Effect of rearing cross-fostered piglets in litters of either uniform or mixed birth weights on preweaning growth and mortality

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ABSTRACT: Cross-fostering is a practice commonly used in the swine industry to equalize litter sizes, however, there is limited understanding of the optimum cross-fostering methods that will maximize piglet preweaning growth and survival. This study evaluated the effects of within-litter variation in birth weight after cross-fostering on piglet preweaning mortality (PWM) and weaning weight (WW) using litters of 15 piglets. A hierarchical incomplete block design was used (blocking factors: day of farrowing and sow parity, body condition score, and number of functional teats) with a 3 × 2 factorial arrangement of 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 15 piglets in each litter of the same BWC), or MIXED (five piglets in each litter from each BWC, i.e., five Light, five Medium, and five Heavy piglets). At 24 h after birth, piglets were weighed and randomly allotted to litter composition treatments from within BWC. The experimental unit was five piglets of the same BWC; there were three experimental units within each Litter Composition treatment litter. There were 17 blocks, each of six litters (one UNIFORM litter of each BWC; three MIXED litters) and 51 replicates (three replicates per block of six litters) for a total of 102 cross-fostered litters and 1,530 piglets. Piglets were weaned at 19.7 ± 0.46 d of age; WW and PWM were measured. PROC GLIMMIX and MIXED of SAS were used to analyze PWM and WW, respectively. Models included BWC, Litter Composition, the interaction, and replicate within the block. There were BWC by Litter Composition treatment interactions ($P \le 0.05$) for PWM and WW. Preweaning mortality was greater ($P \le 0.05$) for Light piglets in MIXED than UNIFORM litters. In contrast, for Heavy piglets, PWM was greater ($P \le 0.05$) and WW was lower ($P \le 0.05$) in UNIFORM than MIXED litters. Medium piglets had similar ($P > 0.05$) PWM and WW in UNIFORM and MIXED litters. The results of this study, which involved large litter sizes typical of current commercial production, suggested that for piglet survival to weaning, using cross-fostering to form litters of piglets of similar birth weight was beneficial for light piglets, detrimental for heavy piglets, and neutral for medium piglets.

Key words: cross-fostering, litter composition, pig, preweaning mortality, weaning weight

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INTRODUCTION

Preweaning mortality levels on commercial sow farms have increased over recent years and currently average around 12% to 15% of piglets born alive (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). This represents a major economic loss to producers and is also a significant welfare concern. This increase in preweaning mortality has been associated with the increase in litter sizes that have occurred over the same time period (PigChamp, 2004, 2019). Currently, in commercial production, the total number of piglets born typically averages between 14 and 17 per litter (SEGES, 2017; PigChamp, 2019). Larger litters have lower average piglet birth weight and an increased number of low birth weight piglets (Quiniou et al., 2002). It has been estimated that typically between 10% and 15% of piglets born are of low birth weight (i.e., weighing < 1 kg; Feldpausch et al., 2019) and that preweaning mortality levels for these piglets are extremely high, in some cases exceeding 70% (Marchant et al., 2000; Herpin et al., 2002). In addition, it is increasingly common for the number of piglets born alive per litter to exceed the number of functional teats on the sow. As a consequence, developing practical approaches to rearing this greater number of piglets is of increasing importance.

Cross-fostering of piglets has been widely used in practice to equalize litter sizes, reduce variation in piglet weight within a litter, and/or match the number of piglets to the number of functional teats on the sow. In practice, there are many potential approaches to cross-fostering, with major factors for consideration including piglet birth weight, the proportion of the litter to be cross-fostered, and the optimum litter size and within-litter variation in weight after cross-fostering. Unfortunately, published research in this area is deficient. Most published studies have evaluated a limited number of the major factors that can contribute to a practical cross-fostering protocol. Some studies have focused on light birth weight piglets, to the exclusion of heavier littermates, rendering the results of this research of limited practical application (e.g., Deen and Bilkei, 2004; English and Bilkei, 2004; Douglas et al., 2014). In theory, light piglets should be better able to compete for teat access when reared with piglets of similar (light) weight. However, as it is not possible to reduce the weight of littermates for all piglets, this approach would also result in rearing heavier birth weight piglets in litters with heavier littermates. It is not clear how this approach would affect piglet competition within the litter for these heavier piglets and, ultimately, the preweaning growth and mortality of the entire population of piglets.

