described here as 1, 2, and 3). Genotype 1 was a Large White sire line, genotype 2 was a Large White dam line and genotype 3 was a Landrace dam line.

Pigs were individually weighed within 24 hours (h) of birth (BiW) and before the majority reached slaughter weight at approximately 100 kg [final live weight (FW)]; for approximately one-half of the pigs (20,297) an intermediate BW (IW) when an animal reached approximately 45 kg was also available. Individual BiW were recorded for all animals born alive. Cross-fostering took place on the unit; however, piglet movement between sows was not recorded in the database; usually this was within the first 24 h, with fostering after this kept to an absolute minimum. Pigs were fed 2 commercial creep feeds, 1 from 5 to 8 kg and the second from 8 to 15 kg. A “rearer” diet was fed from 15 to 30 kg and finally a standard commercial grower diet from 30 kg to slaughter.

Table 3.1 Descriptive statistics (mean, SD and total number of pigs) of the datasets used for risk factor analyses associated with poor growth performance in pigs

	Dataset 1			Dataset 2		
Variable	Total *n*	Mean	SD	Total *n*	Mean	SD
Birth weight, kg[1]	43,571	1.41	0.29	91,210	1.39	0.33
Weaning weight, kg[2]	-	-	-	38,975	6.11	1.38
Intermediate weight, kg[3]	20,297	48.6	4.82	-	-	-
Final weight, kg[4]	20,307	92.5	10.4	5,217	78.0	11.7
Total no. of piglets born per litter[5]	43,571	12.1	3.03	91,557	11.5	2.80
Born alive piglets per litter[6]	43,571	11.5	2.90	91,573	10.9	2.73
Parity[7]	43,571	2.72	1.53	79,393	3.57	2.45
Month of birth, mo[8]	43,571	6.50	3.44	91,573	6.38	3.03
Gestation length, d[9]	-	-	-	79,393	115	1.56
Percentage males[10]	43,571	31.5	-	91,572	52.0	-

[1] Birth weight (kg) of piglets taken within 24 h of birth.
[2] Weaning weight of pigs (kg) adjusted to 23 d.
[3] Adjusted intermediate BW of pigs taken at 105 d.
[4] Slaughter weight of pigs (kg), adjusted to 155 d for dataset 1 and 140 d for dataset 2.
[5] Total number of piglets born per litter, including stillborn.
[6] Total number of piglets born alive per litter.
[7] The number of litters a sow has produced.
[8] Month of birth of each litter (starting as January = 1, December = 12)
[9] Gestation period of the sow (days)
[10] Percentage of pigs in each dataset which are male; the total number is the total number of animals in the dataset with sex specified

Data from breeding company 2 were from pigs produced in 3 units, using the same methods and breeds that are present in the United Kingdom and have previously been described by Kapell et al (2011). The data were generated between January 2005 and September 2006. Management conditions were standardised across units; units were coded and included as a factor in the analyses. Pigs were born out of 13,429 litters with individual BiW available for all pigs; although the time window within which this was taken was unspecified, the expectation was that this would have been within 24 h from birth. A second BW was taken at weaning (WW; approximately 21 to 28 d) and a FW before slaughter at approximately 80 kg. Only a subset of the pigs with BiW had WW and only a subset of those had FW. A percentage of males were intact (purebred) whilst the rest of the male pigs were castrated (crossbred). Information regarding cross-fostering was not available. In addition to individual pig BW, a number of variables were recorded in both of the datasets (Table 3.1). For the majority of pigs these variables were available: sow parity number, total number of piglets born per litter (including born alive and stillborn), date of birth, and sex and number of pigs weaned. For breeding company 2 the length of gestation of the sow was also available.

Data handling and analysis was undertaken using SAS (SAS Inst. Inc., Cary, NC) and the same methodologies were applied to both datasets. Incorrect or doubtful observations were removed or corrected when possible: for example if a BW was greater or less than 4 SD from the mean, then it was removed. In addition to the existing variables, a number of new ones were calculated. As there was variation in the age at which BW were taken, adjusted BW for a specific (average) age was used. Adjusted BW for age was calculated using this formula:

Daily BW gain = (BW 2 – BW 1) / (age BW 2 – age BW 1)
Adjusted BW for age = (daily BW gain x average age at BW 2) + BW 1

Based on the adjusted BW, both adjusted absolute ($g.d^{-1}$) and relative ($g.day^{-1}BW^{-1}$) growth rate were calculated for each pig for each stage of their life (when available). The relative growth rate is the difference in natural logarithms of the first and last BW divided by the time between the 2 BW (Winder et al., 1990) and is commonly used in breeding experiments to account for differences in initial size. Growth rates for each individual animal were then grouped into 1 of 3 categories using percentiles (33%) denoting, high, medium, and low growth rates. Pigs were also retrospectively assigned to a BiW and a IW/WW and a FW group based on percentiles: 12.5% (8 groups), 25% (4 groups) and 50% (2 groups; above and below the mean). In the analysis only the 12.5% groups were used as these gave us a greater number of categories to compare. These groups categorised the BW into groups from low to high (1 denoting the lightest, 8 the heaviest). For all analyses the 2 datasets were analysed separately. Potential variables were normally distributed so were entered into the models without being transformed.

Three types of analysis were conducted on the datasets. First an ordinal logistic regression model using categorised growth rates with covariates as categorical or continuous data. This type of generalized linear model allows the prediction of a dichotomous outcome from multiple variables. Second, a linear plateau regression analysis was constructed, where both the dependent and independent variables were used as continuous variables. This model was chosen to allow estimation of a BW breakpoint, if present in the population of pigs. Finally, the ability of pigs with different BW at birth and weaning/intermediate BW to reduce the deficit for low BW by the end of their productive life was estimated, by determining the percentage of pigs that decreased, increased or remained in the same BW category from BiW/WW/IW to FW.

3.2.1 Logistic Regression

To identify potential risk factors for poor postnatal growth in pigs an ordinal logistic regression model was constructed using absolute and relative growth rate. Initially a univariate logistic regression model was used to identify potential significant risk factors for entry in to the multivariate model. All potential variables were individually fitted to the model to identify those that were significant; any variables which were not significant at 5% level were eliminated from inclusion in the multivariate model. After univariate analyses all variables which were significant were checked for correlation with other variables to be entered into the model. If variables were found to be highly correlated (0.70 or above) then the variable which had the greatest effect in the univariate model was retained and the other excluded from further analysis.

The absolute and relative growth rate of the pigs from BiW to WW/IW, WW/IW to FW and BiW to FW were used as the dependent variable in the models. The reference category for these models was category 3 (high growth rate) compared with the combined effects of categories 1 and 2. A separate multivariate model was run for each of the 3 stages of growth and included risk factors which were applicable to that stage. For example the model from birth to weaning included BiW as an indicator, whereas weaning to finishing included both BiW and WW.

The PROC logistic method (SAS Inst. Inc) was used to run the logistic regression model. Variables entered into the model (where applicable) were total number of pigs born per litter (dead or alive), sex (intact male or female for database 1 and intact, castrated or female for database 2), sow parity, month of birth, BiW and WW/IW (Table 3.1). Breed code was also inputted in to the model for breeding company 1. Independent variables were added into the model by stepwise entry. All variables were entered into the model as categorical with the exception of the total number of piglets born per litter and parity. Separate models were run for each BiW and WW/IW interval. The results of the logistic model gave odds ratios (OR) as well as 95% confidence intervals. All results refer to the absolute growth rate from BiW to FW unless specified.

3.2.2 Continuous linear plateau-model

To examine the effect of BiW and WW on the lifetime growth rate of pigs, a continuous linear plateau model was fitted to the data for all pigs using the NLIN procedure of SAS. The model was adapted from Piegorsch and Bailer (2005) and consisted of a single sloping line intersecting a plateau at a break point value. This type of regression allows for an accurate estimate of the break point and additional variables. The linear plateau model described the growth rate in relation to the BiW (kg) by this pair of equations:

$$Y = a + b \times (X - Xmax) \text{ If } X < Xmax$$

$$Y = c \text{ if } X > Xmax,$$

in which Y is the dependent variable (either absolute or relative growth rate) and X is the independent variable (BiW/WW/IW). Parameter a is the intercept while parameter b is the slope of the line up to point Xmax, which occurs at the intersection of the linear response and the plateau line, and C is the maximum value of Y, also referred to as the plateau yield. Initial estimates for the variables were calculated using the large-sample method (Piegorsch and Bailer, 2005). All data were then fitted to the linear-plateau model using Proc NLIN with the Levenberg-Marquardt fitting algorithm. Residuals were computed to check the assumptions of normality and linearity and all factors were plotted before analysis to examine the relationships. Once the breakpoint had been estimated using the models, linear regression was applied to the data below the breakpoint to identify the variables that were acting on the growth rates. Variables entered into the linear models were the same as previously used (Table 3.1).

3.2.3 Weight category analysis

To investigate whether pigs with different BiW, WW and/or IW had the capacity to compensate for low BW, all pigs at each BW interval were divided using percentiles into 8 categories as previously described. The category of each pig at FW was then compared with its BiW/WW/IW category to determine whether it remained in the same BW category, decreased, or increased at least 1 category.

3.3 Results

3.3.1 Descriptive statistics

Table 3.1 shows the average for variables for breeding company 1. The average BiW was 1.41 (SD = 0.29, range of 0.40 to 2.50) kg, with an average adjusted FW of 92.5 (SD = 10.4, range of 64.8 to 138) kg at 155 d of age and an adjusted IW of 48.6 (SD = 4.82, range of 27.1 to 67.1) kg at 105 d. The majority of pigs were females (69%), with males having a slightly greater average BiW of 1.47 (SD = 0.30) compared to 1.39 (SD = 0.29) kg in females ($P < 0.001$). By IW females were slightly heavier with an average of 49.6 (SD = 4.84) kg and males weighing 48.0 (SD = 4.73) kg ($P = 0.0012$). However, by FW males were heavier once again at 95.6 (SD = 9.96) kg compared to 86.5 (SD = 8.57) kg in females ($P < 0.001$). The correlations between BiW and IW/FW were low, +0.22 and +0.21, respectively ($P < 0.001$), whereas IW and FW had a greater correlation of +0.48 ($P < 0.001$). The total number of piglets born per litter ranged from 2 to 36; however, the maximum total number born alive was 22. The parity number of the sow varied from 1 to 9, parities 2 to 5 had the greatest average BiW, and this pattern was still evident at FW.

Table 3.1 also shows the average for variables for breeding company 2. The results for breeding company 2 showed an average BiW of 1.39 (SD = 0.33; range of 0.32 to 2.70) kg, adjusted WW of 6.11 (SD = 1.38; range of 1.20 to 11.6 kg) at 23 d, and adjusted FW of 78.0 (SD = 11.7; range 38.4 to 120) kg at 140 d. There were a similar number of males and females in the dataset (52 versus 48%). Of the 47,621 males in the dataset, 33% were castrated and 67% were intact. On average males had a slightly greater BiW of 1.52 (SD = 0.33) versus 1.43 (SD = 0.32) kg in females ($P < 0.001$). By weaning, males were still heavier than females at 6.16 kg (SD = 1.37) versus 6.06 kg (SD = 1.33; $P < 0.001$); however by FW this difference had increased and males had an average FW of 78.8 (SD = 11.9) compared with females at 77.0 kg (SD = 11.4; $P < 0.001$). The correlations between BiW and WW/FW were low, +0.31 and +0.29, respectively ($P < 0.001$), and WW and FW were also weakly correlated with +0.29 ($P < 0.001$). The total number of piglets born per litter ranged from 1 to 25 whereas the maximum total number of piglets born alive per litter was 22. The parity number of the sow varied from 1 to 12, parities 1 to 8 had the greatest average BiW, and this pattern was still evident at FW.

3.3.2 Breeding Company 1

The variables that were significant in the multivariate logistic model on absolute growth during the interval BiW to FW (i.e. lifetime growth) were BiW ($P < 0.001$), IW ($P < 0.001$), sex ($P < 0.001$), month of birth ($P < 0.001$), and breed code ($P < 0.001$); parity and total born were not significant. For the additional models looking at BiW to IW and IW to FW, the same variables were significant, with the addition that parity ($P < 0.001$) and total born ($P < 0.002$) were also significant (OR = 1.15 and 1.02, respectively) for the BiW to IW interval. Tables 3.2 and 3.3 show the average BW of each BW category (1 to 8) and the range and average absolute growth rate of each growth rate category (1 to 3) used in the analysis.

Pigs in the lightest BiW category were 1.42 times ($P < 0.001$) more likely to be in a low growth rate group than pigs with a BiW of 1.95 kg or above; all other BiW categories were not significant with the exception of the 2 heaviest, which had even odds ($P < 0.001$) of being in a low growth rate group compared with the reference category. The odds of a pig with a lighter IW (31.1 to 43.1 kg) being in a low growth category were 48.9 times ($P < 0.001$) more likely than a pig with a heavier IW (54.0 to 66.8 kg). Similarly for the interval IW to FW, pigs with the lightest IW were 50.7 times ($P < 0.001$) more likely to be in a low growth rate group. Males were less likely than females to be in a low growth rate category for BiW to FW interval and IW to FW (OR = 0.10 for both intervals; $P < 0.001$); however between BiW and IW, males were 1.62 times ($P < 0.001$) more likely to be in a low growth rate group compared with females. The results of the breed of pig indicated that the odds of a pig that is classified as breed code 3 being in a low growth rate category were 1.50 times ($P < 0.001$) more likely than breed code 1 or 2.

Table 3.2 Mean body weight (and SD) for birth, weaning, intermediate and final body weight categories

BW category[1]	Dataset	BiW[2]	SD	WW[3]	SD	IW[4]	SD	FW[5]	SD
1	1	0.93	0.10	-	-	40.8	2.07	76.0	3.37
	2	0.86	0.12	4.03	0.41	-	-	58.0	5.07
2	1	1.20	0.05	-	-	44.3	0.64	83.0	1.30
	2	1.08	0.05	4.86	0.17	-	-	67.6	1.74
3	1	1.30	0.01	-	-	46.2	0.48	87.0	1.07
	2	1.22	0.03	5.36	0.13	-	-	72.6	1.22
4	1	1.40	0.01	-	-	47.8	0.42	90.5	0.99
	2	1.33	0.03	5.81	0.13	-	-	76.6	1.10
5	1	1.60	0.04	-	-	49.2	0.43	93.8	0.96
	2	1.43	0.03	6.25	0.13	-	-	80.1	0.98
6	1	1.70	0.01	-	-	50.8	0.48	97.3	1.08
	2	1.54	0.03	6.72	0.14	-	-	83.5	1.06
7	1	1.90	0.04	-	-	52.8	0.69	102	1.59
	2	1.68	0.05	7.30	0.20	-	-	88.1	1.64
8	1	2.00	0.13	-	-	56.7	2.34	110	4.83
	2	1.95	0.15	8.47	0.72	-	-	97.1	5.10

[1] Body weight categories were calculated by retrospectively assigning pigs to a group based on their weight at each successive BW (i.e. BiW, IW, and FW) using percentiles of 12.5% (8 groups)
[2]BiW = birth weight (kg) of piglets taken within 24 h of birth
[3] WW = weaning weight of pigs (kg) adjusted to 23 d
[4] IW = intermediate weight of pigs adjusted to 105 d
[5] FW = final BW; body weight of pigs taken at slaughter (kg), adjusted to 155 d for dataset 1 and 140 d for dataset 2

Table 3.3 Mean and range of absolute growth rate (g/day) of pigs derived from 2 datasets during different lifetime stages

Dataset	Time interval	Absolute growth rate category[1]	No. of observations	Absolute growth rate range (g/d)	Mean growth rate (g/d)
1	Birth to intermediate BW[2]	1	6,765	287-433	402
		2	6,761	433-471	452
		3	6,771	471-625	504
	Intermediate to final BW[3]	1	6,765	207-793	665
		2	6,766	793-962	880
		3	6,766	962-1,607	1088
	Birth to final BW[4]	1	6,769	413-559	518
		2	6,769	559-618	589
		3	6,769	618-852	666
2	Birth to weaning BW[5]	1	12,970	49-186	152
		2	12,974	186-237	212
		3	12,974	237-466	279
	Weaning to final BW[6]	1	1,717	268-575	506
		2	1,718	575-655	616
		3	1,717	654-987	717
	Birth to final BW[7]	1	1,717	268-517	458
		2	1,718	517-586	553
		3	1,717	586-857	640

[1] Pigs were categorised into 1 of 3 growth rate categories according to their absolute growth rate for each individual period of growth. Each of the categories contained a similar number of pigs and the number of pigs per interval differed depending on pigs available; for a detailed description see text.
[2] Growth rate for this period was calculated using the birth weight (kg) of piglets taken within 24 h of birth and the intermediate BW of pigs (kg) adjusted to 105 d
[3] Growth rate for this period was calculated using the intermediate BW of pigs (kg) adjusted to 105 d and the BW of pigs at slaughter adjusted to 155 d
[4] Growth rate for this period was calculated using the growth from birth to intermediate BW and then from intermediate to BW
[5] Calculated using the birth weight (kg) of piglets taken within 24 h of birth and the weaning weight of pigs adjusted to 23 d
[6] Calculated using the weaning weight of pigs (kg) adjusted to 23 d and the BW of pigs taken at slaughter (kg) adjusted to 140 d
[7] Growth rate for this period was calculated using the growth from birth to weaning weight and then from weaning weight to final BW

Figure 3.1 shows the relationship between the month of birth and subsequent growth rate. Piglets born during the months of January to April were more likely to be in a low growth rate group (when compared to December), with the greatest odds of 1.26 ($P < 0.001$) occurring in March, and piglets born in all other months were more likely to be in a high growth rate group (when compared to December).

The results for the same models using relative growth rate showed similar patterns for all variables as previously described, with the exception of BiW. Pigs in the lightest BiW category were 0.001 times less likely ($P < 0.001$) to be in a low category for relative growth rate from birth to finish than the heaviest pigs.

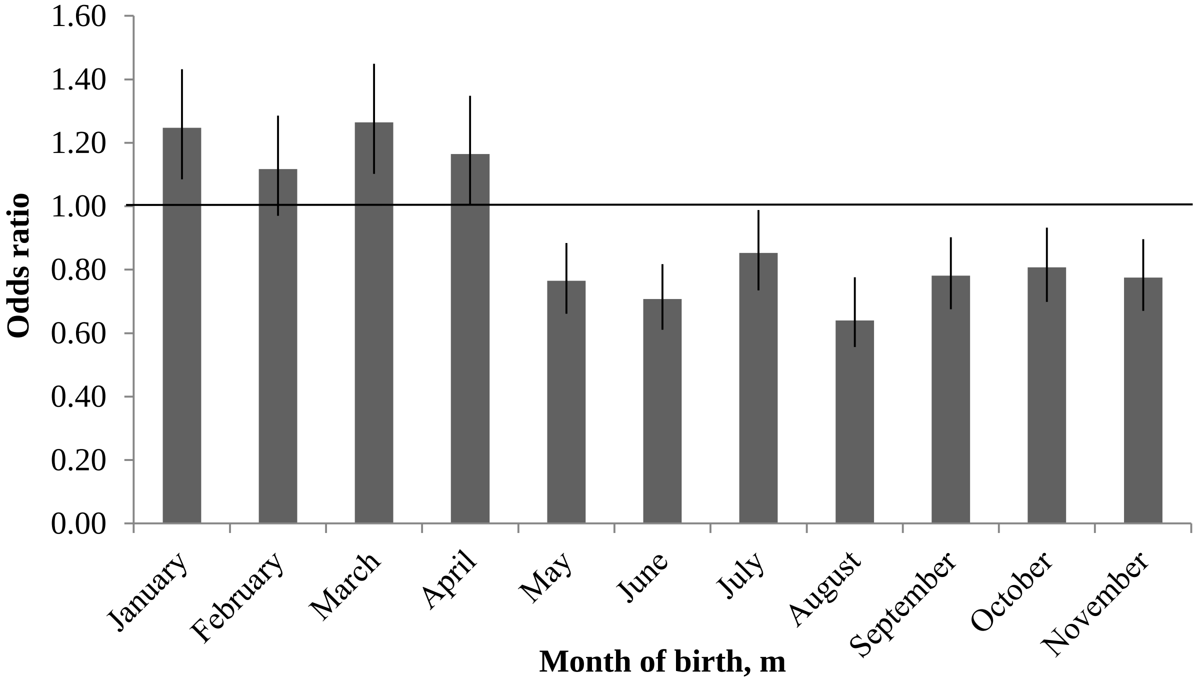

Figure 3.1 Odds ratio and confidence limits for the association of low absolute growth rate of pigs with month of birth, for dataset 1 from birth weight to final body weight (155 d of age) interval. The months January to November are compared to the reference category; this was set as the last month of the year, December. The error bars represent confidence intervals.

