

Effect of within-litter birth weight variation after cross-fostering on piglet preweaning growth and mortality

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ABSTRACT: Cross-fostering is commonly used in commercial swine production to equalize litter sizes and/or adjust piglet birth weights within litters. However, there is limited published information on optimum cross-fostering procedures. This study evaluated the effects of within-litter birth weight variation after cross-fostering (using litters of 14 piglets) on piglet preweaning mortality (PWM) and weaning weight (WW). An RCBD was used (blocking factors were day of farrowing and sow parity, body condition score, and functional teat number) with an incomplete factorial arrangement of the following two treatments: 1) birth weight category (BWC): light (<1.0 kg), medium (1.0 to 1.5 kg), or heavy (1.5 to 2.0 kg); 2) litter composition: uniform, all piglets in the litter of the same BWC [uniform light (14 light piglets); uniform medium (14 medium piglets); uniform heavy (14 heavy piglets)]; mixed, piglets in the litter of two or more BWC [L+M (seven light and seven medium piglets); M+H (seven medium and seven heavy piglets); L+M+H (three light, six medium, and five heavy piglets)]. Piglets were weighed at 24 h after birth and randomly allotted to litter composition treatment from within BWC; all piglets were cross-fostered. There were 47 blocks of six litters (total 282 litters and 3,948

piglets). Weaning weights were collected at 18.7 ± 0.64 d of age; all PWM was recorded. Individual piglet WW and PWM data were analyzed using PROC MIXED and PROC GLIMMIX of SAS, respectively; models included fixed effects of BWC, litter composition, and the interaction, and random effects of sow within the block. There was litter composition by BWC interactions ($P \leq 0.05$) for WW and PWM. Within each BWC, WW generally increased and PWM generally decreased as littermate weight decreased. For example, WW was greatest ($P \leq 0.05$) for light piglets in uniform light litters, for medium piglets in L+M litters, and for heavy piglets in L+M+H litters. Preweaning mortality was lowest ($P \leq 0.05$) for medium piglets in L+M litters, and for heavy piglets in L+M+H litters; however, litter composition had no effect ($P > 0.05$) on PWM of light piglets. In conclusion, increasing the average birth weight of littermates after cross-fostering generally decreased WW and increased PWM for piglets of all birth weight categories. This implies that the optimum approach to cross-fostering that maximizes piglet preweaning growth and survival is likely to vary depending on the birth weight distribution of the population.

Key words: birth weight, cross-fostering, piglet, preweaning mortality, weaning weight, within-litter birth weight variation

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INTRODUCTION

Piglet preweaning mortality is a major economic loss to producers and is also a significant animal welfare concern. Levels of preweaning mortality on commercial sow farms have increased over recent years, currently averaging around 10% to 15% of piglets born alive (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). A major factor that has been associated with these higher levels of preweaning mortality is the increase in litter size that has occurred over the same time period (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). As litter size increases, there is a correlated decrease in average piglet birth weight and an increase in the number of low birth weight piglets (i.e., <1 kg; Tribout et al., 2004; Nielsen et al., 2013; Camargo et al., 2020). Preweaning mortality levels are considerably greater for low birth weight piglets than heavier littermates (Herpin et al., 2002; Vande Pol et al., 2021).

Another consequence of this increase in litter size is that the number of piglets born alive within a litter often exceeds the number of functional teats on the sow. Litter sizes currently average between 14 and 17 piglets (SEGES, 2017; PigChamp, 2019), whereas the average number of functional teats is approximately 14 per sow (Vande Pol et al., 2021). This results in increased piglet competition for teat access during lactation and increased levels of preweaning mortality, particularly for low birth weight piglets (Kobek-Kjeldager et al., 2020a,b). Therefore, it is important to develop practical approaches to rearing this increased number of piglets.

Cross-fostering can be used to equalize litter sizes and/or reduce weight variation within a litter to reduce piglet competition for access to teats. There are a number of possible approaches to carrying out cross-fostering, however, not all of these have been studied for effects on piglet preweaning growth and survival. In addition, many cross-fostering studies have been of limited utility for the development of practical protocols. Most did not have the statistical power to detect practically important differences in

preweaning mortality (Milligan et al., 2001; Huting et al., 2017) and/or confounded important factors such as piglet birth weight and litter size with the cross-fostering process. Arguably the biggest limitation is that most previous research was carried out with litter sizes that are, by current production standards, relatively small (typically ≤ 12 piglets per litter; e.g., English and Bilkei, 2004; Huting et al., 2017).

It has been established in a number of studies that low birth weight piglets have greater preweaning growth and survival when reared with piglets of similar weight rather than with heavier littermates (e.g., Deen and Bilkei, 2004; English and Bilkei, 2004; Huting et al., 2017; Vande Pol et al., 2021). However, such an approach would also result in the heavier birth weight piglets being reared in litters with relatively heavy littermates. The impact of reducing within-litter variation in birth weight for light piglets on the preweaning growth and survival of piglets of all birth weights in the population has not been established.