In addition, most studies that evaluated the effect of within-litter variation in piglet weight were carried out on university research facilities with insufficient replication to detect practically important differences in preweaning mortality (e.g., Milligan et al., 2001; Huting et al., 2017). Other studies have involved retrospective analyses of historical commercial sow production records; by definition, such an approach results in no control over study conditions. In addition, the cross-fostering procedures utilized have often not been clearly defined (e.g., Roehe and Kalm, 2000; Zindove, 2011). Perhaps most importantly, there has been little if any research on cross-fostering carried out with the large litter sizes that are typical of current commercial production. Given this variation in study design and execution, it is not surprising that the historical cross-fostering literature is often contradictory. Therefore, there is a need for a comprehensive research-based evaluation of the major components of cross-fostering to provide objective data for the development of optimum protocols to maximize piglet preweaning growth and survival. One of the fundamental considerations for any practical cross-fostering protocol is the ideal variation in piglet birth weights within each litter. This pilot study was carried out to develop a basic understanding of the effects of piglet birth weight per se and within-litter weight variation after cross-fostering on piglet preweaning growth and mortality, using litter sizes that are typical of prolific sows.

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

This study was carried out from the day after farrowing to weaning (19.7 ± 0.46 d of piglet age), involving a total of 102 sows/litters; sows were from 15 commercial crossbred lines, 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 × 2.07 m long (total pen floor space of 3.15 m^2), 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 × 1.95 m long (floor space within the crate of 1.07 m^2). The thermostat in 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 coolers, and fan ventilation as needed. Sows were moved into the farrowing rooms on d 112 of gestation. All sows within a farrowing room had been inseminated on the same day and were induced on d 114 to farrow on d 115 of gestation using 2 cc of prostaglandin F2α (given at 0600 h; Lutalyse, Pfizer Animal Health US).

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 facility until the start of farrowing, sows were fed approximately 1 kg of feed twice each day (at 0600 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, 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 weighed individually, and each piglet was given a uniquely numbered ear tag. Piglets weighing <0.50 kg, >2.00 kg, or considered by the investigators to be nonviable were not used in the study.

Experimental Design and Treatments

The study utilized cross-fostered litters of 15 piglets in a hierarchical incomplete block design (illustrated in Figure 1) with a 3 × 2 factorial arrangement of the following 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

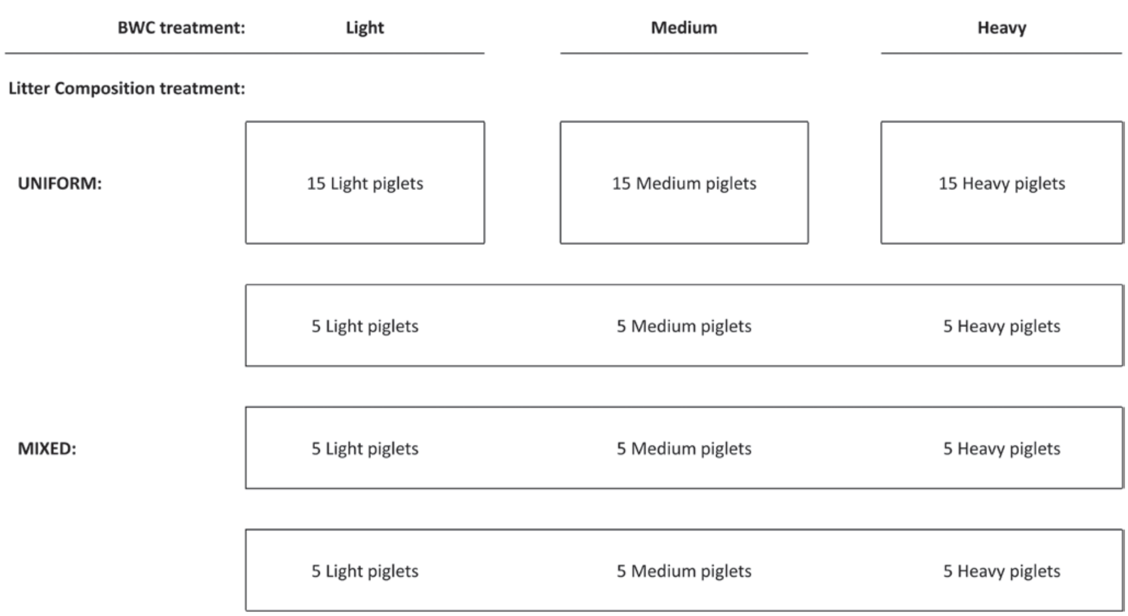

Figure 1. Diagram of the study design: 2 × 3 factorial arrangement of Litter Composition[1] and Birth Weight Category[2] treatments. Each bordered area represents one litter; the set of six litters represents one block. [1]UNIFORM = all piglets within a litter of the same Birth Weight Category (Light, Medium, or Heavy). MIXED = equal numbers of piglets with Light, Medium, and Heavy birth weights within a litter. [2]Light = piglets with birth weights <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.