The linear-plateau model showed a breakpoint of 1.91 kg [Confidence Interval (CI) = 1.84 to 1.95] when BiW was plotted against lifetime growth rate ($P < 0.001$). This estimation was not affected by the 3 genotypes considered. Linear regression applied before the breakpoint indicated that IW was the best predictive factor for lifetime growth rate for those pigs born under 1.91 kg ($r^2 = 0.23$; $P < 0.001$). These variables were also significant predictors of postnatal growth with decreasing r^2 value: sex ($r^2 = 0.19$; $P < 0.001$), month of birth ($r^2 = 0.03$; $P < 0.001$), and BiW ($r^2 = 0.02$; $P > 0.001$). There was no breakpoint for IW vs. lifetime growth rate or vs. IW to FW growth rate.

Figure 3.2 shows the percentage of piglets that remained, increased, or decreased at least 1 BW category from BiW to FW. Piglets in the lightest BiW category had the greatest percentage of increases (74%) whereas the pigs in the heaviest BiW category experienced the greatest percentage of decreases (79%). A similar pattern was observed for the periods BiW to IW and IW to FW. Of those piglets in the lightest BiW category that increased at least 1 category from BiW to FW, 47% had reached or exceeded the BW group (4) by FW.

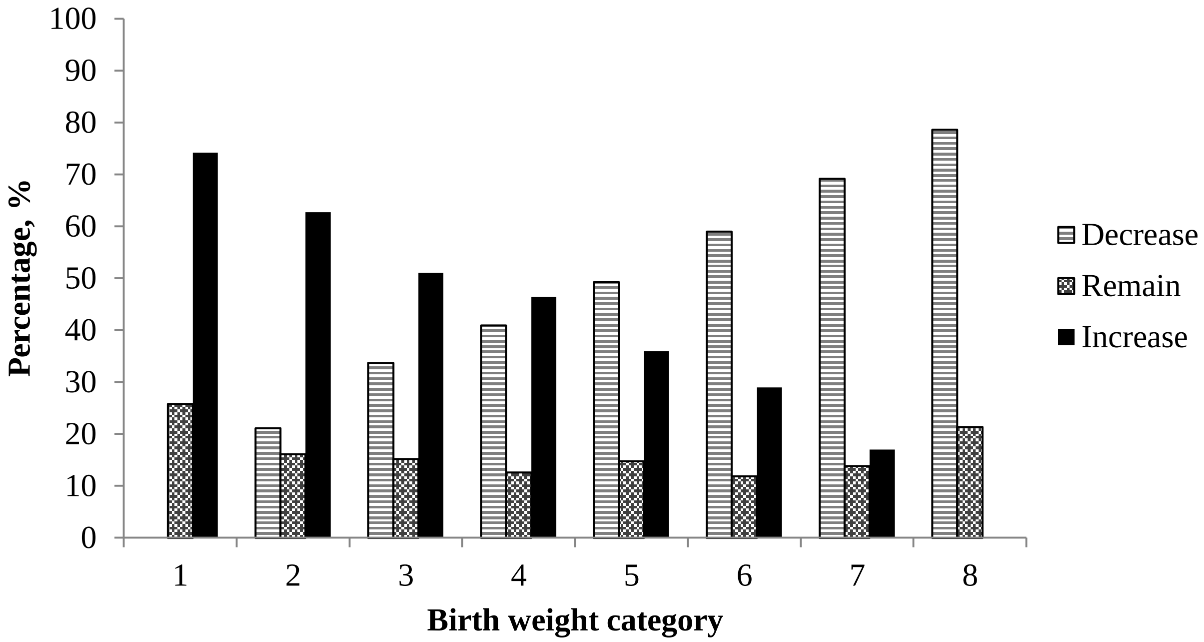

Figure 3.2 Percentage of pigs that remain, increase or decrease at least 1 body weight (BW) category from birth weight (BiW) to final BW (FW) at 155 d of age for dataset 1. All pigs were categorized into 8 BiW groups using percentiles resulting in a similar number of pigs per category; pigs were then categorized at FW using the same method. A pig is categorized as "remain" when it has not changed BW category from BiW to FW. A pig is categorized as an "increase" when it has increased at least 1 category from BiW to FW. A pig is categorized as "decrease" when it has decreased at least 1 category from BiW to FW. Piglets in the top and bottom BiW categories cannot increase or decrease, respectively.

3.3.3 Breeding Company 2

The variables that were significant in the multivariate logistic model on the BiW to FW growth rate were BiW ($P < 0.001$), WW ($P < 0.001$), sex ($P < 0.001$), and month of birth ($P < 0.001$); total number born, parity and length of gestation were not significant. For the additional models looking at BiW to WW and WW to FW growth rates, the same variables were significant with the addition that for BiW to WW, total number born ($P < 0.001$), parity ($P < 0.001$), and length of gestation ($P < 0.001$) were also significant. Table 3.3 shows the range and average absolute growth rate of each growth rate category (1 to 3) used in the analysis.

The effect of BiW on lifetime growth rate showed that piglets in the lightest BiW (0.32 - 1.00 kg) category were 4.55 times ($P < 0.001$) more likely to be in a low growth rate group when compared with those piglets with a BiW between 1.80 and 2.70 kg, with the odds decreasing as BiW decreased (Fig. 3.3). A similar pattern was observed for all intervals examined. Figure 3.4 shows the effect of WW on lifetime growth rate; piglets in the lightest WW category (1.22 to 4.55 kg) were 5.39 times ($P < 0.001$) more likely to be in the low growth rate group when compared to the heaviest WW (7.70 to 11.6 kg). Similarly for the interval WW to FW, pigs with the lightest WW were 4.51 times ($P < 0.001$) more likely to be in a low growth rate group. Males (intact and castrated) were consistently less likely to be in the low growth rate group when compared with females throughout all growth rate intervals examined although during the birth to weaning interval the odds were almost even (OR = 0.96; $P < 0.03$). During the interval WW to FW, castrated males were more likely to be in a low growth rate group compared with intact males (OR = 1.67; $P < 0.002$).

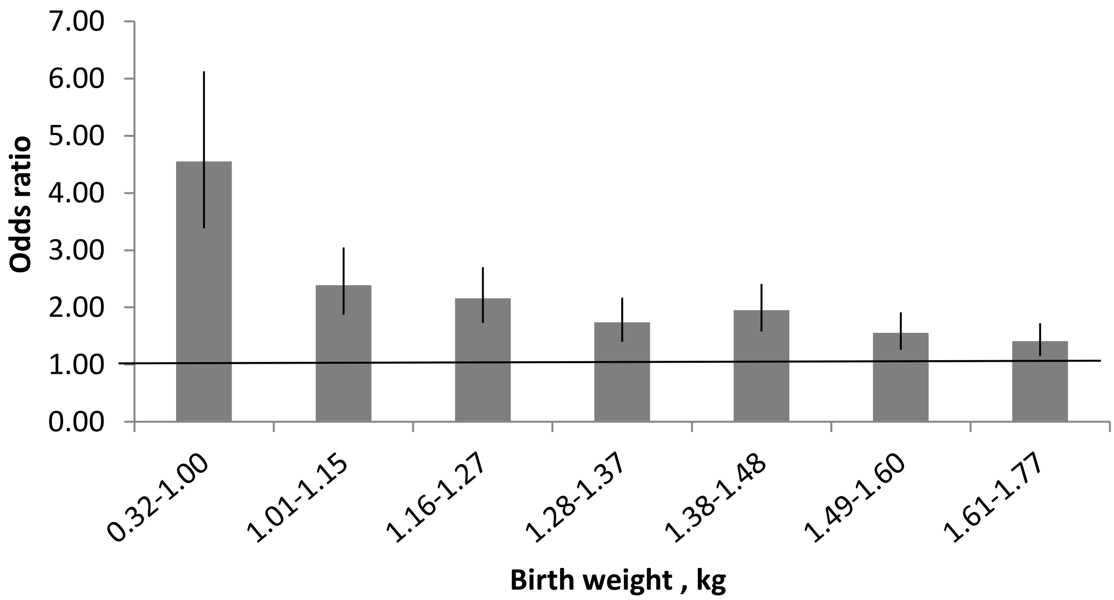

Figure 3.3 Odds ratio and confidence limits for the association of low absolute growth rate in pigs with birth weight (BiW), for dataset 2, from BiW to final body weight (BW) interval (140 d). Birth weight categories were created by grouping adjusted BiW by percentiles with a similar number of pigs per category; for a detailed description please see text. The BiW categories are compared with the reference category; this was set as the heaviest BiW category which is 1.8 to 2.7 kg. The error bars represent confidence intervals.

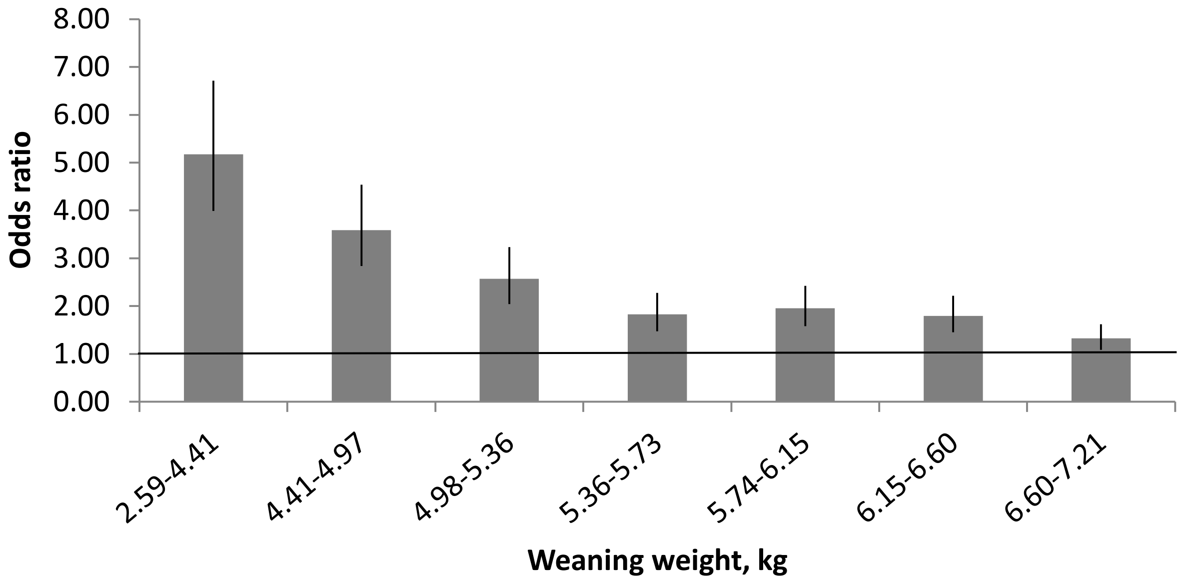

Figure 3.4 Odds ratio and confidence limits for the association of low absolute growth rate in pigs with weaning weight (WW), for dataset 2, from birth weight to final body (BW) interval (140 d). Weaning weight categories were created by grouping adjusted WW by percentiles with a similar number of pigs per category; for a detailed description please see text. The WW categories are compared to the reference category; this was set at the heaviest WW category, which is 7.7 to 11.6 kg. The error bars represent confidence intervals.

The effect of sow parity, although having a significant effect ($P < 0.001$) on the BiW to WW growth rate, did not follow a clear pattern for individual parities; this was also true for piglets born per litter. The length of gestation of the litter was significant ($P < 0.001$) on the BiW to WW growth rate, with an increased length of gestation associated with decreased odds of being in a low growth rate group (OR = 0.98; $P < 0.001$). The month that piglets were born did not show any distinct patterns of seasonality for growth rates with the odds of being in a low growth rate group fluctuating throughout the year.

When using the relative growth rate as the dependent variable in the models, the results followed a similar pattern as described above with the exception of BiW. Those in the lightest BiW category were < 0.001 times less likely ($P < 0.001$) to be in the low growth rate category than the heaviest BiW category. The odds ratio increased slightly for successive categories (2 to 7), with the seventh BiW category still 0.16 times ($P < 0.001$) less likely to be in a low growth rate group than category 8 (1.80 to 2.70 kg). The results for the linear plateau model showed that the breakpoint estimation for BiW against lifetime growth was 1.84 kg (CI = 1.76 to 1.86) for the BiW of the pigs (P < 0.001). When the linear regression model was fitted to the data before the breakpoint, WW (r^2 = 0.07; P < 0.001), BiW (r^2 = 0.03; P < 0.001), parity (r^2 = 0.02; P < 0.001), month of birth (r^2 = 0.01; P < 0.001), and sex (r^2 = 0.01; P < 0.001) were significant predictors of lifetime growth rate. For the model WW versus WW to FW interval, a breakpoint estimation of 7.52 kg (P < 0.001) was obtained. These variables were significant predictors of WW to FW and lifetime growth with decreasing r^2 value: BiW (r^2 = 0.07; P < 0.001), WW (r^2 = 0.04; P < 0.001), parity (r^2 = 0.18; P < 0.001), month of birth (r^2 = 0.01; P < 0.001), and sex (r^2 = 0.01; P < 0.001).

Figure 3.5 shows the percentage of piglets that remained or changed BW categories from birth to finishing. Whilst the percentage of piglets that remained in the same category throughout their life was similar for all BiW categories at 10 to 20%, piglets in the heaviest BiW category had the greatest percentage decrease, meaning that those piglets with the lighter BiW were more likely to increase BW categories. A similar pattern was observed for the period BiW to WW; however, for WW to FW a greater percentage of pigs in the greater WW categories (5 to 8) decreased at least 1 category. Of those piglets in the lightest BiW category that increased at least 1 category from BiW to FW, 52% had reached or exceeded the average BW group (4) by FW.

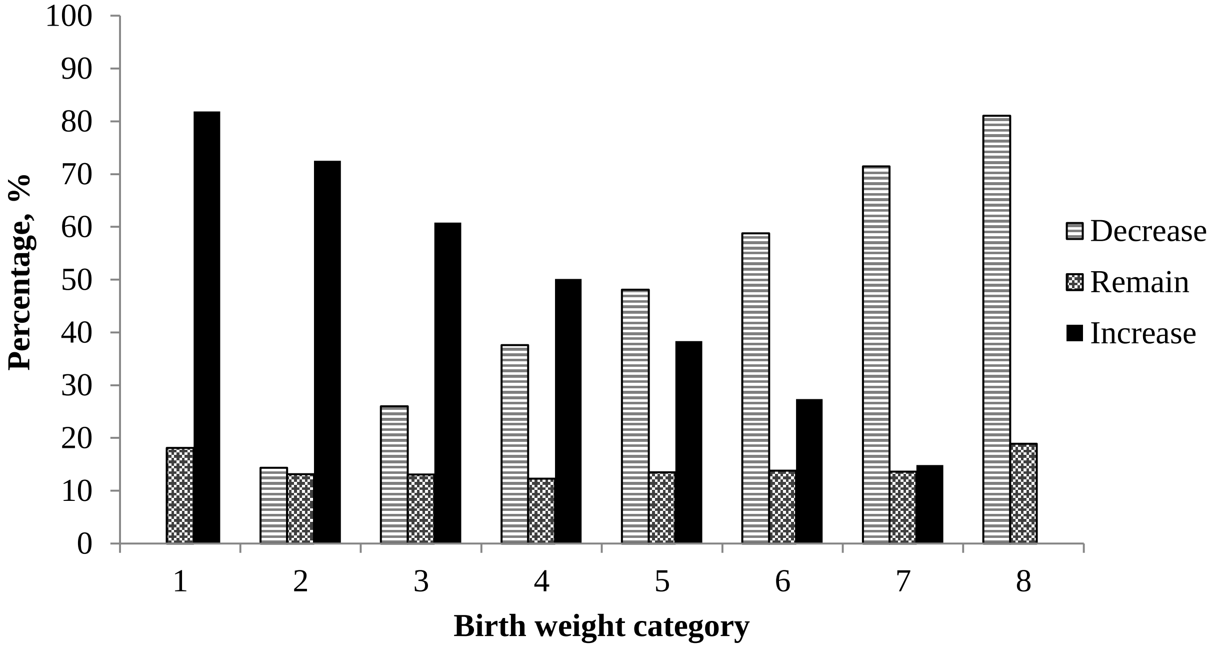

Figure 3.5 Percentage of pigs that remain, increase or decrease at least 1 body weight (BW) category from birth weight (BiW) to final weight (FW) at 140 d of age for dataset 2. All pigs were categorized into 8 BiW groups using percentiles resulting in a similar number of pigs per category; pigs were then categorized at FW using the same method. A pig is categorized as "remain" when it has not changed BW category from BiW to FW. A pig is categorized as an "increase" when it has increased at least 1 category from BiW to FW. A pig is categorized as "decrease" when it has decreased at least 1 category from BiW to FW. Piglets in the top and bottom BiW categories cannot increase or decrease, respectively.

3.4 Discussion

The aim of this paper was to identify risk factors associated with poor growth performance in pigs and to investigate the relationship between BiW and subsequent BW to ascertain whether BiW is the more critical factor in determining lifetime growth rate. In agreement with previous studies (De Grau et al., 2005; Larriestra et al., 2006; Paredes et al., 2012), the data presented here confirm that poor growth performance is associated with a number of variables, including LBiW, low WW and IW as well as litter factors. Additionally, the SD of BiW and FW from both datasets was consistent with previous literature (Fix et al., 2010; Paredes et al., 2012), confirming the reliability of our data. In contrast to other studies (Rehfeldt and Kuhn, 2006), lighter BiW piglets were capable of increasing BW category from birth/weaning to slaughter, suggesting that these light weight pigs have the potential to reduce the deficit during postnatal growth. The results were very consistent between the 2 data sets used, allowing some confidence that the conclusions that can be drawn from them have some generality.

There have been few studies that have investigated more than 2 or 3 factors affecting lifetime growth performance; the number of observations used in such studies is relatively small. Our study differs in both these respects. In addition, previous studies have focused on shorter time intervals, such as the pre-weaning period (Larriestra et al., 2006), or weaning to slaughter (Wolter and Ellis, 2001), as well as having involved relatively few variables (Beaulieu et al., 2010). Most such studies usually exclude pigs considered to have particularly light BiW (usually < 0.8) as they are considered to be runts and would be expected to influence the value of the conclusions drawn (Greenwood et al., 2009). By contrast in our study, piglets with BiW as low as 0.3 kg were considered.

Literature suggests there is an established relationship between BiW and life time growth rate in the pig, with those born underweight having a greater risk of mortality (Rehfeldt and Kuhn, 2006), remaining stunted throughout their life (Quiniou et al., 2002; Gondret et al., 2005; Rehfeldt and Kuhn, 2006) and having poorer meat quality (Gondret et al., 2006). Although the results of the logistic regression show that those pigs born with the lightest BiW were more likely to exhibit poor growth to FW, BiW was not the sole determinant of postnatal growth as both WW, IW and other factors were significant. This is further supported by the weak correlation between the BiW and WW/IW, which disagrees with most current literature (Le Dividich, 1999; Quiniou et al., 2002). The exception is the study of Poore and Fowden (2004) , who did not report a relationship between the BiW of male pigs and subsequent BW at 3 and 12 mo of age. Additionally, the likelihood of pigs with lighter WW and IW having poor growth to FW exceeds that of piglets with LBiW, which implies that LBiW has less effect on performance to finishing in comparison to WW and IW. Furthermore, our results contradict those of Lynch et al (1998) who suggest that WW was poorly related to post weaning performance. However, differences in the management of these pigs during the different stages of production may account for the inconsistent conclusions between studies (Kyriazakis and Houdijk, 2007).

In addition to BiW and WW, a number of variables which contribute to poor growth in pigs were identified; these include litter size, sex and month of birth. Although increase in prolificacy of sows in recent years is seen by many as a positive development, with increased numbers of piglets being weaned per litter, there are also negative effects associated with it, the most common being a reduction in the mean BiW of the litter (Beaulieu et al., 2010). Our results showed that the total number of piglets born per litter is only significant in determining pig growth during the first interval of their life, from birth to weaning. During this interval larger litters were more likely to have poor postnatal growth, similar to previous studies (Beaulieu et al., 2010); however, beyond weaning the impact of litter size on performance is negligible. Although the effect of litter size is likely to be partly a reflection of the BiW of the piglets, it can affect their growth by other routes. Although the sow is able to increase the amount of milk she produces for a larger litter, this will not be proportional to the number of pigs she nurses; as a result there may not be sufficient milk for all piglets (Auldist et al., 1998). Inevitably this can lead to increased competition and mortality, often with the lightest pigs being most affected by any shortage in milk as they have a competitive disadvantage to larger litter mates (Milligan et al., 2002b). This is likely to perpetuate any observed differences in BW during the lactation period ensuring the smallest pigs stay small.