Huting et al. (2017) and Vande Pol et al. (2021) did find that approaches to cross-fostering piglets that reduced the weight of littermates improved the preweaning growth and survival of piglets of all birth weights. This suggests that reducing the within-litter variation in piglet birth weight after cross-fostering would be beneficial for light piglets, but detrimental for heavier piglets. However, the study of Huting et al. (2017) did not include piglets of all birth weights. In addition, in that study and the one of Vande Pol et al. (2021) the cross-fostering treatments evaluated only a limited number of combinations of piglet birth weights that were not representative of the distribution in birth weight typically observed in commercial populations (Feldpausch et al., 2019). The objective of this pilot study was to evaluate the effects on piglet preweaning growth and mortality of rearing piglets in cross-fostered litters with a range of within-litter birth weight variations likely to be applicable in practice, using litter sizes typical of current commercial production.

MATERIALS AND METHODS

This study was carried out on a commercial sow facility of The Maschhoffs, LLC, located near Beardstown, IL, USA. Protocols for the study were approved by the University of Illinois Institute of Animal Care and Use Committee prior to the start of the research.

Animals, Facilities, and Management

A total of 282 sows/litters were used; sows were from 23 commercial crossbred lines and had been mated to commercial sire lines. Housing and management of sows and piglets were in line with commercial procedures and practices. The facilities used consisted of rooms with 48 individual farrowing crates and pens. Farrowing pen dimensions were 1.52 m wide \times 2.07 m long (total pen floor space of 3.15 m²), and pens had solid side walls and woven metal flooring. A farrowing crate was located in the center of each pen, with dimensions of 0.55 m wide \times 1.95 m long (floor space within the crate of 1.07 m²). The thermostat in each of the farrowing rooms was set at 22.4 °C on the day of farrowing and was incrementally reduced to 18.0 °C by weaning. Room temperature was maintained using heaters, evaporative cooling cells, and fan ventilation as needed. Sows were moved into the farrowing facilities on d 112 of gestation. All sows within a farrowing room had been inseminated on the same day and were induced on d 114 of gestation to farrow on d 115 using 2 cc of prostaglandin F2 α (given at 0600 h; Lutalyse, Pfizer Animal Health USA). During gestation and lactation, sows were fed diets formulated to meet or exceed the nutritional requirements proposed by the [National Research Council \(2012\)](#). From entry into the farrowing facilities up until farrowing, sows were fed approximately 1 kg of feed twice each day (at 0600 h and 1400 h). Subsequently, sows had ad libitum access to feed throughout lactation via a sow-operated feed dispenser attached to the feed trough. Sows and piglets had ad libitum access to water via nipple-type drinkers located in the sow feeding trough and farrowing pen, respectively. Standard piglet processing tasks (e.g., tail docking, physical castration of males, and iron and antibiotic injections) were carried out at 5 d after birth. All sows and litters within a room that were allotted to the study had farrowed on the same day, and were taken off-test at the same time, when piglets reached either 19 or 20 d of age.

Preallotment Data Collection

Sow parity, genetic line, body condition score, and the number of teats and teat functionality score were determined on all sows 2 d prior to treatment allotment. Body condition score was based on a 5-point scale (1 = extremely thin to 5 = extremely fat); teat functionality score used a 3-point scale (1 = ideal, elongated and pointed with no visible defects; 2 = not ideal, not as elongated, but with no visible defects; 3 = nonfunctional, the teat was severely damaged or visibly defective). On the day after farrowing, piglets were individually weighed and each piglet was given a uniquely numbered ear tag for identification. Piglets weighing <0.50 kg and those considered by the investigators to be nonviable were not used in the study.

Experimental Design and Treatments

The study used a randomized complete block design; sow blocking factors were a farrowing date, parity (± 1 ; no first parity gilts were used), body condition score (± 1), and a number of functional teats (± 1 ; scores 1 and 2). Sow genetic line was balanced across treatments. Litters of 14 piglets after cross-fostering were used in an incomplete factorial arrangement to compare the following two treatments: 1) birth weight category (BWC): light (<1.0 kg), medium (1.0 to 1.5 kg), or heavy (1.5 to 2.0 kg); 2) litter composition: uniform: all piglets in the litter of the same BWC [uniform light (14 light piglets); uniform medium (14 medium piglets); uniform heavy (14 heavy piglets)]; mixed: piglets in the litter of two or more BWC [L+M (seven light and seven medium piglets); M+H (seven medium and seven heavy piglets); L+M+H (three light, six medium, and five heavy piglets)]. The factorial arrangement was considered incomplete as not all possible combinations of BWC within litter composition treatments were evaluated.

The maximum weight for the light BWC (i.e., 1.0 kg) represented the birth weight below which preweaning mortality increases substantially ([Zotti et al., 2017](#)). The minimum weight for the Heavy BWC (i.e., 1.5 kg) represented the weight above which preweaning mortality is generally unaffected by birth weight ([Zotti et al., 2017](#)). The number of piglets from each BWC for the L+M+H treatment was similar to the birth weight distribution of the population of piglets (i.e., approximately 15% light, 45% medium, and 40% heavy).