Composition: UNIFORM (all 15 piglets in each litter from either Light, Medium, or Heavy BWC) or MIXED (five piglets in each litter from Light, Medium, and Heavy BWC). All piglets were cross-fostered. Sow blocking factors were a farrowing date, parity (±1; no first parity gilts were used), body condition score (±1), and number of functional teats (±1; scores 1 and 2). Sow genetic line was balanced across Litter Composition treatments. The maximum weight for the Light category (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 category (i.e., 1.5 kg) represented the weight above which preweaning mortality is generally unaffected by birth weight (Zotti et al., 2017).

Blocks consisted of six sows/litters, with one litter of each UNIFORM treatment, and three MIXED treatment litters to equalize the number of piglets within each Litter Composition and BWC treatment combination. A replicate consisted of 30 piglets, in six groups of five piglets: two groups from each BWC (Light, Medium, or Heavy), one of which was in the UNIFORM treatment, the other in the MIXED treatment; there were three replicates per block. The study used 17 blocks and 51 replicates, for a total of 102 sows/litters and 1,530 piglets.

Treatment Allocation Process

Treatment allocations were carried out 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 15 piglets, and secondly, sows were allotted to litters. Each litter within a block had no more than three littermates, equal numbers of piglets of each gender (±1), and similar mean birth weights within BWC and gender (±0.05 kg). This was accomplished using outcome groups of six piglets of the same BWC and gender; piglets were randomly allotted to Litter Composition treatments from within each outcome group. 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 allotted to these litters.

Procedures and Measurements

Piglets were weighed at the start and end of the test period (weaning weight; WW; 19.7 ± 0.46 d of piglet age), and weights were used to calculate average daily gain (ADG). Weigh scales used for measurement of piglet weights were validated prior to each use with standard check weights that approximated to the average expected piglet birth and weaning weight (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 able to suckle; 4 = ideal; piglet had adequate body fat, was not lethargic, and was able to suckle). Piglets with vitality score 1 were euthanized; those with a score of 2 were removed from the litter, placed on a nontest sow, and recorded as mortality; 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 mortalities (PWM). If a piglet was removed from the study due to PWM, the date, tag number, vitality score, weight, and cause 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 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 fully 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). The study utilized a hierarchical incomplete block design with 17 blocks (each consisting of six litters) and 51 replicates; 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 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 accounted for the fixed effects of Litter Composition, BWC, and the interaction, and the random effect of replicate 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 a Tukey's adjustment for multiple comparisons.

RESULTS AND DISCUSSION

A summary of sow characteristics for the Litter Composition treatments is presented in Table 1. There were no differences ($P > 0.05$) between Litter Composition treatments for sow parity, body condition score, or teat number. In general, the sows used in this study were typical of those found in commercial production. Average body condition scores were comparable to those reported for sows at farrowing in studies carried out in commercial herds (Esbenshade et al., 1986; Maes et al., 2004). The total number of teats (functional and nonfunctional) were similar to those reported by Kim et al. (2005) for Duroc, Landrace, and Yorkshire gilts (12.5, 14.9, and 13.7, respectively). In addition, the total number of functional teats in the current study was similar to that reported by Charal (2009; 13.3) and Earnhardt (2019; 13.9) for commercial sow populations. Balzani et al. (2016) carried out a subjective evaluation of teat functionality in a population of cross-bred sows and reported that 82% of teats were scored as fully functional, with 16% as partially functional, and 0.2% as nonfunctional. These percentages are similar to those found in the current study for teat functionality scores of 1, 2, and 3 (78.5%, 21.5%, and 2.8%, respectively).

Least-squares means for piglet birth weights across Litter Composition and BWC treatments and effects of treatments on WW, ADG, and PWM are presented in Table 2. By design, there were no differences ($P > 0.05$) between Litter Composition treatments and no Litter Composition by BWC treatment interaction ($P > 0.05$) for piglet birth weight. Birth weights differed ($P \leq 0.05$) between BWC treatments, with Heavy piglets having greater ($P \leq 0.05$) weights than Light piglets, and Medium piglets being intermediate and different ($P \leq 0.05$) to the other two BWC treatments (Table 2). These results confirm that the goals of the treatment allocations were achieved such that birth weights were similar within BWC across the Litter Composition treatments.