The parity of the sow can also affect milk production, which is likely to affect piglet growth. It has been shown that piglets from mid parity sows have the greatest WW (Milligan et al., 2002a). It can also influence BiW with sows in their first parity having piglets with lower BiW, as well as fewer piglets (Milligan et al., 2002b). The effect sow parity has on subsequent piglet growth is unclear. In our study, although parity was identified as a statistically significant factor for growth in all periods of pig life, often the pattern across the consecutive parities was unclear. The seasonality observed in the first dataset suggests that the month in which piglets were born in can affect growth rate. Similar to previous research we found that those pigs born during the warmest months and therefore finishing during the cooler months were more likely to have greater growth rates (Kościński et al., 2009). Additionally, sex appeared to be a key factor for piglet growth, with male pigs exhibiting greater lifetime growth rates in this analysis, although during the birth to weaning interval the growth rates between the sexes were very similar (with females actually having higher growth rates in 1 dataset). It is possible that differences in performance between the sexes are not observed until post puberty; this is supported by previous work that shows sex did not significantly affect ADG in piglets during the lactation period (Skorjanc et al., 2007).

It was previously found that the relationship between lifetime growth rate and BiW is not linear, a threshold can be reached beyond which any further increase in BiW will not increase absolute growth rate (Fix et al., 2010). Similarly we found that the relationship between BiW and growth from BiW to FW is linear up to 1.80 to 1.90 kg, after which any increase in BiW did not result in an increase in growth rate. In the population of pigs below this break point value, WW was the most critical risk factor for predicting lifetime growth whereas BiW was the critical factor for the interval WW to FW when plotted against WW. The absence of any breakpoint for IW indicates a linear relationship for which any increase in IW will result in an increase in growth rate to FW.

Pigs that have undergone a period of limitation in their growth, for example during feed restriction, may compensate when normal feeding is restored to reach a similar BW to unaffected pigs as long as the previous management has not been too severe (Kyriazakis and Emmans, 1991; Kyriazakis et al., 1991). Similarly, it has been postulated that light BiW piglets can exhibit varying degrees of catch up growth to meet or exceed the slaughter weights of littermates with heavier BiW (Handel and Stickland, 1988), the extent of which is reliant upon the number of muscle fibres present at birth (Handel and Stickland, 1988; Dwyer et al., 1993). However this finding is not consistent in the literature, as Rehfeldt and Kuhn (2006) and Beaulieu et al. (2010) have stated that light BiW piglets were more likely to exhibit poor growth rates and lighter BW at successive intervals, pre- and postweaning, therefore not meeting the BW of their heavier littermates. The results of this study support the view that piglets with lower BiW may reduce the deficit in their growth during the postnatal period; in addition almost one-half of these pigs were able to meet or exceed the average FW of the population. When looking specifically at light BiW piglets for each dataset, piglets with the lightest BiW were more likely to increase a weight category by FW than those heavier pigs. Whilst it is inevitable that those piglets in the heaviest and lightest BW categories can only change category in 1 direction (i.e., increase or decrease, respectively), these results do show a degree of catch up growth is occurring in light BiW piglets, and in some cases these piglets were able to catch up to heavier littermates by FW.

3.5 Conclusions

Our results provide a better understanding of the factors affecting postnatal growth in the pig. The implications of this study are that, although a number of risk factors are associated with poor growth in pigs, both light BiW and WW result in poor growth to finishing. However some of these small pigs appear to have the capacity to compensate for low BW at birth, suggesting that there needs to be renewed focus on interventions in the earlier stages of production to maximise postnatal growth of low BW pigs.

Chapter 4: A high nutrient specification diet at 9 weeks of age does not improve the performance of low birth weight pigs

4.1 Introduction

Variability in BW of pigs is an important factor for both producer and processor in detracting from maximum return (Patience and Beaulieu, 2006). Low birth weight pigs contribute to this variation by exhibiting poor growth rates (Poore and Fowden, 2004; Gondret et al., 2005; Rehfeldt et al., 2008; Douglas et al., 2013), likely as a result of restriction in utero (Widdowson, 1971; Wu et al., 2006; Wang et al., 2008), which is exacerbated by competition from heavier pigs for limited resources (Algers and Jensen, 1991; English, 1998; Lay et al., 2002).

As a consequence of restricted nutrition in utero, the body composition of LBiW piglets differs from heavier littermates (Rehfeldt and Kuhn, 2006), and they may be able to meet the BW of heavier littermates (Paredes et al, 2012; Douglas et al, 2013). It is therefore possible that these pigs may benefit from a higher nutrient specification diet rather than a diet that targets the 'average' pig (Wellock et al., 2004; Kyriazakis and Houdijk, 2007). In fact, postnatal growth of LBiW pigs often results in a tendency to deposit more adipose tissue (Bee, 2004; Rehfeldt and Kuhn, 2006), which may be a reflection of such 'inappropriate' feeding. These principles are exploited in human LBiW infants fed a high nutrient formula during the first year of life to increase BW (Kashyap et al., 1994; Premji et al., 2006), with similar results observed in supplementary milk feeding of pigs (Morise et al., 2011; Jamin et al., 2012; Han et al., 2013).

Therefore, we hypothesized that LBiW pigs would respond to feeding of an improved nutrient specification diet which is higher in amino acids: energy, in a manner similar to NBiW pigs which are of similar weight for age due to experiencing a period of feed restriction post weaning. The aim of the experiment was to determine the performance responses of pigs with different weight for age, resulting from different prenatal or postnatal growth, given either a high or standard amino acid: energy ratio diet.

4.2 Materials and method

4.2.1 Experimental design

The experiment was designed as a 3 x 2 factorial with 6 replicates. Treatments comprised 3 BW categories (N = NBiW (1.6 to 2.0 kg), NR = NBiW but fed restrictedly from d 49 to 63 and L = LBiW (≤ 1.25 kg)) and two diet specifications (HP = high amino acid: energy ratio (supplying 14 g SID lysine/MJNE), SP = standard amino acid: energy ratio (supplying 11 g SID lysine/MJNE)) from d 63 to 91 of age. The experiment was conducted at Cockle Park Farm, Newcastle University and was approved by the Animal Welfare and Ethics Review Board at the University.

4.2.2 Farrowing, lactation and weaner management

At the beginning of period 1 (birth to d 49), a total of 180 crossbred pigs (dam was Large White x Landrace cross and sire was Hylean synthetic, Hermitage Seaborough Ltd., Devon) from 6 consecutive farrowing batches were selected based on BiW. Each farrowing batch consisted of approximately 17 litters, and from these L and N piglets were selected. Piglets which did not meet the weight requirements were fostered onto non experimental sows. Within the first 12 h after birth pigs were teeth clipped, weighed and individually ear tagged for identification. Morphometric measurements were also taken during this period: crown-rump length (CRL), snout-ears length and abdominal and cranial circumference.

Efforts were made during the lactation period to maximize the growth of all pigs by reducing limiting factors such as competition from heavier littermates and poor milk supply. During the first 24 h all piglets selected for trial were cross fostered into a litter according to their BiW i.e. 2 sows for N (one will later be restricted to form NR) and one for L. This procedure is commonly used on farms in the UK, where piglets are regrouped to create more uniform litters. This ensures that the teats on the sow are accessible for the size of the piglets. An effort was made to have an equal number of piglets of each sex and from at least 3 different birth litters in each cross fostered litter. All sows used were first or second parity sows to ensure small piglets could access the teats; each sow was also checked to ensure there were sufficient functional teats to support the litter. All litters were offered supplementary Faramate milk (Volac International Ltd, Orwell, Hertfordshire; Protein = 22%, oil = 14%, ash = 7.5%, fibre = 0%) *ad libitum* from birth to weaning (~28 d). This was provided in a metal dish and was refilled twice a day as needed; it was prepared by hand mixing milk powder with warm water. Piglets received commercial creep feed from day 10 onwards; the creep feed was placed once a day on the floor of the heated creep area and was the same as the starter 1 diet offered at weaning (23% crude protein (CP), 16.0 MJ/kg DE, 1.43% total lysine).

Pigs were weaned on 28 d, where they were transferred to nursery accommodation with plastic slatted floors and kept in their pre-weaning litters. Aluminium ear tags were removed and replaced with plastic weaner tags. The temperature in the nursery accommodation was 26 °C and was reduced by 0.2 °C/d to a minimum of 22 °C over a period of 20 d. Each pen had a feeder with 3 spaces and a separate nipple drinker, and all pigs had *ad libitum* access to feed and water. Pigs were fed a 3 stage starter diet regime (Primary Diets, Ripon, North Yorkshire; diet 1 = 23% CP, 16.0 MJ/kg DE, 1.43% total lysine, diet 2 = 22% CP, 15.25 MJ/kg DE, 1.33% total lysine and diet 3 = 21.7% CP, 15.0 MJ/kg DE, 1.28% total lysine) with fixed amounts per pig and given sequentially lasting 2 to 3 wk. Piglets were individually weighed twice a week from birth to d 49 and FI per litter was measured from d 28 to 49.

4.2.3 Experimental management

Treatments did not start until d 49 onwards to ensure that all pigs had recovered from any post-weaning growth check. At d 49 pigs were moved to experimental accommodation, where each litter was split to form 2 treatment groups of 5 pigs each (balanced for sex and litter of origin using SAS Proc plan to randomly allocate pigs to treatments); any additional pigs were removed from the experiment. The accommodation consisted of partly slatted concrete floors; each pen provided 0.96 m^2/pig and had a feeder with 5 spaces and a separate nipple drinker which was located over the concrete slats. A thermostatically controlled heating and fan ventilation system maintained the room temperature between 19 and 21 °C, which was monitored daily using a max-min thermometer.

In period 2, from d 49 to 63, the NR pigs received restricted amounts of feed (600 g/d per pig) with the remaining N and L groups fed *ad libitum* the same commercial weaner diet (A-One Feed Supplements, Thirsk, North Yorkshire; 20.55% CP, 14.46 MJ/kg DE, 1.28% total lysine). The aim was for NR and L pigs to have the same BW by d 63. The amount of feed given to NR pigs was calculated using previous performance data (Average daily feed intake (ADFI) and FCE) of similar weight pigs from Cockle Park.

For period 3, from d 63 to 91, groups within litter were randomly allocated a high (14 g SID lysine/MJNE) or a normal amino acid: energy (11 g SID lysine/MJNE) grower diet for their age, offered *ad libitum* for 4 wk. Table 4.1 reports the composition of the experimental diets used.

From d 49 to 91, pigs were individually weighed twice a wk, on a Monday and Thursday morning. Feed intake was determined by manually recording the total feed given for each 3 or 4 d period, and the feed refusals prior to the next weighing. With these measurements, ADG was calculated for individual animals, and ADFI and FCE were calculated for pens. Both ADG and ADFI were scaled to BW to allow for comparisons and account for the fact that pigs were of different size (Kyriazakis et al., 1991). Various exponents methods were tested to scale ADG and ADFI to BW (e.g. $BW^{0.75}$,$BW^{0.66}$), but, as these had no effect on the conclusions drawn; here we report the outcomes per unit BW. The scaled ADG (SDG) was calculated as ADG/kg BW whilst the scaled ADFI (SFI) was ADFI/kg BW. The BW used to scale the ADG/ADFI was the weight at the start of the specific period in question, for example when calculating the SDG for d 63 to 91, the ADG for this period was divided by the BW on d 63. Morphometric measurements taken at birth were used to calculate the relative CRL (CRL/kg) and PI (BW/CR^3).

Table 4.1 Diet composition and chemical analysis for the dietary treatments, SP and HP, offered from d 63 to 91 of age. The two feeds contained different amino acid: energy ratios

	Diet	
Item	SP	HP
Ingredient, g/kg		
Wheat	57.5	46.1
Micronized barley flakes	20.0	20.0
Soya bean meal	13.4	21.2
Pig finisher premix[2]	0.25	0.25
Full fat soya (Soycomil)	4.75	7.50
L-lysine-HCL	0.49	0.55
DL-Methionine	0.13	0.23
L-Threonine	0.18	0.22
L-Tryptophan	0.02	0.03
Vitamin E	0.01	0.01
Limestone flour	0.28	0.33
Dicalcium phosphate	0.95	0.85
Salt	0.22	0.33
Sodium bicarbonate	0.17	0.00
Binder (Lignobond DD)	0.63	0.63
Soya Oil	1.04	1.82
Analysed composition[2] % as fed		
NE, MJ/kg[3]	10.1	10.1
Ash	3.70	4.10
Crude fibre	2.50	2.80
Crude protein	16.8	21.3
Total lysine	1.09	1.58
Methionine	0.37	0.56
Oil	3.92	4.65
Moisture	11.9	11.3

[1] Provided per kg of complete diet: 9,000 IU of vitamin A, 2,000 IU of vitamin D_3, 35 IU of vitamin E, 2 mg of vitamin K, 1.5 mg of vitamin B_1, 4 mg of vitamin B2, 2.5 mg of B6, 15 µg of vitamin B_{12}, 11 mg of pantothenic acid, 15 mg of nicotinic acid, 50 µg of biotin, 0.5 mg of folic acid, 15 mg of CU ($CUSO_4$), 1.5 mg of Iodine (KI, $Ca(IO_3)_2$), 100 mg of Fe ($FeSO_4$), 35 mg of Mn (MnO), 0.25 mg of Se (BMP-Se), 100 mg Zn ($ZnSO_4$).

[2] Analysis performed by Sciantec Analytical Services Ltd (North Yorkshire)

[3] Values estimated using raw material matrix (Primary Diets., Melmerby, UK)

4.2.4 Statistical analysis

All performance data was tested for normality using the Univariate procedure of SAS version 9.2 (SAS Institute Inc., Cary, NC) and was normally distributed. Sex (entered as a proportion of females in each pen or litter depending upon the period being examined) was included as a factor in all preliminary models but was not significant so omitted for subsequent analysis. Data was blocked by sow to account for litter effects. Treatment x sow interactions were added to all preliminary models, but were not significant. Differences were considered significant at < 0.05 and reported as a tendency towards statistical significance at < 0.10. Data are presented as least square means.

For d 1 to 49 only, the effect of BiW on performance indicators were analysed using repeated measures ANOVA using Proc Mixed of SAS. Suckling group (‘N’ or ‘L’) and time (d 1 to 49) were added as factors. The experimental unit from d 1 to 49 was the litter or suckling groups L or N (11 to 12 piglets). For d 49 to 91, the effect of BW category (N, NR and L), diet specification in period 3 (high or standard amino acid: energy diet) and time were analysed using a repeated measures ANOVA using Proc Mixed. The experimental unit was the pen (5 pigs). Body weight category, diet specification and time were added as factors.

4.3 Results

4.3.1 Performance in period 1, d 1 to 49

The effects of BW categories NR, N and L on weight, ADG, ADFI and FCE from birth to d 91 are shown in Table 4.2. At birth, L pigs had an average weight of 1.02 kg (SD 0.152) whilst N pigs averaged 1.87 (SD 0.103). Focusing specifically on the performance of pigs during lactation (d 1 to 28), there was no difference in the ADG of all groups (P > 0.05). When pigs were weaned at d 28, L pigs still had a lower BW than pigs in the other weight categories (P < 0.001), with over 1.5 kg difference in average WW when L pigs were compared to N. In the initial period following weaning (d 28 to 49), a lower ADG of L pigs in comparison with N was seen (P < 0.001); by d 49 there was a 3 kg difference in the BW of L and N pigs. Average daily feed intake measured for the litters from d 28 to 49 showed that L pigs ate significantly less compared to N pigs (Table 4.2).

In contrast, SDG of L pigs exceeded that of N until weaning, but from d 28 to 49 there was no significant difference between these two groups (Fig.4.1). Scaled feed intake also showed that L pigs exceeded the intake of N pigs from d 28 to 49, relative to their body size ($P < 0.001$) (Fig.4.2).

At birth, L pigs had a shorter CRL of 23.5 cm (SD 2.11) compared to 28.7 cm in N (SD 2.51) ($P < 0.001$). However L pigs had a higher CRL/BW (23.4 cm/kg, SD 2.91) than N pigs (15.4 cm/kg, SD 1.04) ($P < 0.001$). Ponderal index data showed that L pigs had a significantly lower PI (86.5 kg/m^3, SD 13.2) than N pigs (102.1 kg/m^3, SD 11.1) ($P < 0.001$).

4.3.2 Performance in period 2, d 49 to 63

On d 49, BW for L pigs differed significantly from N and NR, which did not differ from each other (Table 4.2). Pigs fed restrictedly during this period (NR) had a lower ADFI and ADG as expected; this resulted in them weighing the same as L pigs by d 63, whilst N pigs were significantly heavier. L pigs grew at a significantly slower rate than N pigs, however they ate the same as N Pigs (absolute FI) ($P < 0.001$). Figure 4.1 and 4.2 demonstrate that for both SDG and SFI, L pigs exceeded N pigs ($P < 0.001$) during this period. There was no significant difference in the BW, ADG or FCE of the different treatment groups prior to starting the nutritional treatments (data not shown).

Table 4.2 The effect of body weight categories on the performance of pigs from birth to d 91. NR were normal birth weight pigs but fed restrictedly (between d 49 to 63), N were normal birth weight pigs and L was low birth weight pigs.

	Body Weight category[1]				
Item	NR	N	L	SEM	P-value[2]
BW, kg					
D1	1.86^{A}	1.88^{A}	1.02^{B}	0.259	< 0.001
D 28	8.38^{A}	8.36^{A}	6.84^{B}	0.345	< 0.001
D 49	17.6^{A}	17.6^{A}	14.4^{B}	0.525	< 0.001
D 63	21.2^{A}	25.8^{B}	21.8^{A}	0.610	< 0.001
D 91	44.2^{A}	46.6^{A}	40.8^{B}	1.048	< 0.001
ADG, kg/d					
D 1 to 28	0.239	0.238	0.213	0.0123	0.452
D 28 to 49	0.437^{A}	0.440^{A}	0.362^{B}	0.0138	< 0.001
D 49 to 63	0.261^{A}	0.595^{B}	0.529^{C}	0.0183	< 0.001
D 63 to 91	0.819^{A}	0.742^{B}	0.684^{B}	0.0278	< 0.001
ADFI, g/kg					
D 28 to 49	483^{A}	472^{A}	430^{B}	17.7	0.023
D 49 to 63	600^{A}	925^{B}	927^{B}	36.6	< 0.001
D 63 to 91	1279^{A}	1224^{A}	1259^{A}	36.2	0.378
FCE					
D 28 to 49	0.971	1.033	0.905	0.0588	0.597
D 49 to 63	0.423^{A}	0.666^{B}	0.552^{C}	0.0303	< 0.001
D 63 to 91	0.660^{A}	0.626^{A}	0.554^{B}	0.0195	< 0.001

[1] A, B, C Within a period, means with different superscripts differ (P < 0.05)

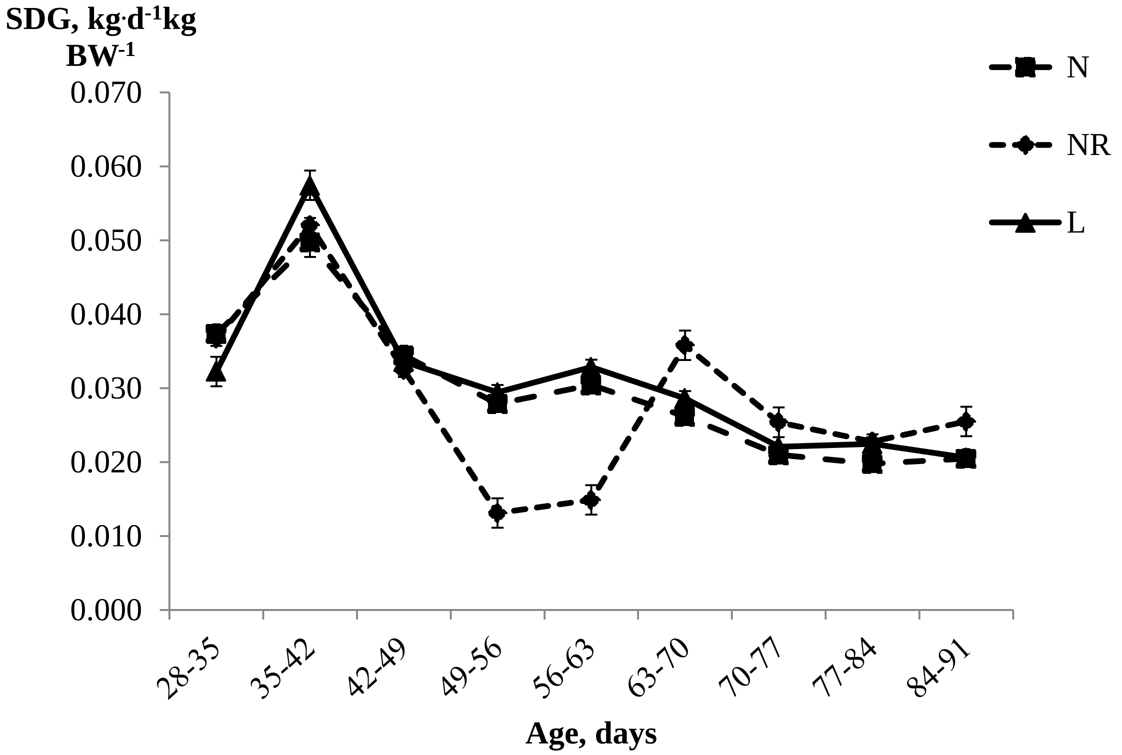

Figure 4.1 The effect of body weight (BW) category (N, NR and L), on the scaled ADG (SDG) of pigs from d 28 to 91. Weight category: N were normal birth weight pigs (1.6 to 2.0 kg), NR was normal birth weight but fed restrictedly (d 49 to 63) and L was low birth weight (≤ 1.25 kg). SDG was calculated as the ADG for specific period/BW at the start of that period. Error bars represent the pooled SEM.