Treatment Allocation Process

Treatment allocations were carried out within a farrowing room on the day after farrowing, immediately after the piglets had been weighed. The treatment allocation process was carried out in two stages; firstly, piglets were allotted to litter composition treatments to form litters of 14 and, secondly, sows were allotted to litters. All piglets were cross-fostered, each litter contained no more than three littermates, and all litters within a block had equal numbers of piglets of each gender (± 1), and similar mean birth weight within BWC and gender (± 0.05 kg). This was accomplished by randomly allocating piglets to litter composition treatments from within each BWC and gender. Piglets were moved between litters as necessary to meet the piglet treatment allocation restrictions described above. After the piglets were allotted, six sows were selected on the basis of the sow blocking factors previously described and randomly allocated to the six litters.

Procedures and Measurements

Piglets were weighed at 24 h after birth and at the end of the test period [weaning weight (WW); 18.7 ± 0.64 d], and average daily gain (ADG) was calculated. Weigh scales used for measurement of piglet birth and weaning weights were validated prior to each time of use with standard check weights that approximated to the expected weights (i.e., 1.00 and 5.00 kg, respectively). Litters were checked daily, and all piglets were assigned a vitality score using a four-point scale (1 = emaciated; piglet was weak, lethargic, and not able to suckle; 2 = very thin; piglet was lethargic, but still able to suckle; 3 = thin; piglet was not lethargic and was able to suckle; 4 = ideal; piglet had normal body fat cover, was not lethargic, and was able to suckle). Piglets with a vitality score of 1 were euthanized; those with a score of 2 were removed from the litter, placed on a nontest sow, and recorded as mortality due to starvation; those with a score of 3 were treated with antibiotics according to farm protocol but remained on-test; those with a score of 4 were not treated and remained on-test. All piglets removed during the study period due to low vitality score or death were considered as preweaning mortality (PWM). For piglets removed from the study due to PWM, the date, tag number, vitality score, weight, and cause of PWM were recorded. The number of live and dead pigs in each litter were recorded daily and reconciled with the previous daily

record of piglet numbers to ensure the validity of all mortality data. Necropsies were performed on all piglets that died during the study period to determine the cause of death and to measure full and empty stomach weights to calculate the weight of stomach contents. Necropsies were carried out by the principal investigator who was trained and experienced in necropsy procedures to ascertain the cause of piglet death.

Statistical Analysis

All data were analyzed using SAS v. 9.4 (SAS Inst. Inc., Cary, NC). This study utilized a randomized complete block design with 47 blocks/replicates, each consisting of six litters, one of each litter composition treatment; the experimental unit was the individual piglet. The PROC UNIVARIATE procedure of SAS was used to verify normality and homogeneity of variances of the residuals. All variables that conformed to the assumptions of normality and homogeneity (directly or through the transformation of the data) were analyzed using the PROC MIXED procedure of SAS (Littell et al., 1996), all other data were analyzed using PROC GLIMMIX. Models included the fixed effects of BWC, litter composition, and interaction, and the random effects of sow within the block. Least-squares means for the effects of litter composition and BWC were separated using the PDIFF option of SAS, being considered different at $P \leq 0.05$. All P -values were adjusted using Tukey's adjustment for multiple comparisons.

Regression analyses were carried out to determine relationships between littermate weight (calculated for each individual piglet as the average weight of all other piglets in the litter) and WW and the log odds of PWM within each BWC. Weaning weight was evaluated using PROC MIXED of SAS; the log odds of PWM were evaluated using PROC GLIMMIX, with PWM considered a binary response. Models included littermate weight as a continuous independent variable, BWC as a categorical independent variable, the interaction, and the random effect of sow within the block.

For both WW and PWM, two separate analyses were carried out to estimate the regression coefficients. Firstly, regressions were estimated for the light and secondly for the medium BWC, and for both analyses, adjustments to these coefficients were determined for the other two BWC treatments. Coefficient adjustments were considered different to zero at $P \leq 0.05$, indicating differences in intercepts or slopes between BWC.

The regression equations for the log odds of PWM within each BWC were used to estimate the predicted probability of PWM for piglet littermate weights across the range utilized in the study, using the formulas:

$$\text{Odds} = e^{\hat{}} (\log \text{ odds}),$$

$$\text{Predicted probability of PWM} = \text{odds} / (1 + \text{odds})$$

RESULTS AND DISCUSSION

A summary of sow parameters for each of the litter composition treatments is presented in Table 1. There were no differences ($P > 0.05$) between litter composition treatments for any parameter, with the exception of the number of nonfunctional teats (score 3). However, treatment differences for this variable were small and would not be expected to influence piglet growth or survival. In general, the sows used in this study were typical of those in contemporary commercial production. Sow parity and BCS were within ranges reported for commercial populations (Maes et al., 2004; Vande Pol et al., 2021). The total number of teats averaged 15.0 across litter composition treatments, which is similar to the teat number reported by Kim et al. (2005) of 14.9 and 13.7 for purebred Landrace and Yorkshire gilts, respectively, and that reported by Charal (2009; 13.3) and Earnhardt (2019; 13.9) for commercial sow populations. The percentage of total teats with functionality scores of 1, 2, and 3

for the current study (across all litter composition treatments) were 84.3%, 13.8%, and 2.0%, respectively. This is in agreement with the study of Vande Pol et al. (2021), which used the same scoring scale as the current study and reported that 78.5%, 21.5%, and 2.8% of the total number of teats had scores of 1, 2, and 3, respectively. Similarly, Balzani et al. (2016) reported that for a population of cross-bred sows 82% of teats were fully functional, 16% partially functional, and 0.2% were nonfunctional.