There were Litter Composition by BWC treatment interactions ($P \leq 0.05$) for WW, ADG, and PWM (Table 2). For Light and Medium birth weight piglets, WW and ADG were similar ($P > 0.05$) in UNIFORM and MIXED birth weight litters. However, Heavy piglets had greater WW and ADG ($P \leq 0.05$) when reared in MIXED than in UNIFORM litters (Table 2). The PWM of Light piglets was greater ($P \leq 0.05$) in MIXED than in UNIFORM litters, whereas the opposite ($P \leq 0.05$) was the case for Heavy piglets (Table 2). Medium piglets had similar ($P > 0.05$) PWM for both Litter Composition treatments.

Relatively few studies have evaluated the effect of within-litter variation in piglet birth weight on piglet preweaning growth or mortality. Two studies that carried out retrospective analyses of historical sow records reported unfavorable effects of increased within-litter variation in birth weight on both WW and PWM (Roehe and Kalm, 2000; Zindove, 2011). However, neither of these studies used cross-fostering, and, therefore, these results

Table 1. Least-squares means for the effect of Litter Composition treatment on sow characteristics

Item	Litter Composition[a]		SEM	P-value
	UNIFORM	MIXED		
Number of litters	51	51	–	–
Average sow parity[b]	4.2	4.3	0.19	0.71
Average sow body condition score[c]	3.4	3.6	0.07	0.06
Average number of teats by functionality score[d]				
Score 1	11.3	11.5	0.23	0.55
Score 2	3.1	2.9	0.25	0.58
Score 3	0.4	0.2	0.08	0.27
Functional teats (score 1 + 2)	14.4	14.4	0.10	0.99
Total teats (score 1 + 2 + 3)	14.7	14.6	0.12	0.48

[1]UNIFORM = all piglets within a litter of the same birth weight category (Light, Medium, or Heavy). MIXED = equal numbers of piglets with Light, Medium, and Heavy birth weights within a litter.

[b]Parity = total number of litters including the one used in the study.

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

[d]Based 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 Litter Composition and Birth Weight Category treatments for piglet birth and weaning weight, preweaning average daily gain, and preweaning mortality

	Birth Weight Category (BWC)*									
	Light		Medium		Heavy					
	Litter Composition (LC)†							*P*-value		
Item	UNIFORM	MIXED	UNIFORM	MIXED	UNIFORM	MIXED	SEM	LC	BWC	LC × BWC
Number of piglets	255	255	255	255	255	255	–	–	–	–
Birth weight, kg	0.86[c]	0.86[c]	1.28[b]	1.28[b]	1.69[a]	1.69[a]	0.008	0.96	<0.0001	0.95
Weaning weight, kg	4.33[c]	4.09[c]	5.29[b]	5.31[b]	5.52[b]	6.34[a]	0.095	0.004	<0.0001	<0.0001
Average daily gain, kg	0.175[c]	0.161[c]	0.203[b]	0.204[b]	0.194[b]	0.235[a]	0.0048	0.01	<0.0001	<0.0001
Preweaning mortality, %	21.7[b]	38.4[a]	12.6[c]	13.7[c]	14.1[c]	4.3[d]	–	0.44	<0.0001	<0.0001

[a,b,c,d]Values within a row with different superscripts differ significantly at $P \leq 0.05$.

*Light = Piglets with birth weights <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.

†UNIFORM = all piglets within a litter of the same birth weight category (Light, Medium, or Heavy). MIXED = equal numbers of piglets with Light, Medium, and Heavy birth weights within a litter.

are not directly comparable to those of the current study. A number of studies that used cross-fostering to create litters with differing variation in birth weight focused mainly on the growth and mortality of low birth weight piglets. Douglas et al. (2014) found that WW of light (<1.25 kg) birth weight piglets reared in litters with other light piglets was greater than for those reared with heavier (1.6 to 2.0 kg) birth weight littermates; however, PWM was not reported. English and Bilkei (2004) and Deen and Bilkei (2004) reported that rearing light (0.9 to 1.0 kg) piglets with lighter compared to heavier (>1.6 kg) littermates increased WW. In addition, light piglets had greater PWM when reared with heavier littermates in large (12 piglets), but not small (eight piglets) litters. This suggests that the impact of within-litter variation in birth weight on PWM may depend on litter size, a concept that warrants further evaluation. Nevertheless, the results of these studies and the current experiment suggest that light birth weight piglets have reduced WW and increased PWM when reared with heavier littermates compared to when reared in litters with lighter piglets.