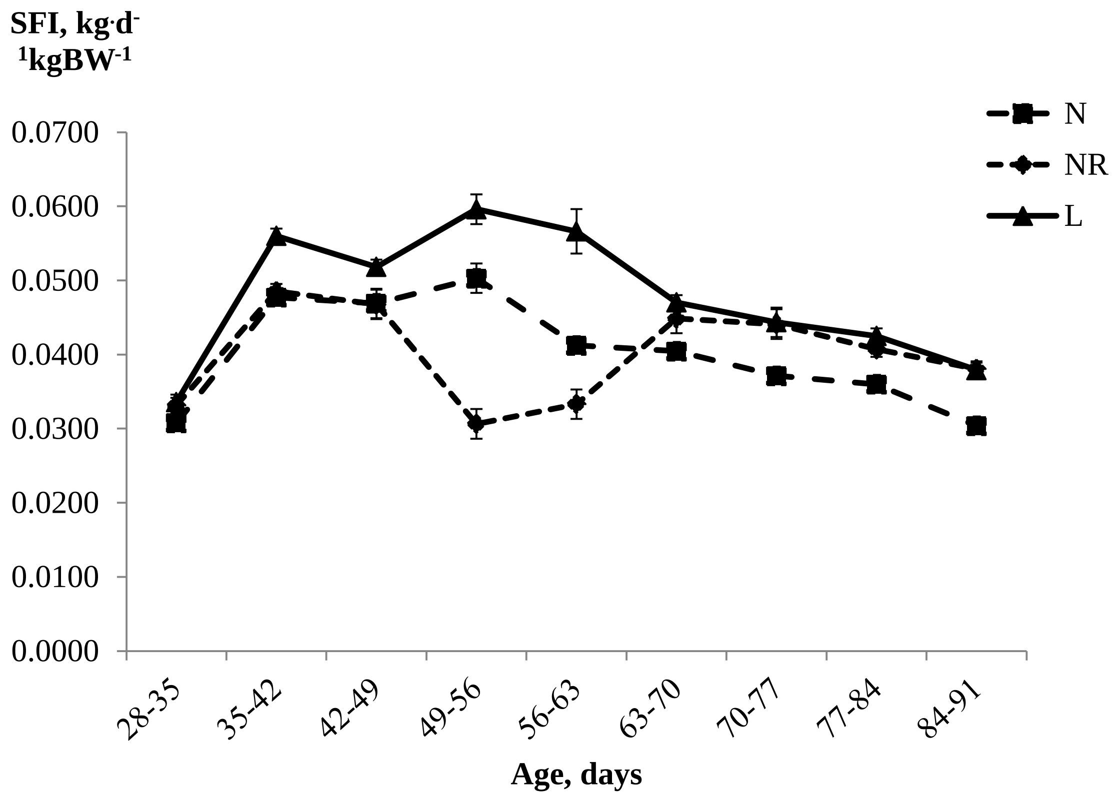

Figure 4.2 The effect of body weight category (N, NR and L), on the scaled feed intake (SFI) of pigs from d 28 to 91. Weight category: N were normal birth weight pigs (1.6 to 2.0 kg), NR were normal birth weight but fed restrictedly (at day 49 to 63) and L were low birth weight (≤ 1.25 kg). Scaled feed intake (SFI) was calculated as the average daily feed intake of a specific period/BW at the start of period. Error bars represent the pooled SEM

4.3.3 Performance in period 3, d 63 to 91

The effects of BW category and diet specification on the live weight, ADG, ADFI and FCE are shown in Table 4.3. For d 63 to 91 there was a significant difference in ADG between BW categories; however there was no effect of diet specification on the performance of pigs or any BW category x diet specification interaction.

Post d 63, there was a significant difference in the ADG of the BW categories; at all stages examined L pigs grew at a slower rate than both N and NR pigs from d 63 to 91 ($P < 0.001$). Conversely, NR pigs performed significantly better than both N and L pigs once the feed restriction was stopped on d 63. NR pigs had a higher ADG compared to other treatments (*P* < 0.001) and by d 91 did not significantly differ in weight from N pigs (*P* < 0.001). There was no effect of BW category, diet specification or an interaction between the two, on the absolute ADFI of pigs for d 63 to 91. From d 63 to 91 L pigs had a reduced FCE in comparison to N and NR pigs. In no case did the diet or interaction between BW category and diet have a significant effect on the FCE.

When taking into account the ADG relative to the BW of the pigs (SDG), L and N pigs grew at a similar rate, whilst NR pigs had greater SDG in comparison (*P* < 0.001). In contrast, NR and L pigs had greater SFI than N pigs from d 63 to 91 (*P* < 0.001).

Table 4.3 The effect of body weight category and diet specification (standard (SP) or high (HP) amino acid: energy ratio) on the performance of pigs from d 63 to 91. NR was normal birth weight but fed restrictedly (d 49 to 63) pigs, N was normal birth weight pigs and L was low birth weight pigs

	Treatment (Body weight category/ diet specification)							Significance		
	NR SP	NR HP	N SP	N HP	L SP	L HP	SEM	Weight category	Diet specification	Weight category x diet specification
ADG, kg/d	0.785	0.854	0.730	0.753	0.683	0.684	0.0276	< 0.001	0.485	0.376
ADFI, g/kg	1,300	1,257	1,214	1,234	1,261	1256	37.4	0.378	0.246	0.357
FCE	0.624	0.697	0.618	0.633	0.551	0.557	0.19	< 0.001	0.481	0.573

4.4 Discussion

We investigated the ability of pigs of different weight for age to exhibit catch up growth when given access to diets which differed in amino acid: energy content. It was hypothesized that LBiW pigs given access to a diet of a higher nutrient specification (diet HP), would be able to show greater ADG in comparison to those fed a standard diet targeting the 'average pig' (diet SP). This was based on the principles of Kyriazakis and Emmans (1991, 1992) who suggested that pigs previously delayed in their growth are able to exhibit a higher degree of catch up growth when they are fed a diet greater in protein: energy ratio. LBiW pigs may have altered body composition in relation to heavier littermates both at birth and slaughter, with a higher percentage of adipose tissue (Bee, 2004; Rehfeldt and Kuhn, 2006; Rehfeldt et al., 2008). Therefore it was expected that they would benefit from a diet which is higher in amino acid: energy ratio, allowing them to exhibit catch up growth, as has been previously demonstrated to be possible (Paredes et al., 2012; Douglas et al., 2013; Pardo et al., 2013b). However, pigs with LBiW given access to such an 'improved' diet in period 3 showed no improvement in performance.

By the end of the experiment NR pigs had partially caught up with N pigs. This was consistent with previous work which has demonstrated that pigs have the potential to compensate for 'moderate' postnatal stunting if subsequently fed an adequate diet for a sufficient period of time (Lynch et al., 1998). While the previously restricted pigs did not increase their absolute FI relative to N controls, an increase in SFI was observed. It seems that the extent of catch up growth of the NR pigs did not depend on the composition of the diet offered post restriction. Kyriazakis and Emmans (1992) and Stamataris et al. (1991) have both suggested that this will depend on the consequences of restriction on the body composition of pigs. Pigs that have been delayed in their growth, but also have a higher lipid to protein ratio in their body are expected to benefit more from a diet of a higher amino acid specification. These results indicate that NBiW pigs that experience a period of involuntary feed restriction (e.g. reduction in the amount of feed provided), are likely to catch up when the non-limiting conditions are resumed, even when not fed a high specification diet.

In contrast, the results suggest that, unlike NBiW pigs, LBiW pigs cannot catch up with heavier littermates, even on a higher specification diet. It was hypothesized that, when given an appropriate nutritional environment, irrespective of the reasons that led to the reduced BW (i.e. LBiW or feed restriction post weaning), pigs would be able to meet the BW of heavier pigs. The absence of any benefit of the LBiW when fed the high specification diet was surprising and could be the result of several reasons.

Firstly, it must be considered whether these pigs are physiologically capable of improving their growth. There is a wealth of literature which focuses on the uterine environment and changes in the physiology of LBiW pigs, as a result of reduced nutrition *in utero*. In agreement with previous literature (Nissen and Oksbjerg, 2011) we found that LBiW pigs had a significantly lower CRL and a higher relative CRL (CRL/BW) than NBiW pigs. When also considering the lower PI associated with LBiW pigs this indicates disproportionate body size at birth which is likely a result of restriction in utero (Poore et al., 2002). It is commonly thought that these pigs are born with a reduced capacity for growth (Foxcroft et al., 2006) and it has been documented that there are a reduced number of muscle fibres in LBiW pigs compared to heavier littermates (Powell and Aberle, 1980; Handel and Stickland, 1988; Dwyer et al., 1994; Rehfeldt and Kuhn, 2006). As the number of these fibres is fixed *in utero*, muscles will only grow by hypertrophy, which consequently may limit growth. These suggestions, however, are not supported by the recent analysis of large data sets that show that such pigs are indeed capable of compensatory growth (Paredes et al., 2012; Douglas et al., 2013).

Secondly, it has been suggested that the FI of LBiW pigs is a limiting factor in their growth (Gondret et al., 2005), although the results presented here dispute this argument. With the exception of the immediate period following weaning (d 28 to 49), there was no difference in the absolute ADFI of LBiW and NBiW pigs. This supports the suggestion of Gondret et al (2006) who concluded that LBiW and high BiW pigs had similar feed consumption during the grower and finisher stages. In addition scaled feed intake (SFI) comparisons showed that, relative to their body size, LBiW pigs were matching or even exceeding the intake of NBiW pigs throughout all periods examined. This was in agreement with the consistently higher relative FI by LBiW reported by Krueger et al (2013).

Thirdly, the experimental method used may have prevented the light pigs from exhibiting catch up. The ability of the animal to overcome its growth constraints will vary between individuals and is dependent on the composition of the food it receives and the environment it is kept in, as well as the current state of the pig following nutritional limitation (Kyriazakis and Houdijk, 2007). In this experiment animals were given access to the diet with a higher ratio of amino acids: energy from 9 wk of age. Between weaning and this age they received a diet that was based on age rather than weight, so possible limiting their growth potential. It is possible that intervention earlier on may show different results.

Whilst LBiW pigs did not show an improvement in ADG when given a diet higher in amino acid: energy, it is important to dissect the overall performance of these pigs during the experiment. During the pre-weaning period, LBiW pigs had similar ADG to heavier piglets, contradicting a number of studies which observed light pigs exhibiting poorer growth rates in this period (Dwyer et al., 1994; Quiniou et al., 2002). Inevitably differences in experimental method will affect the outcomes observed, given the strong influence of pre-weaning competition on piglet growth. For example, in this study all piglets were given access to supplementary milk as well as being grouped in litters with similar sized littermates. Competition for access to teats during suckling and consequently low milk consumption is considered a limiting factor for pre weaning growth (Campbell and Dunkin, 1982). Reducing this disadvantage of LBiW pigs by the addition of milk is likely to enhance their growth and reduce mortality (Azain et al., 1996; Wolter et al., 2002). Whilst the absolute growth rate of N and L pigs from d 63 to 91 were not statistically different, L pigs still grew considerably slower. However when we consider these data on a per kg of BW basis (SDG), LBiW pigs actually grew at the same rate or better than the heavier pigs N. This suggests that LBiW pigs can exhibit growth rates not extremely dissimilar from NBiW pigs given the right conditions.

It has been suggested that LBiW pigs are less efficient than their heavier counterparts, with poorer gain to feed ratios in LBiW pigs having been observed (Roeder and Chow, 1972; Gondret et al., 2005). With the exception of the period following weaning (d 28 to 49), the results presented here support these findings. When the data for both ADG and ADFI of the pigs are considered, despite the LBiW pigs eating at least the same or more than the NBIW pigs their gains are slightly less (although not significantly).

Whilst it is apparent that the appetite of LBiW pigs is not affected (post 7 wk) by restriction *in utero* it is possible other processes may be influenced.

4.5 Conclusions

The results suggest that a diet higher in amino acids: energy ratio at 9 weeks of age does not improve the performance of LBiW pigs. These pigs consume a similar amount of feed, but as they sometimes exhibit reduced BW gains, they are thus less efficient than their heavier counterparts. However, they are capable of exhibiting similar gains to NBiW pigs at certain periods in the production cycle, and this needs to be investigated as a possible method for improving their growth and reducing weight variability at slaughter.

Chapter 5: Management strategies to improve the performance of low birth weight pigs to weaning and their long term consequences

5.1 Introduction

Increases in litter size in recent years have resulted in significantly more piglets born with LBiW (Beaulieu et al., 2010; Baxter et al., 2013; Rutherford et al., 2013). Subsequent growth of these piglets is often below average, and at slaughter these pigs can weigh significantly less than their pen mates. In order to maximize the growth of these LBiW pigs, and reduce variability, there needs to be renewed focus on the earlier stages of production (Pluske et al., 2005; Douglas et al., 2013).

Weight gain of pigs during the preweaning stage varies significantly, given the many influential factors. Piglets are reliant on milk from the sow and, during lactation, sibling competition may have a major effect on survival and growth (Algers and Jensen, 1991; English, 1998; Lay et al., 2002). This is likely to affect small pigs the most, often exacerbating the difference in BW by weaning, leaving these piglets further disadvantaged.

Presently there are few treatments which can improve the growth of LBiW pigs during lactation or at any other stage during production. Providing piglets with supplemental milk replacer during lactation can improve WW (Kim et al., 2001; English and Bilkei, 2004; Morise et al., 2011), although the benefits for growth to slaughter are inconclusive. It has also been suggested that LBiW pigs are at a competitive disadvantage when raised with heavier littermates, therefore they may perform better in litters with less weight variability (English, 1998).

The objective of this study was to determine the effect of littermate weight and milk supplementation during lactation on the growth performance of LBiW pigs to slaughter weight. It was hypothesized that there would be an interaction between littermate weight and milk supplementation, with LBiW pigs in mixed litters being more likely to benefit from milk supplementation due to greater competition from heavier littermates for limited resources. The long term effects of these treatments were also evaluated.

5.2 Materials and Method

5.2.1 Experimental design

The experiment was conducted at Cockle Park Farm, Newcastle University and was approved by the Animal Welfare and Ethics Review Board at the University. The experiment was designed as a 2 x 2 factorial with 6 replicates. A total of 265 crossbred piglets (dam was Large White x Landrace cross and sire was Hylean synthetic, Hermitage Seaborough Ltd., Devon, UK) were cross fostered onto 24 sows. Treatments were litter composition (L = low birth weight pigs only or MX= Low birth weight and normal birth weight pigs) and provision of milk supplement from d 1 to 28 (Y= Yes, N = No). There were 6 replicates of each treatment. The experimental unit was the litter mean of all LBiW pigs.

5.2.2 Animal management

Sows were farrowed on a 3 wk cycle in individual farrowing crates which were equipped with a feeder and drinker for the sow. A total of 6 batches were used, each batch was a full replicate. They were allowed to farrow normally at term over a four day period (Monday to Thursday); sows that had not farrowed within this period were then induced on Thursday by injection of a prostaglandin analogue. All piglets were teeth clipped within the first 12 h of birth, and were tail docked and given an iron injection at d 3. The temperature in the farrowing house was maintained at 21°C by a centrally controlled heating and ventilation system and an infra red heat lamp was located in the creep area for the piglets to provide a microclimate during the lactation period. The nutrition of the sows was standardised across all treatments, with a home milled meal fed prior to and during lactation (18.5% CP, 13.98 MJ DE, 0.95% total lysine). Sows were fed 2.0 kg/d prior to farrowing; this was then increased by increments of 0.5 kg/d until they were fed 10 kg/d. From d 10 onwards, a small amount of pelleted creep feed for the piglets was placed on the floor of the heated creep area once a day and was the same as the starter 1 diet fed at weaning (23% CP, 16.0 MJ DE, 1.43% total lysine).

Pigs were weaned at 28 d, when they were transferred to controlled environment nursery accommodation with plastic slatted floors and housed in their pre-weaning litters. Pigs were vaccinated for *Mycoplasma hyopneumoniae* and Porcine Circovirus Type 2 (Inglevac Mycoflex, Boehringer Ingelheim, Germany). The initial temperature in the nursery accommodation was 26 °C and was reduced by 0.2 °C/day to a minimum of 22 °C. Each pen had a multi-place feeder with 3 spaces and a nipple drinker; all pigs had *ad libitum* access to feed and water. Pigs were fed a standard 3 stage commercial diet regime from d 28 for approximately 2 to 3 wk (Starter diet 1 = 23.0% CP, 16.0 MJ DE, 1.43% total lysine; diet 2 = 22.0% CP, 15.25 MJ DE, 1.33% total lysine; and diet 3 = 21.7% CP, 15.0 MJ DE, 1.28% total lysine). After this period all pigs were fed the same, home milled meal *ad libitum* (20.5% CP, 14.82 MJ DE, 1.28 % total lysine). At approximately 10 wk of age pigs were transferred to a separate controlled environment, fully slatted grower accommodation on site, where they were fed the same home mixed ‘grower’ diet (20.04% CP, 13.98 MJ DE, 1.20% total lysine). At approximately 16 wk of age they were moved again to a fully slatted finishing building where they were fed a purchased ‘finisher’ diet ad libitum (19.0% CP, 13.64 MJ DE, 1.10 % total lysine) until slaughter at approximately 140 d. After pigs were moved to the grower accommodation they were randomly mixed by litters according to farm protocol. In both grower and finisher accommodation, each pen had a multi-space feeder with 3 spaces and a nipple drinker; all pigs had *ad libitum* access to feed and water.

5.2.3 Experimental procedures

Within 12 hours of birth all piglets were weighed and those selected for the experiment were ear tagged for identification. Pigs were individually identifiable at all stages of the experiment. Low birth weight piglets (LBiW) were classified as weighing ≤ 1.25 kg and NBiW piglets as weighing 1.6 to 2.0 kg (Douglas et al., 2013) at birth; piglets that did not meet these weight criteria were cross fostered onto non experimental sows. Morphometric measurements were also taken at birth: CRL, snout-ears length and abdominal and cranial circumference, and used to calculate the relative CRL (CRL/kg) and PI (BW/CRL^3).

To create the experimental litters, all piglets were randomly assigned to a litter within 24 h after birth. Where possible, each experimental litter contained an equal number of piglets of each sex. To ensure there was no litter of origin effect, cross fostered litters consisted of pigs from at least 4 different birth litters, with no more than 3 piglets from the same litter. Litter size was set at 11 or 12 piglets, depending on the number of suitable piglets available in a batch. In L litters 11 to 12 LBiW pigs were grouped together, whereas MX litters consisted of 5 to 6 LBiW and 5 to 6 NBiW piglets. All sows used were first or second parity to ensure small piglets could access their teats.

Each sow was also checked to ensure there were sufficient functional teats to support the litter size allocated.

Once the experimental litters were set, they were randomly assigned within batch to the milk supplementation treatment. Half of the litters were given access to supplementary milk (S), and half were not (N). A feeder containing supplementary milk for the piglets was added to the pen of S litters from 24 h after birth. This comprised a dish attached to the slats at the rear of the pen, which was filled twice a day or as needed. Milk consumption was monitored throughout the day to ensure there was always milk available. If milk was found to be contaminated then it was discarded and fresh milk was added. Any discarded milk was measured to ensure accurate estimation of milk intake. To minimise milk spillage a small metal bowl 25 cm diameter and 3.5 cm depth was used for the first 10 d; this was then replaced with a larger plastic bowl of 37.5 cm diameter and 6.5 cm depth. Milk was prepared by hand mixing 150 g commercial milk powder (Faramate, Volac, Royston, UK; Protein = 22%, oil = 14%, ash = 7.5%, fibre = 0%) with 1 L of warm water. Piglet snouts were dipped in the milk for training on two consecutive days.