Least-squares means for litter composition by BWC treatment interaction subclasses for piglet birth weight, WW, ADG, and PWM are presented in Table 2. With the exception of piglet birth weight, there were litter composition by BWC interactions ($P \leq 0.05$) for all of these measurements. By design, Light BWC piglets had the lowest ($P \leq 0.05$) birth weight, heavy piglets the greatest ($P \leq 0.05$), with medium piglets being intermediate to and different ($P \leq 0.05$) from the other two BWC. However, within each BWC, piglet birth weights were similar ($P > 0.05$) for the litter composition treatments (Table 2), which was expected given that the treatment allocation process was carried out to achieve this.

For light BWC piglets, WW was greater ($P \leq 0.05$) in uniform light than L+M+H litters, with those in L+M litters being intermediate and not different ($P > 0.05$) to those in the other two litter composition treatments that included light BWC piglets (Table 2). Similarly, ADG was greater ($P \leq 0.05$) for light BWC piglets in uniform light

Table 1. Summary of sow parameters by litter composition treatment

Item	Litter Composition ^{1,2}						SEM	P-value
	Uniform light	Uniform medium	Uniform heavy	L+M	M+H	L+M+H		
Number of sows	47	47	47	47	47	47	-	-
Parity ³	4.5	4.4	4.6	4.5	4.4	4.7	0.18	0.82
Body condition score ⁴	3.8	3.7	3.7	3.8	3.7	3.9	0.09	0.67
Number of teats ⁵								
Score 1	12.5	12.6	12.6	12.6	12.4	12.6	0.19	0.73
Score 2	2.2	2.0	2.0	1.9	2.2	2.4	0.17	0.39
Score 3	0.2 ^b	0.4 ^{ab}	0.3 ^{ab}	0.3 ^{ab}	0.3 ^{ab}	0.6 ^a	0.09	0.03
Functional teats (Score 1 + 2)	14.6	14.6	14.7	14.5	14.6	14.7	0.11	0.91
Total teats (score 1 + 2 + 3)	14.8	15.0	14.9	14.8	14.9	15.2	0.13	0.15

^{a,b}Means within a row with differing superscripts differ ($P \leq 0.05$).

¹Light = piglets with birth weights between 0.5 and 1.0 kg; medium = piglets with birth weights between 1.0 and 1.5 kg; heavy = piglets with birth weights between 1.5 and 2.0 kg.

²Uniform light = 14 light piglets; uniform medium = 14 medium piglets; uniform heavy = 14 heavy piglets; L+M = seven light and seven medium piglets; M+H = seven medium and seven heavy piglets; L+M+H = three light, six medium, and five heavy piglets.

³Parity = total number of litters including the one used in the study.

⁴Based on a 5-point scale (1 = extremely thin to 5 = extremely fat).

⁵Based on a 3-point scale (1 = ideal, elongated and pointed with no visible defects; 2 = not ideal, not as elongated, but with no visible defects; 3 = nonfunctional, the teat was severely damaged or visibly defective).

Table 2. Least-squares means for the interaction of birth weight category (BWC)¹ and litter composition (LC)^{2,3} treatments on piglet weights, average daily gain, and preweaning mortality

Item and LC ^{2,3} treatment	BWC ¹			SEM	P-value
	Light (L)	Medium (M)	Heavy (H)		LC × BWC
Number of piglets				–	–
Uniform ²	658	658	658	–	–
L+M ³	329	329	–	–	–
M+H ³	–	329	329	–	–
L+M+H ³	141	280	237	–	–
Piglet weight, kg					
Birth				0.007	0.99
Uniform ²	0.89 ^c	1.28 ^b	1.69 ^a	–	–
L+M ³	0.89 ^c	1.28 ^b	–	–	–
M+H ³	–	1.28 ^b	1.69 ^a	–	–
L+M+H ³	0.89 ^c	1.28 ^b	1.69 ^a	–	–
Weaning				0.413	<0.0001
Uniform ²	4.36 ^e	5.24 ^c	5.97 ^b	–	–
L+M ³	4.08 ^{ef}	5.39 ^c	–	–	–
M+H ³	–	4.96 ^d	6.08 ^{ab}	–	–
L+M+H ³	3.89 ^f	5.14 ^{cd}	6.38 ^a	–	–
Average daily gain, kg				0.2205	<0.0001
Uniform ²	0.200 ^f	0.226 ^d	0.243 ^{bc}	–	–
L+M ³	0.184 ^e	0.234 ^{cd}	–	–	–
M+H ³	–	0.212 ^{ef}	0.249 ^{ab}	–	–
L+M+H ³	0.173 ^e	0.220 ^{de}	0.265 ^a	–	–
Preweaning mortality, %				–	<0.0001
Uniform ²	22.8 ^a	12.2 ^{bc}	9.6 ^{cd}	–	–
L+M ³	26.7 ^a	7.1 ^d	–	–	–
M+H ³	–	14.6 ^b	5.8 ^d	–	–
L+M+H ³	28.4 ^a	10.0 ^{bcd}	1.7 ^e	–	–

^{a,b,c,d,e,f,g}Within measurement, means with differing superscripts differ ($P \leq 0.05$).