A limited number of studies have evaluated the effect of within-litter variation in birth weight after cross-fostering on the growth or mortality of heavier piglets. Bierhals et al. (2012) found no effect on preweaning growth and mortality of rearing light (1.0 to 1.2 kg) and medium (1.4 to 1.6 kg) birth weight piglets in either uniform or mixed weight litters of 14 piglets. However, that study excluded lighter (<1.0 kg) and heavier (>1.6 kg) piglets and, therefore, the two weights categories used were more comparable to the Medium BWC in the current study, which had similar WW and PWM in UNIFORM and MIXED litters (Table 2). Milligan et al. (2001) found no effect on preweaning growth or mortality of rearing piglets in cross-fostered litters with either mixed (lightest and heaviest quartiles) or uniform (two middle quartiles) within-litter variation in birth weight. However, the approach used in that study confounded piglet birth weight with within-litter variation in weight.

Similar to the current study, Huting et al. (2017) found an interaction between piglet birth weight and within-litter variation in birth weight treatments for WW and PWM. Light piglets (≤1.25 kg) had heavier weaning weights but similar PWM in uniform compared to mixed weight litters (with heavy piglets; 1.50 to 2.00 kg), whereas heavy piglets had greater WW and lower PWM in mixed than in uniform litters. These results are generally in line with those of the current experiment; however, the study of Huting et al. (2017) did not include piglets in the middle of the birth weight distribution (between 1.25 and 1.50 kg), and, in addition, had insufficient replication to detect practically important treatment differences in piglet mortality. In general, the results of the current study and previous research discussed above suggest that cross-fostering to reduce within-litter birth weight variation is beneficial for the growth and survival of low birth weight piglets but is detrimental for heavier piglets.

An important practical consideration in relation to the optimal within-litter variation in birth weight after cross-fostering is the effect on total piglet output from the breeding herd. This question can be addressed, at least in part, using data from the current study by comparing the number of piglets weaned from litters on the two Litter Composition treatments. The number of piglets weaned for UNIFORM litters was 12.5 per litter (i.e., average number of piglets weaned for all UNIFORM Light, Medium, and Heavy treatment litters) which was similar ($P > 0.05$) to the number of piglets weaned per litter for the MIXED treatment litters (12.2 piglets; SEM 0.23). However, the average WW was greater ($P \leq 0.05$) for MIXED than UNIFORM litters (5.40 and 5.08 kg, respectively; SEM 0.070). This effect on WW was largely because the proportion of piglets at weaning from the three BWC would differ between the two Litter Composition treatments.

Although UNIFORM and MIXED treatment litters had the same number of piglets from each BWC at the start of the study, mortality levels differed within BWC for the two Litter Composition treatments (e.g., greater Heavy piglet mortality within UNIFORM than MIXED litters) resulting in the percentage piglets of each BWC at weaning differing between the Litter Composition treatments. This can be illustrated by expressing the number of piglets weaned within each of the three BWC for both the UNIFORM and MIXED treatments as a percentage of the total number of piglets weaned for each Litter Composition treatment. On this basis, the percentage of Light, Medium, and Heavy birth weight piglets at weaning for the three UNIFORM treatments combined would be 31.1%, 34.7%, and 34.1%, respectively, compared to 25.3%, 35.4%, and 39.3%, respectively, for the MIXED treatment. Given the potential impact that birth and weaning weight can have on subsequent growth (Fix et al., 2010), the results of the current study would suggest that cross-fostering to form litters of piglets with increased variation in birth weights would maximize the number of piglets weaned that have the greatest subsequent growth potential. However, it should be emphasized that the distribution of birth weights in the MIXED litters of this study (which had equal numbers of piglets of each BWC) was not typical of that commonly observed in commercial populations, which generally follows a more normal distribution (Feldpausch et al., 2019), with fewer piglets from either extreme of the weight range.

Least-squares means for the effect of Litter Composition and BWC treatments on the causes and timing of PWM, age of piglets at death, and the weight of the stomach contents of piglets that died are presented in Table 3. There was no effect of Litter Composition treatment and no interaction ($P > 0.05$) between Litter Composition and BWC treatments for any of these measurements. The percentage of piglets dying from crushing was greater ($P \leq 0.05$) for Medium piglets compared to the other two BWC treatments (Table 3). The reasons for this difference are not clear and no other studies were found that evaluated the effects of piglet birth weight or the effect of within-litter birth weight

Table 3. Least-squares means for the effects of Litter Composition and Birth Weight Category treatments on causes and timing of piglet mortality, piglet age at mortality, and the weight of stomach content of mortalities