Daily milk intake was recorded for each litter by measuring the milk added and refused; in addition cameras were set up to record piglet behaviour at the milk dish. Piglets were observed for signs of diarrhoea (nutritional scours) related to the milk supplement and other illness. Any piglets that exhibited diarrhoea were treated with 0.5 to 1.0 ml of Norodine (Norodine 24 solution for injection, Norbrook, Corby, UK) depending on the BW; if 3 or more piglets in a litter showed symptoms, the whole litter was treated. If piglets did not reach 4 kg BW by d 28 then they were not weaned and were removed from trial.

From d 1 to 28, pigs were individually weighed twice a week, on a Monday and Thursday morning. From d 28 to 49, pigs were weighed once a week on a Thursday morning. Additional weights were taken at 100 d and a final weight was taken on the day before slaughter (approximately d 143). With these measurements, ADG was calculated for individual animals and treatment groups, and average daily milk intake (ADMI) for litters. The CV of BW was calculated for individual litters.

5.2.4 Behavioural observations

Digital video cameras were used to record piglet behaviour. All litters with supplementary milk (both L and MX) were observed on d 13, 20 and 27, in order to cover the period at which lactation yield plateaus (Nielsen et al., 2002; Hansen et al., 2012) and piglets should increasingly seek extra nutrition from the supplementary milk. On observation days, piglets were weighed and marked on the back with individual markings (different symbols and colours). At approximately 9 am the cameras were then turned on and fresh milk supplement was added to the milk bowl. The videos were left on for 24 hours and turned off the following morning at approximately 9 am. From 4pm the lights in the farrowing house were switched off (with the exception of the heat lamps in the creep area) so an additional light was added above the milk dish to allow the cameras to record the piglets. Subsequently a continuous record of each pig's behaviour for an 8 hr period from 8am until 4 pm was obtained using the behavioural research software, Observer 5.0 (Noldus Information Technology, Wageningen, the Netherlands) to quantify the frequency and duration of the following behaviours:

1. Drinking supplementary milk – defined as a piglet being at the bowl with its head down for longer than 3 s, and

2. Suckling – the start of the suckling bout was defined as when 8 or more piglets gather at the sow udder and begin massaging. The suckling bout was finished when 8 or more piglets had stopped massaging and moved away from the udder, or the sow moved position and therefore terminated the suckling bout

5.2.5 Statistical analysis

Growth performance (ADG) was summarised for the following periods: d 1 to 14, d 14 to 28, d 28 to 49, d 49 to 100 and d 100 to 143. All performance data was tested for normality using the Univariate procedure of SAS version 9.2 (SAS Institute Inc., Cary, NC) and was normally distributed. For behavioural data, normality testing showed that the data were skewed, so they were transformed (log or square root) and then results back transformed for presentation. Statistical analyses were conducted at a significance level of 5% and data presented as least square means. Data for all analyses were blocked by farrowing batch (6 batches). Treatment x batch interactions were added to all preliminary models, but were not significant and therefore omitted from subsequent analysis.

A chi-square test was used to compare the effects of litter composition (L or MX) and milk supplementation (S or N) on the reason for removal of pigs from trial and also for the occurrence of diarrhoea. The effect of litter composition on milk intake was estimated using a one way ANOVA using Proc mixed of SAS. For both analyses, the litter was the experimental unit.

For LBiW pigs in L and MX litters only, performance parameters were entered as the dependent variables to determine the effect of treatments on the different performance indicators. The experimental unit was the litter mean of all LBiW pigs; for L this was 11 to 12 piglets, and for MX litters this was 5 to 6 LBiW piglets. After litters were mixed at d 70 then pens were considered the experimental unit. The effect of littermate weight and milk supplementation on performance indicators was analysed with a repeated measures ANOVA using Proc Mixed of SAS. Littermate weight, milk supplementation and time were added as factors to the model. Sex was also included as a factor in the preliminary model, but as it was not significant it was omitted from subsequent analysis. As the number of LBiW piglets in L and MX litters varied, a weighted statistical analysis was used. Using the weight statement of Proc Mixed, a count of the number of LBiW piglets in each litter was added to the model as an additional variable. Behavioural data was also analysed with a repeated measure ANOVA. The same analysis was repeated with the following variables; number of milk feeds per 24 h, time spent feeding (s per 24 h) and number of suckling bouts per 24 h. Time (d 13, 20 or 27) was also included as a factor in the model. An additional model comparing the performance of LBiW piglets in L litters and NBiW piglets in MX litters was run. The experimental unit was the litter mean of LBiW or NBiW pigs. The model was the same as above.

For LBiW and NBiW pigs in MX litters, performance parameters were entered as dependent variables to determine the effect of treatments on the different performance indicators. The experimental unit was the litter mean of LBiW or NBiW pigs. After litters were mixed at d 70 then pens were considered the experimental unit. The effect of littermate weight and milk supplementation on performance indicators was analysed with a repeated measure ANOVA using Proc Mixed of SAS. Birth weight, milk supplementation and time were added as factors to the model. Sex was included as a factor in the preliminary model but as it was not significant it was omitted for subsequent analysis. As LBiW and NBiW piglets were from the same litter and therefore their performance was confounded, data was blocked by litter. Litter x treatment interactions were also tested, however they were not significant so removed from further analysis. For the behavioural data, the repeated measures ANOVA was repeated with the following variables; number of milk feeds per 24 h, time spent feeding (s per 24h) and number of suckling bouts per 24h. Time (d 13, 20 or 27) was also included as a factor in the model.

5.3 Results

Litter composition and milk supplementation had no significant impact on the mortality rate of LBiW piglets or the number of removals from the trial (Table 5.1). Treatment with antibiotic was higher in litters with supplementary milk that those without but no difference between MX and LBiW litters. At birth, LBiW pigs (in MX or L litters) had a shorter CRL of 23.2 cm (SD 1.88) compared to 27.4 cm (SD 2.13) for NBiW piglets ($P < 0.001$). However LBiW pigs had a significantly higher CRL/BW, (21.0 cm/kg, SD 2.81) than NBiW pigs (15.2 cm/kg, SD 1.01) ($P < 0.001$). LBiW pigs also had a significantly lower PI (89.5 kg/m^3, SD 10.3) than NBiW pigs (99.5 kg/m^3, SD 11.5) ($P < 0.001$).

5.3.1 Performance and behaviour of low birth weight piglets (LBiW) in L or MX litters

The effects of litter composition (L or MX) and milk supplementation (S or N) on the BW and ADG of LBiW pigs from birth to slaughter are shown in Table 5.2. There was no effect of milk supplementation on the BW or the ADG of LBiW pigs in L and MX litters for all periods examined, nor was there any interaction between litter type and milk supplementation on the performance of the piglets ($P > 0.05$). There was no effect of litter type or milk supplementation on the within-litter CV of BW of pigs from birth to d 143 (data not shown).

When considering the effect of litter type on the BW of LBiW pigs, there was no significant difference during the earlier part of lactation (d 1 and 14). However at d 28, LBiW pigs in L litters weighed 500g more than LBiW pigs in MX litters ($P < 0.05$). By d 49 there was a 750 g difference between these pigs from L and MX litters, which had increased to 2 kg by d 143; however neither were considered significant ($P > 0.05$).

Similarly, there was no effect of litter type on the ADG of piglets from d 1 to 14 of lactation; however from d 14 to 28 LBiW pigs in L litters grew better than those in MX litters (0.252 kg/d versus 0.271 kg/day; $P < 0.05$). Post d 28 there was no effect of litter type on the ADG of LBiW pigs ($P > 0.05$).

Table 5.1 The reasons and numbers removed from the experiment and the number of antibiotic treatment for scours of low birth weight (LBiW) and normal birth weight (NBiW) pigs on the experiment. Low birth weight pigs (LBiW) were either in litters with other LBiW pigs (L) or in litters with both LBiW and 'normal' pigs (MX). Half of the L and the MX litters were given supplementary milk (S) from d 1 to 28 and the other half were not (N)

	Treatment				
	L		MX		Significance[1]
Milk	S	N	S	N	
No of pigs on trial					
Day 1	66	67	66	66	0.951
Day 28	60	61	61	61	0.949
Day 143	59	61	61	61	0.897
Antibiotic treatment[2]	15	9	14	11	0.644
Reasons for removal					
Scour	2	1	2	-	0.361
Lameness	2	1	2	-	0.361
Hernia	-	1	-	1	-
Meningitis	-	-	-	1	-
Found dead	2	1	1	1	0.709
Under 4 kg at day 28	1	2	-	2	0.361

[1] Absence of statistics indicates there were insufficient observations for a chi-square test
[2] Antibiotic treatments for scours were for individual pigs and for multiple episodes. The values only includes pigs which were treated after being diagnosed with diarrhoea, rather than pigs which were treated as a result of 3 or more piglets in the litter having diarrhoea

Table 5.2 The effect of littermate weight and milk supplementation on the performance of low birth weight pigs (LBiW) pigs from d 1 to 143. The LBiW pigs were either in litters with other LBiW pigs (L) or in litters with both LBiW and 'normal' pigs (MX). Half of L and MX litters were given supplementary milk (S) from d 1 to 28 and the other half were not (N)[1]

	Littermate weight	L		MX			Significance		
	Milk	S	N	S	N	SEM	Littermate weight	Milk	Littermate weight x Milk
BW, kg									
Day 1		1.11	1.14	1.13	1.15	0.256	0.485	0.284	0.691
Day 14		3.84	3.78	3.64	3.89	0.110	0.651	0.456	0.301
Day 28		7.54	7.13	6.73	6.87	0.262	0.045	0.596	0.256
Day 49		15.5	14.5	14.2	14.3	0.523	0.101	0.460	0.345
Day 100		46.2	45.5	45.4	45.5	0.861	0.650	0.760	0.680
Day 143		74.5	74.8	72.3	73.5	1.49	0.291	0.638	0.770
ADG, kg/d									
Day 1-14		0.210	0.203	0.193	0.210	0.010	0.643	0.621	0.245
Day 14-28		0.264	0.239	0.221	0.213	0.015	0.021	0.213	0.556
Day 28- 49		0.381	0.357	0.348	0.358	0.012	0.511	0.786	0.486
Day 49 to 100		0.602	0.608	0.617	0.611	0.013	0.534	0.951	0.654
Day 100 to 143		0.657	0.673	0.624	0.654	0.034	0.411	0.479	0.843

[1] Piglets were grouped in litters from d 1 until d 70; following this 2 litters selected at random were combined.

There was no difference in the number of supplementary milk feeding episodes of LBiW piglets between litter types for all time periods examined ($P > 0.05$). In contrast, milk feeding duration on d 27 was increased in LBiW piglets in MX litters compared to L litters (33 s versus 15.8 s; $P < 0.001$). There was also a difference in the number of nursing episodes between litter types, with L litters suckling more often in an 8 h period than MX litters for d 27 (11.6, SD 4.10 versus 8.17, SD 3.25; $P < 0.001$).

There was a significant difference in the milk intake of L and MX litters. Piglets in L litters had a higher ADMI over the 28 d lactation period in comparison to those in MX litters, with an average of 171 ml/d per pig compared to 138 ml/d respectively ($P < 0.05$).

5.3.2 Performance of low (LBiW) and normal birth weight (NBiW) pigs in mixed litters

Birth weight had a significant effect on BW from d 1 to 143, with LBiW pigs weighing significantly less at all periods examined ($P < 0.001$) (Table 5.3). At birth, NBiW pigs weighed 1.81 kg (SD 0.103) compared to 1.13 (SD 0.109) in LBiW pigs ($P < 0.001$). By d 143 this difference had increased significantly, being almost an 8 kg difference between LBiW and NBiW pigs. Low birth weight pigs exhibited significantly lower ADG than NBiW pigs for all periods examined, with the exception of d 100 to 143, where there was no difference in the performance of the two BiW categories ($P > 0.05$); however the ADG of LBiW pigs was still slightly lower.

Milk supplementation (S or N) had no effect on the BW or ADG of LBiW or NBiW piglets in MX litters, nor was there any interaction between BiW and milk supplementation. Neither milk supplementation nor BiW had a significant effect on the CV of BW for all periods examined. However there was a significant interaction between BiW and milk supplementation for CV of BW, for all d examined with the exception of d 1 (Table 5.3). From d 14 to 143 the CV of LBiW pigs with milk supplementation was less than those without milk. In contrast, the CV of NBiW pigs with milk supplementation was greater than those without milk.

Table 5.3 The effect of birth weight and milk supplementation on the performance of pigs in MX litters (litters with both low birth weight (LBiW) and normal birth weight pigs (NBiW)) from d 1 to 143. Low birth weight pigs were ≤ 1.25 kg and NBiW pigs were between 1.60 and 2.0 kg. One half of the MX litters were given supplementary milk (S) during lactation and the other one half was not (N) [1]

	Birth weight	LBiW		NBiW			Significance		
	Milk	S	N	S	N	SEM	Birth weight	Milk	Birth weight x Milk
BW, kg									
Day 1		1.13	1.15	1.81	1.80	0.014	< 0.001	0.685	0.385
Day 14		3.64	3.89	5.01	5.15	0.198	< 0.001	0.323	0.561
Day 28		6.73	6.87	8.86	9.15	0.323	< 0.001	0.556	0.754
Day 49		14.0	14.4	17.6	17.9	0.533	< 0.001	0.305	0.812
Day 100		45.5	45.6	51.7	52.3	1.01	< 0.001	0.657	0.787
Day 143		72.4	73.7	80.6	80.6	1.53	< 0.001	0.737	0.736
ADG, kg/d									
Day 1-14		0.193	0.211	0.247	0.258	0.015	0.002	0.294	0.789
Day 14-28		0.221	0.213	0.275	0.285	0.015	< 0.001	0.968	0.201
Day 28-49		0.348	0.358	0.414	0.419	0.021	0.004	0.612	0.765
Day 49-100		0.617	0.611	0.669	0.673	0.012	0.001	0.657	0.681
Day 100-143		0.624	0.653	0.672	0.659	0.032	0.411	0.764	0.553
CV									
Day 1		9.92	10.1	5.67	4.97	1.51	0.004	0.745	0.768
Day 14		11.6	16.9	12.4	9.56	1.67	0.100	0.437	0.038
Day 28		13.8	18.6	15.2	8.81	2.09	0.051	0.475	0.011
Day 49		8.25	15.1	12.0	5.66	1.65	0.111	0.735	< 0.001
Day 100		6.21	11.5	9.65	5.26	1.10	0.432	0.547	< 0.001
Day 143		5.21	9.57	7.50	5.16	1.52	0.468	0.136	0.023

[1]Piglets were grouped in litters from d 1 until d 70; following this 2 litters selected at random were combined.

No difference was observed in the number of supplementary milk feeding episodes for NBiW and LBiW pigs in MX litters (7.42 versus 7.86; $P > 0.05$). On d 27 there was an effect of BiW on supplementary milk feeding duration, with LBiW piglets drinking for longer than NBiW pigs (32.97 s, SD 3.10 versus 20.09 s, SD 2.89; $P < 0.001$).

A comparison of the performance of LBiW piglets in L litters with NBiW piglets in MX litters, showed an identical pattern of results to those of LBiW and NBiW piglets in MX litters. Birth weight has a significant effect on performance throughout with the exception of d 100 to 143.

5.4 Discussion

This study investigated the effects of litter composition and milk supplementation during the suckling period on the behaviour and growth performance of LBiW pigs to weaning, and their long term effects to slaughter. It was hypothesized that there would be an interaction between litter composition and milk supplementation, with LBiW pigs in mixed litters being more likely to benefit from milk supplementation due to greater competition from heavier littermates for limited resources (Algers and Jensen, 1991; English, 1998; Lay et al., 2002). The results suggest that: (i) The WW of LBiW piglets can be increased when grouped with similar weight littermates, although the effects do not persist to slaughter and (ii) the provision of supplementary milk does not improve performance but can reduce weight variation in LBiW pigs in mixed litters.

Consistent with the results of Milligan et al (2001b) and Kirkwood et al (2005), we found no effect of litter composition on piglet mortality. Other studies have reported reduced survival of LBiW piglets in mixed litters and differences in the weight classification of LBiW piglets could be the cause. Our study defined LBiW piglets as ≤ 1.25 kg, but previous studies have selected pigs of lower weights, for example < 1.0 kg (Milligan et al., 2002a; Milligan et al., 2002b). As piglet BiW decreases this can have a significant effect on performance (Paredes et al., 2012; Douglas et al., 2013) and survivability (Bilkei and Biro, 1999). Therefore small differences in the BW of LBiW pigs may affect mortality.

Low birth weight piglets benefitted from being cross fostered into a litter with other LBiW piglets, specifically during the latter part of the preweaning period, exhibiting higher ADG and greater WW. The results support the hypothesis of Cutler et al (1999) and Fraser et al (1979 and 1995) that LBiW piglets are at a competitive disadvantage when raised with heavier littermates. In contrast, LBiW pigs given access to supplementary milk demonstrated no improvement in performance. This was contrary to the expectation that LBiW pigs would benefit from additional milk, in particular those in mixed litters. However, there was an interaction between BiW category and milk supplementation on the CV of mixed litters. LBiW piglets in these litters with supplementary milk had a lower CV from d 14 to 143 than those without supplementary milk. Such a benefit was not observed in NBiW piglets in mixed litters which instead saw an increase in CV. This treatment interaction suggests that supplementing mixed litters with milk during lactation can decrease variation to slaughter in LBiW pigs, which would be advantageous.

It is common farm strategy, in Europe at least, to cross foster piglets to create littermates of similar weights, with the aim of reducing mortality and improving performance. However research into this area has provided contradictory results. Whilst Milligan et al (2001b) reported no statistical difference in the weight gain of LBiW piglets whether grouped with heavier or similar sized littermates, there was a tendency for LBiW piglets to gain more when grouped with heavier pigs. As this weight gain was most prominent in smaller litters with only 8 or 9 piglets, maternal resources of the sow were less likely to be limited and therefore piglets wouldn't have been exposed to the same level of competition as they would in a larger litter. In contrast with the results of Milligan et al (2001b) this paper and others (Deen and Bilkei, 2004; English and Bilkei, 2004), found a decrease in the growth performance of LBiW piglets when grouped with heavier litters. As effects were only observed in the latter part of lactation, it is unlikely that direct competition from heavier littermates was the cause of poor performance of LBiW piglets in MX litters. As ownership of a teat is usually established within the first few days after birth (McBride, 1963) any effect of direct competition for access to a teat would have been expected within the first week following parturition. Instead sow milk is likely to be the limiting factor for piglet growth, with a plateau in the amount available from d 21 onwards as piglet demand increases (Klobasa et al., 1987). As pigs with heavier BiW can command higher quality teats, smaller piglets are more likely to suckle from the less productive posterior teats (English et al., 1977; Fraser, 1984). Additionally the BW of the pig may affect how well piglets can stimulate the teat. Algers and Jensen (1984) proposed the 'restaurant hypothesis', in which the individual piglet effectively orders the size of its next meal by massaging its own teat post ejection. Therefore heavier piglets which are able to drain and massage the teats more vigorously (Fraser, 1984), are more likely to stimulate milk production and have access to a great amount of milk at their teat at the expense of lighter pigs (Drake et al., 2008), resulting in an unequal distribution of milk across teats in mixed litters.

Additionally, it was observed that MX litters suckled less frequently in comparison to litters composed of all LBiW piglets. The consequence of this is likely to be poorer performance for LBiW piglets in these litters unless they consume more milk per suckle (Campbell and Dunkin, 1982). The cause of this difference in suckling bout frequency remains unclear. One possible explanation is that L litters initiate a higher number of suckling bouts towards the end of lactation, as they require a greater amount of milk than they are able to stimulate. Whilst in the first few days following parturition suckling is initiated by the sow (Fraser, 1980), as the piglets' age they are more likely to attempt to instigate suckling although this is not always successful (Marchant-Forde, 2008). If LBiW piglets drink less per suckle (Campbell and Dunkin, 1982), they may therefore be more likely to solicit additional suckling bouts from the sow. More information is needed however to confirm the effect of piglet weight on suckling frequency and the reasons behind this.

Despite an advantage in the WW of LBiW pigs grouped with other LBiW pigs, there was no significant benefit observed for performance to slaughter. A potential explanation for this lack of effect post weaning is that, although numerical differences in BW are maintained to finishing, these relatively small differences cannot be detected in the latter stages due to the increasing weight variation, as put forward by Wellock et al (2009).