¹Light = piglets with birth weights between 0.5 and 1.0 kg; medium = piglets with birth weights between 1.0 and 1.5 kg; heavy = piglets with birth weights between 1.5 and 2.0 kg.

²Uniform = all piglets within a litter of the same birth weight category (uniform light = 14 light piglets; uniform medium = 14 medium piglets; uniform heavy = 14 heavy piglets).

³L+M = seven light and seven medium piglets; M+H = seven medium and seven heavy piglets; L+M+H = three light, six medium, and five heavy piglets.

than those in either L+M or L+M+H litters, which had similar ($P > 0.05$) ADG. For medium BWC piglets, WW and ADG were greater ($P \leq 0.05$) in uniform medium and L+M litters than those in M+H litters, with those in L+M+H litters being intermediate and not different ($P > 0.05$) from the other litter composition treatments that included medium BWC piglets (Table 2). In contrast, WW and ADG of Heavy BWC piglets were greater ($P \leq 0.05$) in L+M+H than uniform heavy litters, with those in M+H litters being intermediate and not different ($P > 0.05$) from the other litter composition treatments that included heavy BWC piglets.

Preweaning mortality was similar ($P > 0.05$) for light BWC piglets in the three litter composition treatments that involved this BWC (Table 2). However, PWM of medium BWC piglets was

greater ($P \leq 0.05$) in uniform medium and M+H litters than in L+M litters, with those in L+M+H litters being intermediate and not different ($P > 0.05$) from the other three litter composition treatments that involved medium BWC piglets (Table 2). Preweaning mortality of heavy BWC piglets was lower ($P \leq 0.05$) in L+M+H litters compared to those in uniform heavy and M+H litters, which were similar ($P > 0.05$) for this measurement. In general, these results suggest that, in terms of preweaning growth and mortality, rearing piglets in litters of uniform compared to mixed birth weights was positive for light piglets and negative for heavy piglets. The outcome for medium piglets was more variable, depending on the weight of the other piglets within the litter.

In any finite population of piglets, the average birth weight is fixed, and, by definition,

cross-fostering to reduce the weight of littermates for one BWC of piglets must result in an increase in littermate weight for piglets of other BWC. On this basis, decisions on the optimum cross-fostering procedure for any situation can only be made by considering the birth weight distribution of the population in question. In the population of piglets used in this study, light piglets accounted for approximately 15% of the population, whereas medium and heavy piglets accounted for approximately 45% and 40% of the population, respectively. This distribution in birth weights is similar to distributions found in other commercial populations of piglets (e.g., [Feldpausch et al., 2019](#)). Combining the PWM results ([Table 2](#)) with the distribution of birth weights from the current study suggests that a cross-fostering strategy that reduced the average birth weight of littermates for heavy piglets would produce a greater total number of piglets weaned than one that minimized littermate weight for light piglets. For example, comparing two approaches of cross-fostering in this population involving rearing piglets in litters either of uniform birth weight (i.e., in uniform light, uniform medium, and uniform heavy litters) or of mixed birth weight (i.e., in all L+M+H litters) would result in overall PWM levels for the whole population of 12.8% and 9.4%, respectively. For this calculation, three steps were used: 1) the percentage PWM for each of the BWC within the two approaches was determined from [Table 2](#); 2) these percentages were multiplied by the percentage of the population represented by that BWC; 3) the resulting percentages were summed across the three BWC to estimate the overall PWM for each approach. The approach based on the L+M+H treatment would also result in a greater number of heavy birth weight piglets surviving to weaning compared to that based on the three uniform treatments. As heavier birth weight piglets have been shown to have greater postweaning growth and survival than lighter littermates ([Fix et al., 2010a,b](#)), such an approach would also be potentially beneficial for postweaning performance.

There has been limited research evaluating the effect of within-litter variation in birth weight on piglet preweaning growth and survival. Several studies that reported retrospective analyses of production records suggested detrimental effects of increased within-litter variation in piglet weight at birth on both WW ([Zindove, 2011](#)) and PWM ([Roehle and Kalm, 2000](#); [Milligan et al., 2002a,b](#); [Zindove, 2011](#)). However, a number of confounding factors, such as litter size and average piglet birth weight within litters, may have contributed to

these differences rather than effects of within-litter weight variation per se ([Wolf et al., 2008](#)). Of the studies that have used controlled cross-fostering treatments, results on the effects of within-litter variation in birth weight have been variable. In contrast to the current study, [Bierhals et al. \(2012\)](#) and [Milligan et al. \(2001\)](#) found no effect of either piglet birth weight or within-litter birth weight variation on preweaning growth or survival. However, these studies may not have had sufficient replication to detect important differences, particularly in PWM. In addition, [Bierhals et al. \(2012\)](#) did not include piglets with medium birth weights (i.e., between 1.0 and 1.6 kg), and the study of [Milligan et al. \(2001\)](#) confounded within-litter weight variation with mean piglet birth weight. Some studies that evaluated the effect of within-litter birth weight variation focused only on light birth weight piglets ([Deen and Bilkei, 2004](#); [English and Bilkei, 2004](#); [Douglas et al., 2014](#)). Similar to the current experiment, these studies generally found that light birth weight piglets had greater PWM and lower WW when reared with heavier littermates. However, these studies used relatively small litter sizes and did not evaluate effects on heavier piglets and, consequently, the general utility of these results is limited.