	Litter Composition (LC)[a]		Birth Weight Category (BWC)[2]			*P*-value		
Item	UNIFORM	MIXED	Light[b]	Medium	Heavy	LC	BWC	LC × BWC
Number of mortalities	120	144	150	67	47	–	–	–
Causes of mortality, % of total								
Crushing	61.7	56.3	52.7[b]	74.6[a]	55.3[b]	0.72	0.02	0.27
Starvation	30.8	34.0	32.7	23.9	44.7	0.94	0.09	0.24
Other	7.5	9.7	14.6[a]	1.5[b]	0.0[b]	0.22	0.02	0.99
Timing of mortality, % of total								
Day 1 to 2[c]	15.0	19.4	20.7[a]	17.9[a]	6.4[b]	0.96	0.01	0.22
Day 1 to 7[c]	55.0	72.9	75.3[a]	59.7[b]	38.3[b]	0.23	0.01	0.61
Day 8 to weaning[c]	45.0	21.7	24.7[b]	40.3[a]	61.7[a]	0.23	0.01	0.61
Age at death, d[d]	7.2	6.1	5.6[b]	7.2[ab]	9.6[a]	0.23	<0.0001	0.56
Weight of stomach content, g[e]	20.1	16.3	13.3[b]	24.4[a]	17.0[ab]	0.21	0.0003	0.35

[a,b]Values within a treatment and row with different superscripts differ significantly at $P \leq 0.05$.

[a]UNIFORM = all piglets within a litter of the same birth weight category (Light, Medium, or Heavy). MIXED = equal numbers of piglets with Light, Medium, and Heavy birth weights within a litter.

[b]Light = piglets with birth weights <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.

[c]Days of the study period from 24 h after birth to weaning at either 19 or 20 d of age.

[d]For all piglets removed for PWM; data were transformed using a square root transformation to correct for normality and homogeneity of variance of the residuals.

[e]For piglets that died during the study period; data were transformed using a natural log transformation to correct for normality and homogeneity of variance of the residuals.

variation on the causes of PWM. Overall, crushing and starvation were the primary causes of PWM, accounting for 85.4%, 98.5%, and 100.0% of losses for Light, Medium, and Heavy piglets, respectively, which is generally in agreement with most studies (e.g., Dyck and Swierstra, 1987; Marchant et al., 2000).

The timing of PWM differed ($P \le 0.05$) between BWC treatments, with the Light and Medium BWC treatments having a greater percentage ($P \le 0.05$) of total losses within the first 24 h of the study period (24 to 48 h after birth) than the Heavy BWC. In addition, Light piglets had a greater ($P \le 0.05$) percentage of PWM in the first week of the study period but a lower ($P \le 0.05$) percentage in the subsequent period to weaning than the Medium or Heavy piglets (Table 3). As a result, the age of piglets at death was greater ($P \le 0.05$) for Heavy than Light, and intermediate but not different ($P > 0.05$) to the other BWC for Medium piglets (Table 3). Le Dividich et al. (2017) also found that low birth weight piglets (with birth weights one SD below the mean or less) had a lower average age at death than heavier piglets (1.8 and 6.9 d, respectively). Other studies have generally shown that the majority of piglet deaths occur within the first week after birth (e.g., Dyck and Swierstra, 1987; Su et al., 2007; KilBride et al., 2012). In the current study, this was the case for Light and Medium piglets, however, Heavy piglets had a greater percentage of PWM in the last 2 wk of the study period. It is difficult to compare these results with previous literature, as the current study did not include piglet mortality within the first 24 h after birth, and, also, mortality due to starvation included piglets removed for low vitality in addition to those that died for this reason. However, it was likely that piglets that were removed for low vitality would have died if they had remained on the study. No other published research has reported on the relationship between birth weight and the timing of piglet mortality.

There was an effect ($P \le 0.05$) of BWC treatment on the weight of stomach content of piglets that died during the study (Table 3), which was greater ($P \le 0.05$) for Medium than for Light piglets, with Heavy piglets being intermediate but not different ($P > 0.05$) to the other BWC treatments for this measurement. There has been limited research carried out to evaluate the relationship between piglet mortality, birth weight, and stomach content. Piglets that die of starvation are more likely to have low stomach content (Kielland et al., 2018), which was the case in the current study; piglets that died due to starvation had lower ($P \le 0.05$) weights of stomach content than those that died due to crushing (3.1 ± 6.15 and 20.1 ± 18.20 g, respectively; data not reported). Hales et al. (2013) found that piglets, which died within 24 h after birth had lower stomach content than those that died later, which suggests that the stomach content of mortalities should increase with time after birth. In support of this concept, Light piglets in the current study had numerically the lowest weights of stomach content and the lowest average age at death. On this basis, it was surprising that Heavy piglets did not have the greatest weights of stomach content of all of the BWC, as they had the highest age at death. However, there was a tendency ($P = 0.09$) for the percentage of piglet mortality due to starvation to be greater for Heavy piglets than the other two BWC (Table 3). Additional research is needed to clarify the relationship between piglet weight and the content of the stomach in relation to PWM.