Nutrient intake of piglets can be limited during the lactation period which can have a negative effect on growth performance (Pluske et al., 2005). Therefore providing additional nutrition such as supplemental milk replacer can result in improved BW gains to weaning (Azain et al., 1996; Zijlstra et al., 1996; Dunshea et al., 1998; Dunshea et al., 1999; Wolter et al., 2002). However, whether any benefits persist in the long term remains uncertain. In this study there was no effect of supplementary milk on the growth performance of piglets irrespective of BiW or litter composition. Despite this, a difference in the behaviour of LBiW piglets in different litter types was apparent, with

LBiW in MX litters drinking the supplementary milk for a longer period than both heavier littermates and LBiW pigs in L litters. There are several possible explanations for this change in behaviour, but absence of any benefit. First, it has been suggested that, as a result of nutrient restriction in utero, LBiW pigs have a reduced capacity for growth (Foxcroft et al., 2006). However, as an improvement was observed in the performance of LBiW pigs in L litters this is unlikely. Second, it is possible that piglets did not consume enough milk for any difference in ADG to be observed, especially as in comparison to previous studies, milk intake was low (Azain et al., 1996; Wolter et al., 2002; Miller et al., 2012). The ADMI for piglets in both L and MX litters during lactation was 167 ml/d, whereas Azain et al (1996) had intakes of 471ml/d in litters where the greatest effect on performance was observed. The provision of creep feed during lactation may have had an effect on supplementary milk consumption. Limited nutrient availability pre weaning is a major determinant of ADG during this period (Klindt, 2003), however if piglets are receiving sufficient additional nutrition from creep feed, this may reduce their supplementary milk intake. This is supported by the fact that previous studies which saw a positive effect of supplementary milk on performance did not provide creep feed (Azain et al., 1996; Zijlstra et al., 1996; Dunshea et al., 1998; Dunshea et al., 1999).

Whilst the results presented here demonstrate that the performance of LBiW pigs can be improved, in comparison to NBiW pigs they still had poorer growth rates and were unable to catch up. Heavier BiW pigs not only retained their BW advantage from, birth but this difference increased with age. This has been observed previously, with preweaning management improving growth performance but inevitably BiW always plays a greater role (Wolter et al., 2002), with pigs that are inherently heavier performing better (Lawlor et al., 2002). Only in latter part of the finishers a similar growth rate was observed between the two BiW groups, an observation which has been noted in previous studies (Gondret et al., 2005). One possibility is that the pigs' environment in the later stages imposes a constraint and differentially affects pigs of varying weights. For example, pigs of greater BW have a lower thermoneutral zone (Baker, 2004) and, in situations of high environmental temperature, will show a greater drop in FI and thus a reduced growth performance (Nienaber et al., 1996).

5.5 Conclusions

This paper offers novel insights in the management of LBiW pigs and their behaviour during the lactation period when provided with supplementary milk. First, the results suggest that the WW of LBiW pigs can be increased by cross fostering LBiW piglets with similar weight littermates, however this BW advantage does not persist long term. Second, the addition of supplementary milk does not benefit their growth, but does reduce the variation in BW of pigs and an increase in the duration of supplementary milk intake was noted for LBiW pigs in mixed litters.

Chapter 6: High specification starter diets improve the performance of low birth weight pigs to 10 weeks of age

6.1 Introduction

Starter regimes are critical to minimize any growth check at weaning, as well as to maximize FI and growth performance not only in the nursery period but also to slaughter (Lawlor et al., 2002). In the UK, a starter regime typically consists of a series of diets fed in succession formulated for the 'average pig', which decrease in cost and specification. The aim of such regimes is to allow pigs to reach a particular BW after which they can progress to a cheaper compound diet, all in a relatively short period of time.

Low birth weight pigs are likely to be substantially lighter at weaning than NBiW pigs (Douglas et al., 2013; Douglas et al., 2014). As a result of their reduced BiW, LBiW pigs may have immature digestive systems, including reduced secretion of digestive enzymes at birth (Xu et al., 1994; Wang et al., 2008; D'Inca et al., 2010b) and a less developed digestive tract at weaning (Michiels et al., 2013) hindering adaptation to post weaning diets compared to heavier pen mates (Pluske et al., 2003). Recent research suggests LBiW pigs can improve growth performance when provided with a better quality regime (Beaulieu et al., 2012); however whether these improved regimes are economical is uncertain. Similarly, high allowances of starter regimes in comparison to low allowances have positive effects on performance of light pigs from weaning (Lawlor et al., 2002; Magowan et al., 2011b) although the effect on exclusively LBiW pigs is unknown.

The aim was therefore to investigate whether a high specification starter regime and the provision of an extra amount of feed (corresponding to the last feed in the regime) can have additive or synergistic effects on the performance of LBiW pigs at weaning. The cost of the different feeding regimes was investigated to determine if any successful treatments were economically viable. It was hypothesized that LBiW pigs would benefit most from both a high specification regime as well as an increased allowance of the final diet in the starter regime.

6.2 Materials and method

6.2.1 Experimental design

The experiment was conducted at Cockle Park Farm, Newcastle University and was approved by the Animal Welfare and Ethics Review Board at the University. The experiment was designed as an incomplete 2 x 2 x 2 factorial with 6 replicates; a total of 180 crossbred pigs (dam was Large White x Landrace cross and sire was Hylean synthetic, Hermitage Seaborough Ltd., Devon, UK) were used. The factors used were starter regime (High specification starter regime [H] or Standard starter regime [S]), birth weight (Low birth weight [BWL] or normal birth weight [BWN]) and increased allowance of the final diet in the starter regimes (Feed 3) (Yes [Y] or no [N]). None of the BWN pigs received the increased allowance of feed 3 resulting in an incomplete experimental design.

6.2.2 Animal management

Sows were farrowed on a three week cycle in individual farrowing crates which were equipped with a feeder and drinker for the sow. The nutrition of the sows was standardized across all treatments, with identical diets fed before and during lactation. The temperature in the farrowing house was maintained at 21°C by a centrally controlled heating and ventilation system; an infra-red heat lamp was located in the creep area for the piglets to provide a microclimate during the lactation period.

Efforts were made during the lactation period to maximize the growth of all pigs by reducing limiting factors such as competition from heavier littermates and poor milk supply. A feeder containing supplementary liquid milk for the piglets was added to the pen of all litters from 24 hours after birth and was removed on d 7. Piglets were observed for signs of diarrhoea (nutritional scour) and other illness related to the milk supplement. Any piglets that exhibited diarrhoea were treated with 0.5 to 1 ml, depending on BW, of Norodine (Norodine 24 solution for injection, Norbrook, Corby, UK): if 3 or more piglets in a litter showed symptoms, the whole litter was treated. Within the first 12 h of birth, pigs were teeth clipped, weighed and ear tagged with metal chick wing tags for identification. Male pigs were not castrated. Morphometric measurements were also taken: CRL, snout-ears length and abdominal and cranial circumference. Piglets were tail docked and given an iron injection at d 3. From d 10 onwards, a small amount of creep feed was placed on the floor of the heated creep area once a day and this was an equal mix of the first diet of starter regimes H and S (see below for details).

6.2.3 Experimental management

Approximately 17 sows farrowed per batch and piglets from these sows were weighed within 12 h of birth. Low birth weight piglets were classified as ≤ 1.25 kg (the minimum BW was 700 g) and normal birth weight piglets as 1.6 to 2.0 kg (Douglas et al., 2013); piglets that did not meet the weight criteria were cross fostered onto non experimental sows. According to the normal husbandry practice on farm, during the first 24 h after birth all piglets selected for trial were cross fostered into one of three litters according to birth weight, so experimental litters contained either low BWL or BWN piglets. Litter size was set at 11 or 12 piglets, depending on the number available.

Pigs were weaned at d 28 (+/- 1 d) of age, when they were transferred to controlled environment nursery accommodation with slatted plastic floors; each pen provided 0.42 m^2/pig and had a feeder with 3 spaces and a separate nipple drinker giving ad libitum access to water. If pigs did not reach 4 kg by d 28 then they were not weaned and removed from trial (5 BWL and 2 BWN in total). Ear tags were removed and replaced with plastic weaner tags and pigs were vaccinated for *Mycoplasma hyopneumoniae* and Porcine Circovirus Type 2 (Inglevac Mycoflex, Boehringer Ingelheim, Germany). A thermostatically controlled heating and fan ventilation system initially maintained the room temperature at 26 °C; this was then reduced by 0.2 °C/day to 22 °C.

On d 28 piglets, when weaned and moved to experimental accommodation, pigs were randomly assigned within birth weight category to form treatment groups of 5 pigs per pen balanced for sex and litter of origin using SAS Proc plan of version 9.2 (SAS Institute Inc., Cary, NC) to randomly allocate pigs to treatments. Any additional pigs were removed from the experiment. Pigs assigned to regime H or S received the appropriate starter regime which was fed on a kg/pig basis; both BWL and BWN pigs were assigned to these regimes. Feed was available to pigs at all times during the experiment.

Pigs offered regime H were given 2.5 kg/pig of feed 1 (24.0 % CP, 17.3 MJ DE, 1.75 % total lysine and 20.0 % lactose), 2 kg/pig of feed 2 (23.8% CP, 16.0 MJ DE, 1.60 %

total lysine and 15.0 % lactose) and 3 kg/pig of feed 3 (23.4 % CP, 15.3 MJ DE, 1.50 % total lysine and 5.00 % lactose) (Primary Diets, Ripon, North Yorkshire) (Table 6.1 and 6.4). Pigs offered regime S were given 2 kg/pig of feed 2 (23.8% CP, 16.0 MJ DE, 1.60 % total lysine and 15.0 % lactose) and 3 kg/pig of feed 3 (23.4 % CP, 15.3 MJ DE, 1.50 % total lysine and 5.00 % lactose). Feeds were offered in succession, with the next feed provided once the previous had been consumed.

Table 6.1 Ingredient composition on an as-fed basis and chemical analysis of the four diets used[1]

	Diet			
Item	1	2	3	W
Ingredient, g/kg				
Micronized barley	75.0	75.0	75.0	150.0
Wheat	-	234.1	438.1	487.6
Micronized wheat	150.0	50.0	25.0	-
Micronized maize	25.0	25.0	-	-
Porridge oats	100.0	75.0	25.0	-
Wheat feed	-	-	12.5	25.0
Herring meal	75.0	75.0	60.0	25.0
Hi-pro soya	94.4	145.2	223.3	250.0
Full fat soya bean	65.6	25.0	25.0	-
Pig weaner vitamin/trace element supplement[2]	5.00	5.00	5.00	5.00
Whey protein concentrate	50.0	-	-	-
Dried Skim Milk Powder	75.0	61.3	-	-
Whey	195.8	173.2	69.4	-
Potato protein	12.5	12.5	-	-
L-lysine	2.30	1.68	2.45	3.74
DL-Methionine	2.11	1.45	1.31	1.56
L- Threonine	1.53	1.15	1.19	1.57
L-Tryptophan	0.42	0.23	0.01	0.13
Vitamin E	0.41	0.41	0.21	0.10
Benzoic acid	5.00	5.00	5.00	5.00
Limestone flour	-	0.76	-	1.09
Dicalcium phosphate	-	-	5.11	8.94
Salt	-	-	1.21	4.06
Binder (lignobond DD)	-	-	-	6.25
Soya oil	65.0	33.2	25.2	25.0
Analysed composition, % as fed[3]				
CP	22.4	21.7	21.0	18.0
Crude Fibre	1.80	2.00	2.60	2.90
Moisture	9.60	11.0	11.7	11.9
Ash	5.60	5.50	5.10	4.70
Calculated composition, % as fed or as specified[4]				
DE, MJ/kg	17.30	16.00	15.30	14.80
Calcium	0.62	0.59	0.54	0.59
Phosphorous	0.60	0.59	0.54	0.59
Lactose	20.00	15.00	5.00	0.00
Lysine	1.75	1.60	1.50	1.40
Methionine	0.67	0.60	0.54	0.50

[1]Diets were supplied by Primary Diets, Ripon, North Yorkshire

[2] It provided per kg of complete diet: 11,500 IU of vitamin A, 2,000 IU of vitamin D_3, 100 IU of vitamin E, 4 mg of vitamin K, 27.5 µg of vitamin B_{12}, 15 mg of pantothenic acid, 25 mg of nicotinic acid, 150 µg of biotin, 1.0 mg of folic acid, 160 mg of CU ($CUSO_4$), 1.0 mg of Iodine (KI, $Ca(IO_3)_2$), 150 mg of Fe ($FeSO_4$), 40 mg of Mn (MnO), 0.25 mg of Se (BMP-Se), 110 mg Zn ($ZnSO_4$)

[3]Proximal analysis performed by Sciantec Analytical Services Ltd (North Yorkshire)

[4]Values estimated using raw material matrix (Primary Diets, Ripon, North Yorkshire)

Once BWL pigs had consumed their starter regime allocation they were either fed an extra 2.5 kg of feed 3 (treatment Y) or not (treatment N). The consequence of the incomplete experimental design was that whilst BWL pigs were assigned to both regimes, BWN were not given access to the extra feed 3. By d 49 pigs had consumed all experimental diets, irrespective of treatment. Once the allocated starter feeds had been consumed, pigs were given a weaner feed (W; 21.6 % CP, 14.8 MJ DE and 1.40 % total lysine) which was fed ad libitum until d 70. Thus there was a logical progression in the composition of the feeds 1 to W, with the former being based on more high quality ingredients and greater nutrient concentration. Table 6.1 reports the composition and chemical analysis of all diets used for each feeding regime. The chemical analysis of the feeds was performed in accordance with AOAC (AOAC, 1990) standards using proximate analysis and the calculated composition was estimated from the values in the Premier Atlas ingredients matrix (Hazzledine, 2008).

From d 1 to 70, pigs were individually weighed twice a wk, on a Monday and Thursday morning. Feed intake per pen was measured twice a week from d 28 to 70 by weighing residual feed at the same time that pigs were weighed. With these measurements, ADG was calculated for both individual animals and treatment groups, and ADFI for pen groups only. The CV of BW was calculated for within pen (5 piglets per pen). Individual morphometric measurements taken at birth were taken to calculate the relative CRL (CRL/BW) and ponderal index (PI) (BW/CR^3). The period d 28 to 49 and 49 to 70 were chosen for statistical analyses as by d 49 all pigs, regardless of treatment, had consumed their experimental diets; therefore from d 49 to 70 is when animals were only consuming feed W.

For the economic analysis, the cost per tonne of each feed was provided by the company that manufactured the feed (based on the raw material costs, correct as of November 2013); this was then used to calculate the feed cost per pig of each regime. The cost per kg of BW gained was then calculated as: feed cost per pig / BW gain per pig. Finally the margin over feed (MOF) was calculated by the following formula: MOF = [BW gain x proportion of carcass weight from live weight (0.75) x current pig price per kg carcass weight (as of Nov 2013, £1.70) - feed cost per pig].

6.2.4 Statistical analysis

All performance data was tested for normality using the Univariate procedure of SAS version 9.2 (SAS Institute Inc., Cary, NC) and was normally distributed. Sex was included as a factor in all preliminary models was not significant so omitted for subsequent analysis. Data for all analyses were blocked by farrowing batch (6 batches). Treatment x batch interactions were added to all preliminary models, but were not significant and therefore omitted from subsequent analysis. Differences were considered significant at $P < 0.05$ and reported as a tendency towards statistical significance at $P < 0.10$. Data are presented as least square means.

The experimental design addressed two hypotheses. The effects of the different feeding regimes and their interactions, for BWL pigs only, were analysed as a repeated measure ANOVA using Proc Mixed of SAS version 9.2 (SAS Institute Inc., Cary, NC). Starter regime (H or S), extra feed 3 (Y or N) and time were added as factors. Two separate models were run with data analysed on a litter basis from d 1 to 28 (11 or 12 piglets) and on a pen basis from d 28 to 70 (5 pigs). To investigate whether BiW differentially affected H or S pigs, a repeated measures ANOVA using Proc Mixed of SAS was used with BiW category (BWL or BWN) and starter regime (H or S) as factors using the same methods as previously described.

To test whether any of the feeding regimes allowed BWL pigs to catch up with BWN pigs, a comparison between the best regime (regime HY) and BWN pigs on either regime H or S was made by using a set of orthogonal contrast statements.

An economic analysis was run as a one way ANOVA to allow comparison of all treatment combinations (that is starter regime, extra feed 3 and BW). All statistical analyses were conducted at a significance level of 5%. Data are presented as LS means and differences were considered significant at < 0.05 and reported as a tendency towards statistical significance at < 0.10.

6.3 Results

Total pre weaning mortality after litter allocation was 3.4% and similar between BWL and BWN piglets (3 versus 4 pigs died). No pigs were removed from the trial due to illness or other causes from d 28 to d 70. At birth, BWL pigs weighed 1.08 kg (SD

0.150) versus 1.82 kg (SD 0.098) in BWN pigs (*P* < 0.001). At weaning BWN were almost 1.5 kg heavier than BWL pigs, with a strong correlation between BW at birth and weaning (r = 0.695; *P* < 0.001) and those pigs lighter at birth weighing significantly less at weaning (7.15 kg, SD 1.29 vs. 8.62 kg, SD 1.23; *P* < 0.001)). As well as differences in BW at birth, BWL pigs had a shorter CRL of 24.2 cm (SD 1.50) compared to 27.2 cm (SD 1.67) for N piglets (*P* < 0.001). However BWL pigs had a significantly greater CRL/BW, (21.6 cm/kg, SD 2.01) than BWN pigs (15.2 cm/kg, SD 1.34), and a significantly lower PI (81.1 kg/m^3, SD 8.3 vs. 91.4 kg/m^3, SD 9.5) (*P* < 0.001). The mean age of pigs at weaning was 28 d (± 1 d) and at the end of the nursery period 70 d (± 1 d).

6.3.1 Performance of low birth weight pigs

Starter regime had a significant effect on the ADG of BWL pigs between d 28 and 49 (Table 6.2), with pigs that received the starter regime H performing better than those that did not (regime S) (ADG = 0.397 vs. 0.362 kg/d respectively). The only residual effect seen on the performance of the pigs between d 49 to 70 was due to starter regime on ADG (H = 603 kg/d, S = 664 kg/d; *P* = 0.017). From d 28 to d 49, the provision of the extra feed 3 also resulted in improved performance, with pigs fed the extra feed 3 exhibiting a significantly greater ADG (0.399 kg/d) than those which were not (0.360 kg/d). There was an interaction between starter regime and extra feed 3 (*P* = 0.029) from d 28 to 49). The interaction was due to the fact that pigs fed starter regime H with (treatment HY) exhibited the greatest daily gain (0.452 kg) in comparison to all other treatments (*P* = 0.029), whilst S pigs showed much less response to additional feed 3. In contrast, there was no effect of starter regime or additional feed 3 on the ADFI of BWL pigs from d 28 to 70. However there was an interaction, with pigs on regime HY and SN eating more than those on HN or SY (*P* = 0.026). Whilst there was no effect of starter regime or an interaction during this period on FCE, there was a significant effect of extra feed 3 provision, with those that received extra showing an improved FCE in comparison to those which did not (Y = 0.93, N = 0.83; *P* < 0.030).

Whilst there was no effect of starter regime on BW at d 49, by d 70, there was a significant effect with pigs fed starter regime H weighing almost 2 kg more than those on S (29.0 kg versus 27.3; *P* = 0.014). In contrast, the effect of provision of extra feed 3 on BW tended to be significant at d 49 (Y = 15.27 kg, N = 14.67 kg; *P* = 0.094) and was significant at d 70, with and those given extra feed 3 weighing over 1.5 kg heavier than those pigs which were not at the end of (28.9 kg versus 27.4; $P < 0.027$). There was no effect of starter regime, extra feed 3 or an interaction, on the CV of BW of BWL pigs from d 29 to 70.