Two studies that evaluated the effects of within-litter variation in birth weight for heavier piglets also found similar results to those of the current experiment. [Huting et al. \(2017\)](#) reared piglets in litters of uniform [12 light (≤ 1.25 kg) or 12 heavy piglets (1.5 to 2.0 kg)] or mixed (six light and six heavy piglets) birth weight. [Vande Pol et al. \(2021\)](#) used the same BWC as in the current study, and compared litters of uniform (15 light, medium, or heavy piglets) or mixed (five light, five medium, and five heavy piglets) birth weights. For both of these studies, light piglets had lower PWM in uniform than in mixed weight litters, whereas the opposite was the case for heavy piglets. However, the study of [Huting et al. \(2017\)](#) used relatively small litter sizes (12 piglets) and, also, did not include piglets with birth weights between 1.25 and 1.5 kg. Interestingly, [Vande Pol et al. \(2021\)](#) found that the growth and mortality of medium weight piglets were similar in uniform and mixed birth weight litters. This appears to differ from the results of the current study, which showed that PWM was greater for medium weight piglets reared in uniform than in mixed litters with light piglets. However, the mixed weight litters used in the study of [Vande Pol et al. \(2021\)](#) included piglets of all birth weights (light, medium, and heavy) and were,

Table 3. Least-squares means for birth weight category¹ and litter composition² treatments on the causes and timing of piglet mortality, and the stomach content of piglets that died during the study period

Item	Birth weight category (BWC) ¹			Litter composition (LC) ²						P-value ³	
	L	M	H	Uniform light	Uniform medium	Uniform heavy	L+M	M+H	L+M+H	BWC	LC
Number of piglets											
Allotted	1128	1596	1224	658	658	658	658	658	658	–	–
Mortalities	283	183	86	150	80	63	120	67	72	–	–
Cause of mortality, % of total mortalities within treatment											
Crushed	74.2	79.2	86	79.3	77.5	85.7	70.8	86.6	70.8	0.06	0.06
Starvation	20.1 ^a	14.8 ^a	5.8 ^b	17.3	13.8	6.3	20.8	10.4	22.2	0.01	0.08
Other	5.3	5.5	5.8	3.3	8.8	7.9	6.7	1.5	5.6	0.98	0.36
Time of mortality, % of total mortalities within treatment											
1 to 2 d	18.0 ^a	8.7 ^b	24.4 ^a	18.7	8.8	23.8	15	17.9	11.1	0.003	0.17
1 to 7 d	76.8	70	75.6	78	73.8	77.8	71.6	76.1	70.8	0.26	0.60
8 d to weaning	23.2	29.9	24.4	22	26.3	22.2	28.3	23.8	29.2	0.23	0.75
Age at death, d ⁴	5.1 ^b	6.1 ^a	5.1 ^b	4.7	5.7	5.1	6.2	5.6	5.5	0.05	0.54
Stomach content, g ⁵	13.7 ^b	25.4 ^a	29.1 ^a	14.2 ^b	28.1 ^a	32.1 ^a	18.1 ^b	19.4 ^{ab}	16.2 ^b	0.001	0.01

^{a,b}Means with differing superscripts differ at $P \leq 0.05$.

¹L = light: piglets with birth weights between 0.5 and 1.0 kg; M = medium: piglets with birth weights between 1.0 and 1.5 kg; H = heavy: piglets with birth weights between 1.5 and 2.0 kg.

²Uniform light = 14 light piglets; uniform medium = 14 medium piglets; uniform heavy = 14 heavy piglets; L+M = seven light and seven medium piglets; M+H = seven medium and seven heavy piglets; L+M+H = three light, six medium, and five heavy piglets.

³All LC by BWC interaction P -values were >0.05 .

⁴Data were transformed prior to analysis using an inverse square root to correct for normality and homogeneity of variance of the residuals.

⁵For piglets that died during the study period. Data were transformed prior to analysis using a natural log to correct for normality and homogeneity of variance of the residuals.

therefore, more equivalent to the L+M+H treatment in the current study, which had similar PWM levels for medium piglets as those on the uniform medium treatment (Table 2).

Least-squares means for the effect of litter composition and BWC treatments on the causes and timing of piglet mortality, age of piglets at death, and the weight of the stomach content of mortalities are presented in Table 3. There was no effect ($P > 0.05$) of litter composition treatment on the causes or timing of piglet mortality, and no interaction ($P > 0.05$) between litter composition and BWC treatments. In agreement with most other studies (Dyck and Swierstra, 1987; Marchant et al., 2000; Vande Pol et al., 2021), crushing and starvation were the primary causes of piglet mortality, accounting for 94.3%, 94.0%, and 91.8% of total mortality for light, medium, and heavy piglets, respectively. However, it should be emphasized that in the present study mortality included piglets that were removed due to low vitality score, as it was considered that these piglets would have died without intervention. Piglets removed from the study due to a low vitality (score 1) accounted for 15.2% of total PWM, and there were no differences ($P > 0.05$) between BWC or litter composition treatments for this percentage (data not reported). In addition, it

should be noted that mortality within the first 24 h after birth was not included, as this occurred before the start of the study period.