In conclusion, the results of the current study, which involved litter sizes and piglet birth weights typical of prolific sows, suggested that, in terms of preweaning growth and mortality, cross-fostering to reduce birth weight variation within a litter was beneficial for light birth weight piglets, detrimental for heavyweight piglets, and had limited effect for medium weight piglets. One approach to cross-fostering that has been recommended is to rear low birth weight piglets in litters of uniform weight. This study highlights that it is important to consider the impact of such an approach on the growth and mortality of piglets of all weights within the population. Consequently, the optimum cross-fostering strategy is likely to depend on the birth weight distribution of the specific population in question. In this regard, it should be emphasized that the birth weight distribution in the MIXED treatment litters was not representative of the birth weight distribution typically found in current commercial populations. The scientific literature currently available to define best cross-fostering procedures for optimal litter growth and survival is inadequate, and further research in this area is needed.

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LITERATURE CITED

Agriculture and Horticulture Development Board. 2020. Indoor breeding herd key performance indicators. Available from https://pork.ahdb.org.uk/prices-stats/costings-herd-performance/indoor-breeding-herd.

Balzani, A., H. J. Cordell, and S. A. Edwards. 2016. Relationship of sow udder morphology with piglet suckling behavior and teat access. Theriogenology 86:1913–1920. doi:10.1016/j.theriogenology.2016.06.007

Bierhals, T., D. Magnabosco, R. R. Ribeiro, J. Perin, R. A. da Cruz, M. L. Bernardi, I. Wentz, and F. P. Bortolozzo. 2012. Influence of pig weight classification at cross-fostering on the performance of the primiparous sow and the adopted litter. Livest. Sci. 146:115–122. doi:10.1016/j.livsci.2012.02.026

Charal, J. W. 2009. Timing and causes of pre-weaning mortality, variation in birth and weaning weights and evaluation of the effect of colostrum supplementation to neo-natal piglets on pre-weaning survival. Master's Thesis. Illinois, USA: Univ. Illinois Urbana-Champaign.

Deen, M. G. H., and G. Bilkei. 2004. Cross fostering of low-birthweight piglets. Livest. Prod. Sci. 90:279–284. doi:10.1016/j.livprodsci.2004.02.012

Douglas, S. L., S. A. Edwards, and I. Kyriazakis. 2014. Management strategies to improve the performance of low birth weight pigs to weaning and their long-term consequences. J. Anim. Sci. 92:2280–2288. doi:10.2527/jas.2013-7388

Dyck, G. W., and E. E. Swierstra. 1987. Causes of piglet death from birth to weaning. Can. J. Anim. Sci. 67:543–547. doi:10.4141/cjas87-053

Earnhardt, A. L. 2019. The genetics of functional teats in swine. Master's Thesis. North Carolina, USA: N. Carolina. St. Univ. Raleigh.

English, J. G. H., and G. Bilkei. 2004. The effect of litter size and littermate weight on pre-weaning performance of low-birth-weight piglets that have been cross-fostered. Anim. Sci. 79:439–443. doi:10.1017/S1357729800090305

Esbenshade, K. L., J. H. Britt, J. D. Armstrong, V. D. Toelle, and C. M. Stanislaw. 1986. Body condition of sows across parities and relationship to reproductive performance. J. Anim. Sci. 62:1187–1193. doi:10.2527/jas1986.6251187x

Feldpausch, J. A., J. Jourquin, J. R. Bergstrom, J. L. Bargen, C. D. Bokenkroger, D. L. Davis, J. M. Gonzalez, J. L. Nelssen, C. L. Puls, W. E. Trout, et al. 2019. Birth weight threshold for identifying piglets at risk for preweaning mortality. Transl. Anim. Sci. 3:633–640. doi:10.1093/tas/txz076

Fix, J. S., J. P. Cassady, J. W. Holl, W. O. Herring, M. S. Culbertson, and M. T. See. 2010. Effect of piglet birth weight on survival and quality of commercial market swine. Livest. Sci. 132:98–106. doi:10.1016/j.livsci.2010.05.007

Hales, J., V. A. Moustsen, M. B. Nielsen, and C. F. Hansen. 2013. Individual physical characteristics of neonatal piglets affect preweaning survival of piglets born in a noncrated system. J. Anim. Sci. 91:4991–5003. doi:10.2527/jas.2012-5740