Table 6.2 The effect of starter regime and additional allowance on the growth performance of low birth weight pigs, from d 1 to d 70 [1, 2, 3]

	Treatment					Significance		
Item	H Y	H N	S Y	S N	SEM	SR	AF	SR x AF
BW, kg								
D 1	1.09	1.10	1.06	1.05	0.032	0.172	0.911	0.817
D 28	6.85	7.14	7.26	7.15	0.177	0.241	0.613	0.271
D 49	15.8	14.7	14.7	14.6	0.340	0.103	0.094	0.145
D 70	30.1	27.9	27.7	26.9	0.629	0.014	0.027	0.320
ADG, kg/d								
D 1 to 28	0.213	0.224	0.230	0.226	0.007	0.177	0.642	0.310
D 28 to 49	0.452	0.361	0.365	0.358	0.014	0.019	0.010	0.029
D 49 to 70	0.688	0.640	0.619	0.586	0.024	0.017	0.100	0.748
D 28 to 70	0.560	0.500	0.492	0.472	0.013	0.001	0.005	0.129
ADFI, g/d								
D 28 to 49	452	418	410	447	21.4	0.770	0.948	0.110
D 49 to 70	1,049	967	998	1,011	39.8	0.834	0.467	0.203
D 28 to 70	742	679	673	713	21.4	0.427	0.610	0.026
FCE								
D 28 to 49	0.970	0.871	0.897	0.801	0.044	0.102	0.030	0.969
D 49 to 70	0.658	0.674	0.634	0.584	0.041	0.196	0.780	0.430
D 28 to 70	0.756	0.743	0.737	0.665	0.032	0.149	0.209	0.376
CV								
D 1	11.7	10.3	13.4	11.5	2.19	0.385	0.346	0.895
D 28	18.7	13.9	19.3	17.6	2.71	0.438	0.243	0.577
D 49	12.9	11.7	12.7	14.3	1.28	0.369	0.879	0.282
D 70	10.2	10.4	11.0	13.1	1.12	0.133	0.320	0.433

[1] Starter regime: H (high specification regime) = 2.5 kg feed 1, 2.0 kg feed 2, 3.0 kg feed 3; S (standard commercial regime) = 2.0 kg feed 2, 3.0 kg feed 3

[2] Additional feed 3: N = no additional feed 3, Y= Yes additional feed, 2.5 kg feed 3

[3] Low birth weight (BWL) pigs were selected at birth (≤ 1.25 kg)

6.3.2 Comparison of low birth weight and normal birth weight pigs

There was a significant effect of BW category on ADG during all periods examined, with BWN performing better; although during the period d 49 to 70 this was only a tendency (BWL = 0.613 kg/d, BWN = 0.659 kg/d; $P = 0.07$). Similarly, there was an effect of BiW category on the BW of pigs from d 1 to 70, with BWL pigs weighing less at all periods examined ($P < 0.001$) (Table 6.3). At birth, BWN piglets weighed 1.82 kg (SD 0.095) compared to 1.08 kg (SD 0.150) for BWL piglets. By d 70 this difference had increased to over 3 kg in BW ($P < 0.001$). Whilst BWL pigs ate less than BWN pigs for all periods examined ($P < 0.05$), there was no effect of body weight category on FCE ($P > 0.05$).

There was no effect of starter regime or interaction between starter regime and birth weight category of pigs on any of the performance parameters measured (ADG, ADFI or FCE; $P > 0.05$) from d 28 to 70. However there was also a tendency for an interaction between BW category and starter regime for ADG from d 49 to 70 ($P = 0.095$), with BWL pigs on regime H and BWN pigs on regime S performing better than pigs on other treatments.

Orthogonal contrasts comparing the best performing BWL pigs (treatment HY) and the combined effect of BWN pigs (treatments H and S), showed that by d 49 there was no significant difference in BW (15.8 kg versus 16.9; $P = 0.135$). By d 70, BWL pigs on treatment HY had completely caught up with normal weight pigs (H and S) (30.0 kg versus 30.6; $P = 0.413$). In addition, BWL on regime HY consumed a similar total amount of feed as BWN pigs (H and S) from d 28 to 49 (452 g/d versus 515; $P = 0.118$), but less during d 49 to 70 (1049 g/d versus 1174; $P = 0.040$). For both periods examined, BWL pigs on regime HY had an improved FCE in comparison to BWN pigs (d 28 to 49 = 0.97 versus 0.80; $P < 0.001$, d 49 to 70 = 0.66 versus 0.57; $P = 0.045$), even though consuming the same diet during the latter period.

Table 6.3 The effect of starter regime on the performance of low birth weight and normal birth weight pigs at weaning, from d 1 to d 70 [1, 2]

	Treatment					Significance		
Item	BWL H	BWL S	BWN H	BWN S	SEM	BW	SR	BW x SR
BW, kg								
D 1	1.10	1.05	1.81	1.82	0.035	< 0.001	0.584	0.385
D 28	7.14	7.15	8.57	8.67	0.170	< 0.001	0.306	0.331
D 49	14.7	14.6	16.9	16.8	0.498	< 0.001	0.855	0.958
D 70	27.9	26.9	30.3	30.9	0.875	< 0.001	0.809	0.347
ADG, kg/d								
D 1 to 28	0.221	0.226	0.235	0.253	0.008	0.021	0.189	0.449
D 28 to 49	0.361	0.358	0.415	0.396	0.019	0.025	0.582	0.679
D 49 to 70	0.640	0.586	0.644	0.674	0.024	0.066	0.608	0.095
D 28 to 70	0.496	0.467	0.530	0.535	0.018	0.012	0.540	0.375
ADFI, g/d								
D 28 to 49	418	447	512	518	29.5	0.012	0.554	0.695
D 49 to 70	967	1,011	1,157	1,190	49.7	0.001	0.446	0.916
D 28 to 70	693	729	834	854	31.9	< 0.001	0.387	0.792
FCE								
D 28 to 49	0.871	0.801	0.818	0.773	0.035	0.266	0.118	0.730
D 49 to 70	0.674	0.584	0.560	0.571	0.039	0.105	0.307	0.191
D 28 to 70	0.743	0.665	0.637	0.629	0.030	0.095	0.148	0.230
CV								
D 1	9.31	11.5	4.89	5.67	1.69	0.007	0.385	0.670
D 28	13.9	17.6	14.3	9.71	3.17	0.249	0.892	0.209
D 49	11.7	14.3	11.5	9.51	1.40	0.089	0.826	0.119
D70	10.4	13.1	10.5	8.83	0.983	0.045	0.610	0.042

[1] Low birth weight (BWL) and normal birth weight (BWN) pigs were selected at birth (BWL = ≤ 1.25 kg, BWN = 1.6 to 2.0 kg)
[2] Starter regime: H (high specification regime) = 2.5 kg feed 1, 2.0 kg feed 2, 3.0 kg feed 3; S (standard commercial regime) = 2.0 kg feed 2, 3.0 kg feed 3

6.3.3 Economic analysis

The most expensive starter regime was regime H which had a total feed cost of £6.15 per pig in comparison to regime S which was the cheapest at £3.48 per pig (Table 6.4). The cost of the additional feed 3 was £1.47 per pig. This meant that the most expensive treatment combination was treatment HY, which cost £7.62 in total. However when considering the amount of feed W consumed post treatment, BWN pigs on regime H were the most expensive (£15.9), whilst BWL pigs fed regime SY had the lowest total feed costs at £12.7 per pig. There was a tendency towards significance ($P = 0.087$) for the cost per kg of BW gained, with BWL on regime SY having the lowest in comparison to BWN pigs fed regime H which was the highest (0.62 £/kg vs. 0.72 £/kg). Whilst there was no statistical difference between the treatments for the margin over feed cost ($P > 0.05$), the highest value was for BWL pigs fed regime HY, whilst the lowest was for BWL pigs fed regime SN (£14.5 versus 12.3).

Table 6.4 The effect of birth weight, starter regime and additional allowance on the mean cost of feeding a pig from d 28 to 70 and margin over feed [1,2,3]

	BWL				BWN			Significance
Item	HY	H N	SY	SN	H	S	SEM	Treatment
Regime[4]								
Feed 1	2.5	2.5	-	-	2.5	-	-	-
Feed 2	2.0	2.0	2.0	2.0	2.0	2.0	-	-
Feed 3	5.5	3.0	5.5	3.0	3.0	3.0	-	-
Total starter (kg/pig)	10.0	7.50	7.50	5.00	7.50	5.00	-	-
Total feed (kg/pig)	30.4	28.7	28.9	31.0	34.6	35.4	0.652	0.001
Starter diet costs, £/pig[5]	7.62	6.15	4.95	3.48	6.15	3.48	0.409	< 0.001
Total cost of feed, £/pig[6]	15.0	13.8	12.7	12.9	15.9	14.4	0.417	< 0.001
£/kg gain	0.65	0.66	0.62	0.65	0.72	0.65	0.096	0.087
Margin over feed[7] £/pig	14.5	12.7	13.5	12.3	12.4	14.1	1.10	0.293

[1] Low birth weight (BWL) and normal birth weight (BWN) pigs at weaning (BWL = ≤ 1.25 kg, BWN = 1.6 to 2.0 kg)
[2] Starter regime: H (high specification regime) = 2.5 kg feed 1, 2.0 kg feed 2, 3.0 kg feed 3; S (standard commercial regime) = 2.0 kg feed 2, 3.0 kg feed 3. After which a standard feed W was offered *ad lib* in both regimes until d 70
[3] Additional allowance: N = no additional feed 3, Y= Yes additional feed, 2.5 kg feed 3
[4] Diets were fed in succession once the previous feed had been consumed, i.e. feed 1, feed 2 then feed 3
[5] Diets 1, 2 and 3 cost per tonne: Feed 1= £1069, Feed 2 = £858, feed 3 = £588, Feed W = £360
[6]Pig prices (Nov 13): carcass price= £1.70/kg deadweight

6.4 Discussion

This study investigated the short to medium term effects of feeding a high specification starter regime with or without extra feed on the performance from weaning of LBiW pigs. Treatments were fed on a kg/pig basis, lasting approximately three weeks, to assess if dietary manipulation could improve the nursery exit weight of these LBiW pigs. Our hypothesis was that the combination of an improved starter regime and the provision of the extra feed (corresponding to the last feed of the starter regime) would improve the performance of LBiW pigs post weaning compared to a standard regime. It is further hypothesized that this improved regime is unlikely to improve NBiW pig performance or be economic. The hypothesis was based on the findings : 1) diets based on cooked cereals, containing a higher lysine content and lactose appear to confer advantages on LBiW pigs and 2) increased amounts of standard starter regimes have positive effects on performance of light pigs from weaning (Lawlor et al., 2002; Magowan et al., 2011b). The increase in performance of LBiW pigs fed an improved starter diet was consistent with our hypotheses. Most importantly, the findings demonstrate that the additional cost of feeding LBiW pigs improved diets is offset by BW gains and is therefore economically viable.

Weaning weight is likely to be a reflection of both pre and post-partum factors (Lawlor et al., 2002), with uterine environment as well as lactation management affecting preweaning growth performance. Selecting piglets by birth weight (low (≤ 1.25 kg) or normal (1.6 to 2.0 kg)) for treatment at weaning, meant that pigs were more likely to have a similar underlying cause for low weight at weaning (birth weight) and therefore similarities in their nutritional requirements, rather than selecting pigs based solely on WW which may be due to a number of reasons. An effort was made to reduce limiting factors during the preweaning stage to give LBiW pigs every chance to grow to their full potential. Piglets were cross fostered into litters by BiW to reduce the competition from heavier littermates and supplementary milk was also provided. However as expected, BiW was a good determinant of WW (Gondret et al., 2005; Bérard et al., 2010; Douglas et al., 2013), with a high correlation between the two. At birth, there was an average difference of 0.7 kg between the two weight categories, however by d 28 this had increased to almost 1.5 kg. Whilst the majority of pigs born with low BW remained light at weaning, there was a small minority of pigs which met or exceeded the average BW of NBiW pigs at weaning, possibly as a result of the experimental design which reduced limiting factors.

Light weight pigs can be problematic at any stage of production, and the question of how best to feed these pigs at weaning and beyond to ensure maximum performance often results in conflicting advice. It has been suggested, in accordance with the predictive adaptive response hypothesis (Gluckman et al., 2005; Rehfeldt et al., 2012), that as a result of restriction in utero LBiW pigs have reduced absolute nutrient requirements, for example reduced dietary protein (Nissen and Oksbjerg, 2011). In contrast, this study and another (Beaulieu et al., 2012) hypothesized that feeding LBiW pigs a diet higher in nutrient concentration can actually benefit the performance of these pigs at weaning. Whilst other studies have also investigated the effect of high input dietary regimes (Magowan et al., 2011b) or high density diets (Lawlor et al., 2002) on the performance of light pigs at weaning, these were not exclusively LBiW but pigs which were light at weaning possibly as a result of other factors. Low weaning weight influences digestive enzyme activity and gut maturation (Owsley et al., 1986; Mahan and Lepine, 1991) with lighter pigs at weaning as a result of LBiW having a delayed gut maturation (Michiels et al., 2013) which may hinder adaptation to post weaning diets, and therefore likely to benefit from a highly digestible diet with high nutrient density.

In agreement with the above hypothesis, LBiW pigs at weaning benefitted significantly from provision of a high specification feed. Identification of any individual ingredient which may have benefitted BWL pigs is not possible; however high digestibility, high lactose content and inclusion of cooked cereals have all been shown to improve nursery pig growth performance (Mahan, 1992, 1993; Medel et al., 2004; Kim et al., 2010; Menoyo et al., 2011), in particular for those pigs with immature guts as observed in LBiW pigs at weaning (Michiels et al., 2013). Whilst it has been previously demonstrated that high specification starter diets (Beaulieu et al., 2012) can improve the performance of LBiW pigs at weaning, and increased amounts of standard starter regimes (Lawlor et al., 2002; Magowan et al., 2011b, a) can improve the performance of light weight pigs at weaning, a combination of both improved starter diet quality and increased amount had not previously been investigated.

The results presented demonstrate that provision of a high nutrient dense and highly digestible diet can improve performance of LBiW pigs, but this alone was not enough to maximize growth of these pigs, and an extra provision of feed 3 was needed. Provision of both of these nutritional treatments resulted in a 3 kg weight increment at nursery exit and reduced variability in BW in LBiW pigs, and subsequently there was no significant difference in BW compared to pigs which were heavier at birth and weaning. The combined effects of the treatments on growth performance are likely to be the result of a synergistic effect, as indicated by the interaction of starter regime and additional feed 3 on ADG, rather than simple additivity. The positive impact on performance is not likely to be a result of an improved FI, as there was no difference in absolute consumption between LBiW pigs on the different dietary treatments, but rather due to an improved FCE as noted previously (Lawlor et al., 2002; Magowan et al., 2011b). However as the high density does show improved performance, it could indicate that FI is a limiting factor in LBiW pig performance as suggested by others (Gondret et al., 2005).

Whilst an improvement in performance was observed for LBiW pigs on different dietary regimes, there was no difference in growth performance of NBiW pigs fed dietary regime H or S (without extra feed 3). This suggests that the 'standard' feeding regime was appropriate for the NBiW pigs. It is apparent that pigs of different weight respond differently to starter regimes of different specifications. Despite no differences in the growth performance of BWN pigs on different dietary treatments, they still had greater growth rates than BWL pigs on comparable treatments. This is in agreement with previous work which has shown that BiW has a greater effect on post weaning performance than a starter regime alone (Mahan et al., 1998; Lawlor et al., 2002). The exception to this was the first two weeks post weaning where no difference in growth performance was noted, as well as no difference in the FI during the first week post weaning. It has been noted that heavier pigs at weaning often experience a greater growth check than lighter pigs (Lewis and Wamnes, 2006)(although this was observed in pigs weaned at d 17), possibly as a result of decreased consumption of creep feed as they have access to more productive teats. Therefore they may not transition to solid feed as well which results in a temporary drop in performance. However the design of this experiment means this is unlikely to occur as pigs of different BiW categories were in different litters so NBiW pigs will have been competing with similar sized littermates for teat access.

A weight increment of over 3 kg for BWL pigs was observed at nursery exit as a result of the nutritional treatments. However, subsequent performance to slaughter was not investigated and therefore whether any gain in BW is retained remains uncertain. Previously, we have demonstrated that pigs retain any increase in BW as a result of pre weaning treatments (Douglas et al., 2014), although treatment differences were not significant at slaughter, possibly as a result of the increased variation in BW at a greater age (Wellock et al., 2009). In contrast, other studies have found that whilst pigs fed starter diets which were higher in quality did benefit nursery performance, beyond this, effects on BW and ADG diminished with age (Meade et al., 1969; Whang et al., 2000). However, the improved growth of H pigs during the subsequent period on a standard diet suggests longer term benefits may persist.

To be an economically viable treatment, the price of feeding the higher quality diets must be offset by the gains in BW or improved food utilization (Lawlor et al., 2002). Feeding LBiW pigs the high specification starter regime with extra feed 3 was the most expensive; however the margin over feed was better in comparison to other regimes. These results suggest that not only can LBiW pigs at weaning benefit from an improved dietary regime, but that it is cost effective for producers with an increased return per pig, and should be preferred to a standard commercial regime which has the poorest margin over feed. In contrast, for normal weight pigs the standard commercial regime was the least expensive, had the greatest margin over feed and resulted in the lowest variability in BW.

6.5 Conclusions

Pigs of different BiW are better suited to different starter diet regimes and should be fed as such. Based on the conclusions of both the growth performance and economic analysis, the following management techniques can be recommended for improving the growth performance of pigs with low weights at weaning as a result of LBiW: (1) Feeding a high specification starter diet with extra feed 3 can not only result in a similar nursery exit weight of low BW and normal BW pigs and reduced variability in BW, but is the most economical diet regime, (2) Separation of pigs with low BW at weaning will allow selective feeding of an improved regime as heavier pigs are best suited to a standard commercial diet. Limiting the usage of the most expensive regime to low BW pigs only, will ensure maximum growth performance as well as increased profitability.

Chapter 7. General Discussion

The aim of this thesis was to provide understanding of risk factors that are associated with the occurrence of light weight pigs and, by providing such understanding, to develop nutritional and management treatments that might enable these pigs to decrease the deficit in their BW.

Initially the risk factors associated with poor lifetime performance were investigated (Chapter 3). In particular, low BiW and WW resulted in poor growth to finishing, which highlighted the need to focus on earlier stages of production. The effect of a high specification diet (higher in amino acid: energy content) introduced at 9 weeks of age on the subsequent growth of LBiW pigs was investigated, to determine if there is a critical window in early life for interventions to improve growth performance (Chapter 4). As LBiW pigs did not benefit from this nutritional intervention during the grower stage, the effect of the preweaning environment on performance to slaughter was explored (Chapter 5). Whilst reducing competition from heavier littermates increased the WW of LBiW pigs, there was no effect on growth post weaning. Subsequently the nursery period was targeted, and the effect of a post weaning starter regime specifically formulated for LBiW pigs was investigated (Chapter 6).

The main conclusions from this thesis were: BiW has a significant effect on future growth, with initial differences in BW perpetuated with age. Environmental factors at different stages of production may limit the growth of LBiW pigs and, as such, these pigs are disadvantaged by commercial pig production practices. The majority of LBiW pigs did not compensate for their lower BW as they did not grow significantly faster than their NBiW pigs counterparts at any later stage. However this thesis did demonstrate ways of improving growth of LBiW pigs through improved nutrition that not only allowed them to match the BW of heavier littermates at d 70 of age but that was also cost effective. Ultimately this thesis has shown that LBiW pigs have the capacity to grow at the same rate as NBiW pigs and this can be exploited to reduce the deficit in their relative weight.

7.1 Can low birth weight pigs grow as fast as normal birth weight pigs?

In swine literature much emphasis is placed on the poor postnatal growth performance of LBiW pigs (Rehfeldt and Kuhn, 2006), which may be a consequence of permanent physiological changes, such as a lower number of muscles fibres (Nissen et al., 2004; Gondret et al., 2005; Paredes et al., 2013). The data presented in this thesis confirm an effect of BiW on postnatal growth, with BiW having a significant effect on both ADG and BW at most stages of production (Chapters 3 to 6). The exception to this was in finisher pigs, where no effect of BiW was noted (Chapter 5). Despite this, initial differences in BiW were perpetuated with age; a 500 g average BW advantage of NBiW pigs at birth, translated to over a 7 kg advantage at slaughter.

It has been stated that LBiW pigs are not able to compensate during postnatal life for their reduced BW at birth (Rehfeldt and Kuhn, 2006; Wu et al., 2006; Beaulieu et al., 2010). Whilst the majority of animals studied in this thesis were unable to naturally meet the BW of heavier littermates without intervention, a small minority were. In Chapter 3, despite the poor performance associated with pigs of low BiW and WW, a number of pigs achieved a similar weight for age to higher BiW contemporaries by finishing. A similar effect was observed in Chapters 4 and 6 where, prior to experimental diets being fed, a small number of piglets with LBiW were able to meet or exceed the average weight of NBiW pigs at weaning. These pigs exhibited BW gains that were similar to or above those of NBiW pigs without any treatments, although this does not occur in the majority of pigs and what allows some pigs and not others to do this remains uncertain. Further investigation found no specific traits associated with these pigs that were able to catch up (e.g. LBiW pigs of a higher BiW or PI) nor were these piglets from the same birth or cross fostered litter. It could be hypothesized that the ability to catch up may be a reflection of the intrauterine environment. For example Handel and Stickland (1988) previously suggested that LBiW pigs that are capable of catching up with heavier littermates may have a similar number of muscle fibres to NBiW pigs. However it could just as likely be a result of the postnatal environment, for example access to superior teats by chance. It would be particularly beneficial to identify what allows some pigs to catch up with heavier pigs without intervention, as this could be exploited to help the remainder of LBiW pigs

Whilst the majority of LBiW pigs do not appear to have the capacity to naturally reduce the deficit in BW, they do have the potential to grow at a similar rate to NBiW pigs during certain stages of production. Both nutritional and management intervention has demonstrated that growth performance of LBiW pigs can be improved, and as a result, BW can be increased. (Wolter et al., 2002; Morise et al., 2011; Beaulieu et al., 2012; Han et al., 2013). However it has not been previously shown that these pigs can achieve the same BW for age as heavier littermates. The data presented here indicate that, in fact, these LBiW pigs can reach the same BW as heavier littermates when given appropriate nutritional treatments, suggesting that commercial pig production practice is limiting the growth potential of these pigs rather than their just their physiology or inherent growth potential.