The percentage of mortality due to starvation was lower ($P \leq 0.05$) for heavy than light and medium piglets, which were similar ($P > 0.05$) for this measurement. There was a trend ($P = 0.06$) for the percentage mortality due to crushing to be lower for the Light than the heavy treatment with the medium treatment being intermediate (Table 3). These results are at variance with those from the study of Vande Pol et al. (2021) which used the same BWC as the current study and found that heavy piglets had lower mortality from crushing than medium piglets and tended to have greater mortality from starvation than light or medium piglets. It is not apparent why the results of these relatively similar studies differed for the effect of piglet birth weight on the causes of mortality. However, the current study and that of Vande Pol et al. (2021) were not specifically designed to determine differences between treatments for the causes and timing of PWM.

The results from the current study for the timing of PWM are presented in Table 3. The majority of piglet mortality (between 70.0% and 76.8% of total PWM, depending on BWC) occurred within the first 7 d of the study period, which is in agreement with

most previous research (Dyck and Swierstra, 1987; Su et al., 2007; KilBride et al., 2012). There was no effect ($P > 0.05$) of litter composition treatment on the timing of piglet mortality; however, a greater ($P \leq 0.05$) percentage of light and heavy than medium piglets died within the first day of the study period (24 to 48 h after birth). There was no difference ($P > 0.05$) between BWC treatments for the percentage of total mortality occurring in any of the other time periods (Table 3). Age at death was greater ($P \leq 0.05$) for medium compared to light or heavy piglets, although treatment differences were relatively small (1 d; Table 3). There is limited published information on the relationship between birth weight and timing of piglet mortality; however, the results of the current study are generally in disagreement with others. Le Dividich et al. (2017) found that the average age at death was lower for piglets with birth weights less than one SD below the mean than heavier piglets (1.8 and 6.9 d, respectively). Vande Pol et al. (2021) also found that light birth weight piglets had a lower age at death than heavy piglets, with Medium piglets being intermediate (5.6, 9.6, and 7.2 d, respectively).

There was an effect ($P \leq 0.05$) of both BWC and litter composition on the weight of stomach content of mortalities, which was greater ($P \leq 0.05$) for medium and heavy compared to light BWC piglets (Table 3). In addition, the uniform medium and uniform heavy had greater ($P \leq 0.05$) weight of stomach content than the uniform light, L+M, and L+M+H treatments, with the M+H being intermediate and not different to the other litter composition treatments ($P > 0.05$). This difference between litter composition treatments for the weight of stomach content is most likely a reflection of the differences in piglet birth weight between treatments and the greater percentage of deaths due to starvation for light piglets. Previous research has shown that piglets dying of starvation are more likely to have empty stomachs (Hales et al., 2013). Vande Pol et al. (2021), using the same BWC as the current study, also found that light piglets had lower weights of stomach content compared to medium but not heavy piglets. However, in that study there was also a tendency for a greater percentage of mortality for heavy piglets to be due to starvation than for medium or light piglets. The relationships between piglet birth weight and the causes and timing of piglet mortality and the weight of stomach content of piglets that die are complex and merit further study.

Comparison of treatment means within each BWC (Table 2) suggested an unfavorable relationship between the weight of littermates and piglet

performance, with increases in littermate weight generally being accompanied by increases in PWM and reductions in WW. For example, for heavy BWC piglets, as littermate birth weight increased across the L+M+H, M+H, and uniform heavy treatments (mean littermate birth weights of 1.32, 1.47, and 1.69 kg, respectively), PWM increased (1.7%, 5.8%, and 9.6%, respectively) and WW decreased (6.56, 6.26, and 6.14 kg, respectively; Table 2). Relatively similar changes in these measurements were observed for the treatments involving light and medium BWC piglets (Table 2). On this basis, regression analyses were conducted to evaluate the relationship between average littermate weight and piglet WW and PWM within each BWC.

The results of the regression analysis for piglet WW (using light BWC piglets as the basis) are presented in Table 4 and illustrated in Figure 1. The regression of WW on littermate weight was linear. The intercept and slope for the light BWC were significantly different to zero ($P \leq 0.05$). Intercepts differed ($P \leq 0.05$) between BWC, being lower for light than for heavy piglets (Table 4), with medium piglets being intermediate to and different ($P \leq 0.05$) from the other two BWC. However, slopes were similar ($P > 0.05$) for the three BWC (Table 4). These results indicate a relatively large unfavorable effect of increasing littermate weight on WW for all BWC. However, the rate of decrease in WW with increasing littermate weight was similar for the three BWC, suggesting that cross-fostering to modify within-litter birth weight variation will have a limited impact on the average WW for the entire population of piglets.