Herpin, P., M. Damon, and J. Le Dividich. 2002. Development of thermoregulation and neonatal survival in pigs. Livest. Prod. Sci. 78:25–45. doi:10.1016/S0301-6226(02)00183-5

Huting, A. M. S., K. Almond, I. Wellock, and I. Kyriazakis. 2017. What is good for small piglets might not be good for big piglets: the consequences of cross-fostering and creep feed provision on performance to slaughter. J. Anim. Sci. 95:4926–4944. doi:10.2527/jas2017.1889

Kielland, C., H. Wisløff, M. Valheim, A. K. Fauske, O. Reksen, and T. Framstad. 2018. Preweaning mortality in piglets in loose-housed herds: etiology and prevalence. Animal 12:1950–1957. doi:10.1017/S1751731117003536

Kilbride, A. L., M. Mendl, P. Statham, S. Held, M. Harris, S. Cooper, and L. E. Green. 2012. A cohort study of preweaning piglet mortality and farrowing accommodation on 112 commercial pig farms in England. Prev. Vet. Med. 104:281–291. doi:10.1016/j.prevetmed.2011.11.011

Kim, J. S., D. I. Jin, J. H. Lee, D. S. Son, S. H. Lee, Y. J. Yi, and C. S. Park. 2005. Effects of teat number on litter size in gilts. Anim. Reprod. Sci. 90:111–116. doi:10.1016/j.anireprosci.2005.01.013

Le Dividich, J., R. Charneca, and F. Thomas. 2017. Relationship between birth order, birth weight, colostrum intake, acquisition of passive immunity and pre-weaning mortality of piglets. J. Agric. Res. 15:e0603. doi:10.5424/sjar/2017152-9921

Littell, R. C., G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. SAS systems for mixed models. Cary, NC, USA: SAS Inst. Inc.

Maes, D. G. D., G. P. J. Janssens, P. Delputte, A. Lammertyn, and A. de Kruif. 2004. Backfat measurements in sows from three commercial pig herds: relationship with reproductive efficiency and correlation with visual body condition scores. Livest. Prod. Sci. 91:57–67. doi:10.1016/j.livprodsci.2004.06.015

Marchant, J. N., A. R. Rudd, M. T. Mendl, D. M. Broom, M. J. Meredith, S. Corning, and P. H. Simmins. 2000. Timing and causes of piglet mortality in alternative and conventional farrowing systems. Vet. Rec. 147:209–214. doi:10.1136/vr.147.8.209

Milligan, B. N., D. Fraser, and D. L. Kramer. 2001. Birth weight variation in the domestic pig: effects on offspring survival, weight gain and suckling behaviour. Appl. Anim. Behav. Sci. 73:179–191. doi:10.1016/s0168-1591(01)00136-8

National Research Council (NRC). 2012. Nutrient requirements of swine. 11th revised ed. Washington, DC, USA: National Academies Press.

PigChamp. 2004, 2019. Benchmarking summaries. Available from www.pigchamp.com/benchmarking. Accessed June 11, 2020.

Quiniou, N., J. Dagorn, and D. Gaudré. 2002. Variation of piglets' birth weight and consequences on subsequent performance. Livest. Prod. Sci. 78:63–70. doi:10.1016/S0301-6226(02)00181-1

Roehe, R., and E. Kalm. 2000. Estimation of genetic and environmental risk factors associated with pre-weaning mortality in piglets using generalized linear mixed models. Anim. Sci. 70:227–240. doi:10.1017/S1357729800054692

SEGES. 2017. National average productivity of Danish pig farms. Available from https://pigresearchcentre.dk/Research-results. Accessed June 11, 2020.

Su, G., M. S. Lund, and D. Sorensen. 2007. Selection for litter size at day five to improve litter size at weaning and piglet survival rate. J. Anim. Sci. 85:1385–1392. doi:10.2527/jas.2006-631

Zindove, T. J. 2011. Effects of within-litter birth weight variation of piglets on performance at three weeks of age and at weaning. Master's Thesis, Pietermaritzburg, South Africa: Univ. KwaZulu-Natal.

Zotti, E., F. A. Resmini, L. G. Schutz, N. Volz, R. P. Milani, A. M. Bridi, A. A. Alfieri, and C. A. da Silva. 2017. Impact of piglet birthweight and sow parity on mortality rates, growth performance, and carcass traits in pigs. R. Bras. de Zootech. 46:856–862. doi:53410.1590/s1806-92902017001100004