As a result of the database analysis in Chapter 3, LBiW pigs in this thesis were defined as those which weighed ≤ 1.25 kg. The definition of LBiW pigs is highly variable in the literature, with what may be classed as LBiW in one paper not necessarily in another. As it remains uncertain whether BiW has a graded effect (variations in the degree of damage) or a threshold effect (where piglets below a point will be significantly affected) on performance, the differences in classification may have an effect on any results obtained.

7.2 Improving the growth performance of low birth weight pigs

As expected, nutrition played a critical role in the growth performance of LBiW pigs. During the preweaning period, the piglet is solely reliant on the sow for nutrition and, as a result of its small size, are at a competitive disadvantage when raised with heavier littermates which can command better quality teats and stimulate these more vigorously to achieve favourable partitioning of milk supply (Fraser and Jones, 1975; Cutler et al., 1999). In agreement with this hypothesis, reducing competition by creating litters of similar sized pigs improved growth during the latter part of lactation, a time when milk supply plateaus but piglet demand increases (Klobasa et al., 1987). This resulted in a 500 g advantage at weaning in comparison with LBiW piglets grouped with heavier littermates. Whilst in Chapter 5 no effect of supplementary milk on growth performance was noted, the provision of creep feed during lactation may have had an effect on supplementary milk consumption. If piglets are receiving sufficient additional nutrition from creep feed then it is possible their supplementary milk intake may decrease. Therefore, in hindsight, piglets should not have been fed creep feed during lactation and an improved design would ensure that the only source of nutrition available to piglets is sow milk and supplementary milk. However on a practical basis, the provision of creep feed is vital as there would be no behavioural or gut conditioning to solid feed (BPEX, 2013a) which is likely to have an impact on post-weaning growth (Kuller et al., 2007).

Post weaning, the piglet is no longer reliant on the sow for nutrition, but instead must adapt to a solid feed. As a result of their LBiW they are more likely to have a reduced BW at weaning, which may alter their nutritional requirements. However what these requirements may be has been cause of some debate. Gluckman et al (2005) hypothesized that a mismatch of the pre and postnatal environment of an animal could be detrimental. They state that, as a result of an adverse environment in utero, the foetus makes irreversible alterations to its development trajectory; as such the animal has developed under the expectation of a nutritionally deprived environment and are not adapted for a nutrient rich environment. Subsequently, Nissen et al (2011) investigated the effect of a low protein diet on the performance of LBiW pigs, although no benefit was noted. In contrast, it was hypothesized in this thesis and by others (Schinckel et al., 2003; Beaulieu et al., 2012) that LBiW pigs at weaning may benefit from a diet increased in nutrient density as well as digestibility. Diets are fed based on the ‘average pig’ and, as a result, are unlikely to meet the requirements of pigs with BW that deviates from the normal. These LBiW may not only differ in body composition but also their digestive function, both of which may affect their dietary requirements. This was confirmed as the provision of a specialised starter regime demonstrated that LBiW pigs are not only capable of BW gains which are equal to those of NBiW pigs but that they can match the BW of the average weight pigs leaving the nursery.

7.2.1 The importance of timing

Despite the improvement of LBiW pigs at weaning with a high specification diet, in Chapter 4, no difference in performance was observed between LBiW pigs fed either the standard or high specification feed from 9 to 13 weeks of age. It has been suggested that different periods of the pig’s life are under different influences and this is one possible explanation for the differences observed. For example, during the early phase, from birth to the end of the nursery period, both the environment and BiW may play a major role in pig performance (Dwyer et al., 1993). This could include the physiological effects of BiW such as reduced gut maturity at weaning (Michiels et al 2013) and reduced enzyme activity associated with lower BW (Jensen 1997) which may affect both pre and post weaning performance. However after this period, growth performance may be partially explained by the number of muscle fibres (Dwyer et al 1993) with increased growth performance in this period associated with a higher number of muscle fibres and pigs therefore may be less susceptible to intervention.

However it is also possible that the experimental design may have prevented LBiW pigs from improving their performance in Chapter 4. Efforts were made to minimise nutrient intake restriction during the lactation period by the provision of supplementary milk and grouping with similar sized littermates; as such there was no effect of BiW on ADG during this period. At weaning, however, all pigs were fed a series of starter diets which were standard for their age and therefore may not have been adequate for LBiW pigs. Therefore the experimental design may have inadvertently disadvantaged LBiW piglets post weaning. This is supported by a significant effect of BiW during the period between weaning and provision of the experimental diets (d 28 to 63). After this period from d 63 to 91, there was no significant difference in the performance of NBiW (that weren't previously restricted) and LBiW pigs, although LBiW still grew considerably slower. As the impact of early life experiences and previous growth performance (Klindt, 2003; Pluske et al., 2005) can affect subsequent growth, it is possible that the mis-feeding of LBiW pigs affected their future growth. In hindsight, prior to nutritional treatments being fed, LBiW pigs should have been provided with a diet from weaning that was specifically formulated for their reduced BW (including increased digestibility and nutrient specification). This would prevent LBiW piglets from being disadvantaged and subsequently the actual impact of nutritional treatments applied during the grower phase could be investigated.

7.2.2 The feed intake and efficiency of low birth weight pigs

As reducing competition from heavier littermates and the provision of a high specification diet increased growth performance, FI is likely to be partly responsible for the relationship between BiW and postnatal growth (Dwyer et al., 1993). As such, it is important to determine whether feed intake is a cause or an effect of reduced ADG in LBiW pigs (Jones et al., 2012). Whilst many have observed lower FI in LBiW pigs in comparison to their heavier littermates, that was not necessarily the case in this thesis and there was not a consistent effect of BiW on feed intake, although it is likely that a certain amount of this variability is due to the different diets provided. During the post weaning period, in comparison to NBiW pigs, LBiW pigs consumed either the same amount of feed or less. At no point in the experiments did LBiW pigs' absolute feed intake exceed that of NBiW pigs, although their feed intake relative to their BW did, an effect which has been recognised in recent literature (Krueger et al., 2013).

When considering the difference in FI between LBiW pigs on different nutritional treatments, there was also no difference in FI. However, pigs fed the high specification feed had increased ADG. This suggests that FI may be a limiting factor for LBiW piglet performance (Gondret et al., 2005). In general pigs consume feed to satisfy their energy requirements (Lammers et al., 2007); however it seems that, whilst LBiW pigs benefit from a nutrient dense diet, they do not increase their FI when fed a standard diet. One possible explanation is that physiology of LBiW pigs is preventing them from increasing their FI. As the gut capacity of weaned pigs may limit feed intake (Varley et al., 2001), it could be expected that pigs which weigh significantly less at weaning have a lower capacity than heavier littermates. In addition, the development of the digestive tract of LBiW piglets is retarded at weaning, with a decreased small intestinal weight: length ratio (Michiels et al., 2013). Therefore LBiW pigs may already be eating at capacity, which is why no difference was noted in this thesis when pigs ate diets of different specifications. If this is the case then it would be expected that, as they mature, FI would no longer be limiting, which may explain why, in the finisher phase, they were able to exhibit similar ADG to NBiW. However this would require further investigation. In addition to morphological limits, it is possible that physiological factors are limiting the FI of LBiW pigs. Gastric emptying can influence FI in pigs (Gregory et al., 1989) and as it may be delayed in LBiW humans neonates (Neu, 2007), this may be the same in LBiW pigs, although there is currently no evidence to support or refute this.

The modern commercial pig is often bred for higher lean tissue growth potential. Inevitably the composition of the gain will vary amongst individuals and poor efficiency in animals may be indicative of increased fat and reduced protein deposition (Hodgson and Coe, 2005). As LBiW pigs may be susceptible to increased fat deposition, it would be expected that they are less efficient than heavier littermates (Wolter et al., 2002; Gondret et al., 2006; Bérard et al., 2008; Schinckel et al., 2010). One theory is that prenatal programming affects the postnatal phenotype of the muscle (Karunaratne et al., 2005), with LBiW pigs pre-programmed to grow more lipid at the expense of protein hence their inefficiency. Whilst, at certain points in this thesis, LBiW pigs were less efficient, this was not consistent both within and between experimental chapters. It is difficult to directly compare the results of Chapters 4 and 6 as pigs were fed different experimental diets and this is likely to influence FCE. However, in general, LBiW pigs were either less efficient or similar to NBiW pigs depending on the period in question. Another theory for reduced feed efficiency in LBiW pigs is that they have inadequate digestive ability (Gondret et al., 2006; Morise et al., 2008), with normal gut maturation retarded at birth and at weaning in LBiW pigs (Wang et al., 2005; Michiels et al., 2013). Although it is not possible to speculate on which ingredients in the high specification diets used in Chapter 6 improved ADG, the diet was highly digestible, amongst other things, which may have contributed towards the improved efficiency. It has also been hypothesized LBiW piglets may have reduced nutrient utilization (Wang et al., 2008; Jones, 2012) which may be responsible for their decreased efficiency although as the diets fed in Chapter 6 were both nutrient dense and highly digestible, it is not possible to separate the two.

In terms of carcass composition, if LBiW pigs were less efficient throughout production then a carcass with a higher percentage of fat would be expected. Whilst it has been reported that they have increased fat but lower lean muscle content (Powell and Aberle, 1980; Rehfeldt and Kuhn, 2006), as well as lower tenderness of meat (Gondret et al., 2006), other studies have found little (Bérard et al., 2008) to no effect (Jones, 2012) of BiW on carcass composition. These differences in results may arise from differences in breeds, feeding strategies and variation in the definition of LBiW. However the absence of a definitive conclusion on the effect of BiW on carcass composition may indicate that LBiW pigs are not consistently less efficient than heavier littermates.

7.3 What are the long term effects of interventions on growth?

To increase the likelihood of adoption by the Pig Industry, the long term effects of any successful treatments should be considered. There has been no indication that the growth trajectory of LBiW pigs has been altered by the treatments applied in this thesis. Rather, interventions give LBiW pigs a BW advantage which may or may not be retained in the long term.

A 500 g increase in WW was found with manipulation of litter composition during lactation; however no subsequent benefit was noted for ADG or BW post weaning.

Despite this, a numerical difference was observed at slaughter with LBiW pigs grouped with similar weight littermates almost 2 kg heavier at slaughter than those in mixed litters. One possible explanation for this lack of effect post weaning is that, although differences in BW are maintained to finishing, these relatively small differences cannot be detected in the latter stages due to the increasing weight variation (Wellock et al., 2009). Whilst Klindt et al (2003) found that those piglets with heavier BW at weaning had better post weaning performance, the manner in which a heavier WW is attained may also be important (Lawlor et al., 2002; Pluske et al., 2005). Piglets with naturally higher weights are more likely to retain any weight advantage, whereas weight which is higher as a result of interventions is more likely to be lost in the long term (Lawlor et al., 2002). It is likely that BiW plays an important part in this observation, as it is commonly reported that BiW is more important than the effects of any subsequent treatments (Wolter et al., 2002) and is the greatest determinant of lifetime performance (Dunshea, 2003). Manipulation of post weaning starter regime also had an effect on future BW, with a 3 kg improvement at exit from the nursery (Chapter 6). Although this was not a long term study, LBiW pigs did continue to show improved ADG for 3 weeks after the experimental feed was consumed. This suggests that there may be long term effects of post weaning feeding regime on the performance of LBiW pigs. Inevitably, whether any BW advantage is retained will depend on the future growth of LBiW pigs, which is likely to be dependent on the environment. If limiting conditions are once again present, then it is likely that any BW advantage will be lost.

7.4 Management of low birth weight pigs on farm

Effective treatments for improving the performance of LBiW piglets are few and far between, and, in most cases, variation is managed rather than reduced. The findings from this thesis have highlighted the importance of the postnatal environment for LBiW pigs and a number of treatments have been proven successful in improving performance. It is important to consider not only how these treatments can be applied on farm, but also whether they are economic. Ultimately, treatments which are straightforward to implement but also economically viable will have the greatest uptake by producers.

7.4.1 Preweaning management

The results of this thesis suggest that a non-competitive environment is particularly important to LBiW pigs in early life. Reducing competition from heavier pigs by cross fostering LBiW piglets to litters with similar weight littermates, improved the WW of LBiW pigs. In practice, this means cross fostering piglets to create litters which comprise solely of LBiW pigs. The process of cross fostering, if done correctly, is unlikely to have detrimental effects on performance (Milligan et al., 2001a; Deen and Bilkei, 2004; Bishop, 2011). Timing is particularly important; piglets must stay with sows long enough to consume sufficient colostrum but be moved before a teat hierarchy can be established (McBride, 1963). It is also beneficial, where possible, to move heavier littermates and leave the smallest pigs on their birth sow (Barrie, 2006), and to always ensure the sow has enough functional teats to support the litter. Whilst extensive cross fostering is likely to be labour intensive, selective cross fostering of heavier piglets from litters with LBiW piglets is a feasible technique as cross fostering is undertaken on most EU farms to equalize litter sizes. However it is important to consider that there may be implications of selective cross fostering for NBiW pigs. If NBiW pigs are being cross fostered into litters with similar sized littermates this means that half of these pigs will now get access to the poor teats whereas in a litter with LBiW pigs they would have had access to the superior anterior teats. This may mean that in comparison to being grouped with LBiW pigs, they may not grow as well.

Although the provision of supplementary milk did not benefit LBiW piglet performance or survival, it did reduce BW variation to slaughter weight. Reducing variation would be favourable on farm, as having a smaller BW range of LBiW pigs would make management easier. In the majority of literature, supplementary milk has a positive effect on piglet performance (Azain et al., 1996; Zijlstra et al., 1996; Dunshea et al., 1998; Dunshea et al., 1999; Wolter et al., 2002), therefore this should not be ruled out as a management tool for improving piglet performance during lactation. Additionally, if LBiW piglets are grouped with similar sized littermates, then providing milk to those litters that need it most will ensure costs are kept low rather than providing milk to a larger number of litters.

7.4.2 Postweaning nutrition

The correct choice of starter feed regime is critical to minimize the post-weaning growth check as pigs transition from liquid to solid feed. It was demonstrated that feeding a high specification starter diet with extra feed (corresponding to the last diet of the starter regime) can not only improve LBiW performance, but result in a similar nursery exit weight of low BiW and normal BiW pigs (Chapter 6). In practice, producers will not separate by BiW as done in this thesis, but rather by BW at weaning. By default, a number of low WW pigs will be low BiW pigs, given the high correlation between BiW and WW. However, little is known about the difference in the physiology of pigs which are light at weaning as a result of different factors and therefore how they respond to treatments. Despite this, it has been shown that pigs which are light at weaning can benefit from enhanced starter regimes (Mahan and Lepine, 1991; Magowan et al., 2011b) and, as these studies selected by WW rather than BiW, pigs were likely to have been of low weight for a number of different causes. It is likely, therefore, that we can extrapolate results obtained in chapter 6 to low weaning weight pigs as well.

To be an economically viable treatment, the price of feeding the higher quality diets must be offset by the gains in BW or improved food utilization (Lawlor et al., 2002). The results presented here suggest that not only can low birth weight pigs at weaning benefit from an improved dietary regime, but that it is cost effective for producers with an increased return per pig, and should be preferred to a standard commercial regime which has poorer margin over feed cost. In contrast, for NBiW pigs the standard commercial regime was the least expensive and had the greatest margin over feed cost. Separation of pigs with low BW at weaning will allow selective feeding of an improved regime, as heavier pigs are best suited to a standard commercial diet.

7.4.3 The economic implications of low birth weight pigs

It has been suggested that it may be more economical to cull LBiW pigs and some producers may in fact cull pigs below a certain BiW, on the assumption that they will not perform well. However, the results presented here confirm that LBiW pigs can perform very well indeed if managed/fed appropriately. This thesis included some pigs of particularly low BiW, as low as 0.6 kg, with approximately 20 % of LBiW pigs in each experiment below 0.8 kg. On closer inspection of particularly LBiW pigs in

Chapter 6 (≤ 0.8.kg), the majority of these pigs were able to meet BW of heavier littermates by d 70. In addition to improved growth rates, it was demonstrated that low pre weaning mortality rates can be achieved with extra care of LBiW pigs.

Independent of the methods used to improve the performance of LBiW pigs, what is of particular interest is the trade-off between having increased litter sizes in comparison to dealing with the problems LBiW pigs may present. The problem faced by producers is whether to rear LBiW pigs which may or may not perform well, versus culling these pigs at birth which is a potential loss of earnings. The economic impact of rearing LBiW pigs will be dependent on their ability to convert feed efficiently, financial penalties at the abattoir, costs associated with managing variation during production as well as current pig and feed prices. Therefore the impact of any future increases in litter size should be weighed against the consequences of LBiW pigs and their potential impact on system efficiency

7.5 Scope for future research

It was observed in this thesis that a number of pigs with LBiW were able to 'naturally' compensate during lactation and the nursery period. In future it would be therefore be beneficial to identify any common traits at birth amongst these pigs that enable them to catch up with heavier littermates. It has been suggested that the body shape of piglets at birth is reflective of foetal growth restriction and has a pronounced influence on early postnatal development and behaviour (Litten et al., 2001). As demonstrated by Baxter et al (2008), morphological measurements such as PI can be indicative of survivability in new born pigs, therefore it is possible that these measurements may also be related to postnatal performance. Ponderal index may also have a significant influence on the postnatal changes in levels of plasma IGF-1 from d 3 to 150 in pigs (Litten et al., 2004), which is important in growth regulation. More recently, head morphology has been identified as a good indicator of IUGR in pigs and is related to colostrum intake (Amdi et al., 2013). Therefore morphological characteristics, such as PI, BMI and CRL may be indicative of the intrauterine environment, and be able to predict postnatal performance and warrant investigation.

Ultimately prevention of LBiW pigs is preferred to management, although at the present time this is not possible. Whilst previously prevention has focused on maternal nutrition during gestation, current thinking indicates that causal factors of LBiW pigs occur earlier than this. For example, increasing the period in between weaning and the next pregnancy in sows has been shown to reduce the CV and increase the total litter weight at birth, likely related to enhanced restoration of follicle development (Wientjes et al., 2013). High ovulation rates have also been associated with intrauterine crowding and low birth weight pigs (Foxcroft et al., 2006), with a LBiW litter phenotype identified (Foxcroft et al., 2009). It has been hypothesized that, as a result of intrauterine crowding driven by high ovulation rates, all pigs in a litter would have this phenotype, in comparison to non-restricted litters which have a NBiW phenotype. Subsequent work has confirmed that this LBiW litter phenotype is associated with increased intrauterine crowding and poor lean growth performance (Smit et al., 2013). Whilst it is early days, results suggest that genes controlling differences in ovarian follicular development may contribute to differences in ovulation rate (Foxcroft, 2013), with possible differential gene expression profile between high and low birth weight litter phenotypes. This would eventually allow for identification of embryos with high or low potential for growth and may explain differences in pigs being able to compensate that BiW seems unable to fully answer.

7.6 Final conclusion and findings from the thesis

The findings of this thesis demonstrate the importance of BiW for future growth and how initial differences are perpetuated as pigs progress from birth to finishing. Whilst LBiW pigs may be inherently disadvantaged from birth, the postnatal environment disadvantages them further, making it difficult for them to catch up. Dietary and management interventions targeted at specific populations have been used with varying degrees of success to manipulate future BW.

This thesis also offers novel insights into the crucial stages of postnatal growth for LBiW pigs, with LBiW pigs benefitting from interventions in earlier stages of production. Most importantly, it was established that LBiW pigs are able to exhibit growth rates similar to heavier littermates post weaning, enabling them not only to decrease the deficit in their weight but also to match the BW of heavier pigs on exit from the nursery. However, whether a weight advantage is still present at slaughter remains uncertain. Ultimately this thesis provides much needed practical management solutions for LBiW pigs that are cost effective.

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