Table 4. Regression of piglet weaning weight on average littermate weight¹, within birth weight category² treatment

Item	Coefficient	SE	P-value
Intercept for light	5.54	0.336	<0.0001
Intercept adjustment for medium	1.61	0.457	0.0004
Intercept adjustment for heavy	2.87	0.660	<0.0001
Linear coefficient for light	-1.11	0.305	0.0003
Linear coefficient adjustment for medium	-0.25	0.387	0.51
Linear coefficient adjustment for heavy	-0.31	0.498	0.54

¹The average birth weight of all other piglets within the litter for each piglet.

²Light = piglets with birth weights between 0.5 and 1.0 kg; medium = piglets with birth weights between 1.0 and 1.5 kg; heavy = piglets with birth weights between 1.5 and 2.0 kg.

The results of the regression analysis for log odds of PWM (using light piglets as the basis) are presented in Table 5. The regression of the log odds of PWM on littermate weight was linear. The intercept and slope of the log odds of PWM for the light BWC were different to zero ($P \leq 0.05$). The intercept for light piglets was greater ($P \leq 0.05$) than for heavy piglets, with that of medium piglets being intermediate to and different ($P \leq 0.05$) from the other two BWC. The slope of the log odds for PWM was greater ($P > 0.05$) for light than for heavy piglets, with medium piglets being intermediate and similar ($P > 0.05$) to the other two BWC (Table 5). The predicted probabilities of PWM for each BWC estimated using these regression equations are illustrated in Figure 2. Based on the litter composition treatments used in this study, the range in littermate weight for light, medium, and heavy BWC treatments was approximately 0.7, 0.5, and 0.5 kg, respectively. Reductions in littermate weight across

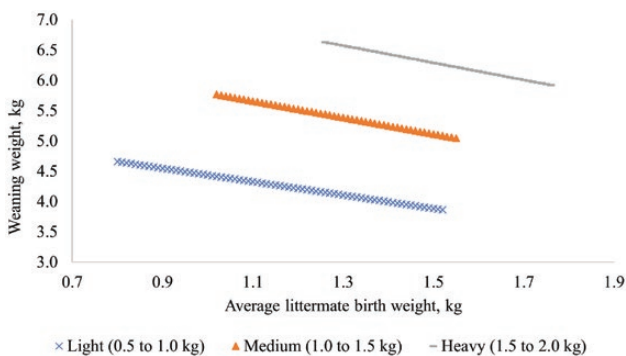


Figure 1. Effect of average littermate birth weight¹ on predicted weaning weight, within Birth Weight Category treatment².

¹The average birth weight of all other piglets within the litter for each piglet.

²Light = piglets with birth weights between 0.5 and 1.0 kg; medium = piglets with birth weights between 1.0 and 1.5 kg; heavy = piglets with birth weights between 1.5 and 2.0 kg.

Table 5. Regression of the log odds of piglet pre-weaning mortality on average littermate weight¹, within birth weight category² treatment

Item	Coefficient	SE	P-value
Intercept for light	-2.26	0.495	<0.0001
Intercept adjustment for medium	-2.22	0.981	0.02
Intercept adjustment for heavy	-5.92	1.634	0.0003
Linear slope for light	1.09	0.464	0.02
Linear slope adjustment for medium	0.71	0.792	0.37
Linear slope adjustment for heavy	2.42	1.080	0.03

¹The average birth weight of all other piglets within the litter for each piglet.

²Light = piglets with birth weights between 0.5 and 1.0 kg; medium = piglets with birth weights between 1.0 and 1.5 kg; heavy = piglets with birth weights between 1.5 and 2.0 kg.

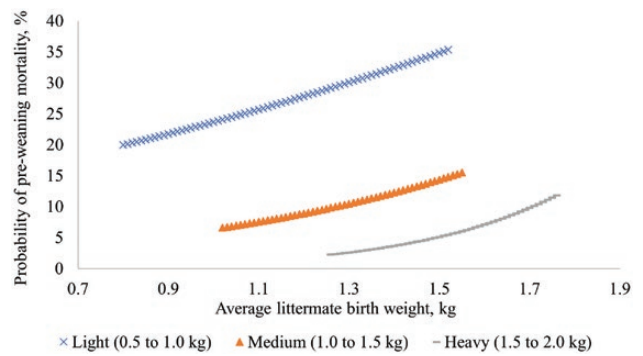


Figure 2. Effect of average littermate birth weight¹ on predicted probability of preweaning mortality, within birth weight category treatment².

¹The average birth weight of all other piglets within the litter for each piglet.

²Light = piglets with birth weights between 0.5 and 1.0 kg; medium = piglets with birth weights between 1.0 and 1.5 kg; heavy = piglets with birth weights between 1.5 and 2.0 kg.

these ranges were associated with decreases in the probability of PWM of approximately 15, 9, and 10 percentage units, respectively. These regression relationships can be used to calculate piglet WW and PWM for litters with differing average littermate birth weight after cross-fostering within the range evaluated for each BWC.

In conclusion, the results of this study suggest that increases in the average weight of littermates after cross-fostering was unfavorably associated with both PWM and WW for piglets of all birth weights. This suggests that optimal cross-fostering strategies to maximize the number of piglets weaned from a population should be based on the birth weight distribution of the population in question, as littermate weight cannot be reduced for all piglets.

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