Effect of rearing cross-fostered piglets in litters of differing size relative to sow functional teat number on preweaning growth and mortality

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ABSTRACT: Litter sizes of commercial sows have increased considerably over recent decades, and often exceed the number of functional teats on the sow. The objective of this study was to evaluate the effect of litter size after cross-fostering relative to sow functional teat number on piglet preweaning growth and mortality. A total of 39 litters (561 piglets) were used in a randomized complete block design; blocking factors were farrowing day and sow parity, body condition score, and functional teat number. Three Litter Size treatments were compared (relative to sow functional teat number): Decreased (two piglets less); Control (same number of piglets); Increased (two piglets more). Piglets were randomly allotted to treatment at 24 h after birth to form litters of the appropriate size, with similar mean and CV of birth weight within block. Weaning weights (WW) were collected at 19.5 ± 0.50 d of age; preweaning mortality (PWM) was recorded. Litter sizes were between 11 and 17 piglets, depending on block and treatment. The Decreased treatment had lower ($P \leq 0.05$) PWM than the Increased (7.7% and 17.9%, respectively); the Control was intermediate (11.5%) and not different ($P > 0.05$) from the other treatments. The rate of decline in litter size from birth to weaning was greater ($P \leq 0.05$) for the Increased than the Decreased treatment (−0.16 vs. −0.05 piglets per day), with the Control (−0.09 piglets per day) being intermediate and different ($P \leq 0.05$) to the other two treatments. Litter sizes at weaning were greater ($P \leq 0.05$) for the Increased than the Decreased treatment (13.3 and 11.3, respectively); the Control treatment was intermediate (12.6) and not different ($P > 0.05$) to the other treatments. The log odds of PWM increased with the decreasing birth weight, at a similar rate ($P > 0.05$) for all Litter Size treatments. However, the intercept was greater ($P \leq 0.05$) for the Increased compared with the Decreased treatment; the Control was intermediate and different ($P > 0.05$) to the other two treatments. Mean WW tended ($P = 0.07$) to be greater for the Decreased (6.17 kg) compared to the Control and Increased treatments (5.86 and 5.84 kg, respectively). In conclusion, increasing litter size after cross-fostering relative to the number of functional teats of the sow increased piglet PWM, and tended to decrease WW.

Key words: cross-fostering, litter size, piglet, preweaning mortality, weaning weight

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INTRODUCTION

Preweaning mortality (PWM) is both a major economic loss for producers and, also, a significant concern for piglet welfare. There is evidence that PWM levels on commercial sow farms have increased over recent years (currently averaging 10% to 15% of piglets born alive) in parallel with the increases in litter size that have occurred over the same time period (PigChamp, 2004, 2019; SEGES, 2017; Agriculture and Horticulture Development Board, 2020). Currently, the number of piglets born to sows averages between 14 and 17 per litter (SEGES, 2017; PigChamp, 2019; Agriculture and Horticulture Development Board, 2020). In contrast, commercial sows generally have, on average, between 13 and 15 functional teats (Kim et al., 2005; Rothe, 2011; Vande Pol et al., 2021a, 2021b). As a result, it is increasingly common for the total number of piglets born alive within a litter to exceed the number of functional teats on the sow. This increased competition for teat access results in higher piglet mortality, particularly for those of low birth weight (Kobek-Kjeldager et al., 2020a, 2020b). Therefore, it is increasingly important to develop practical approaches to rearing this greater number of piglets.

Cross-fostering has been widely used in commercial production to reduce competition by equalizing the number of piglets across litters born at the same time. In practice, there are a number of components of cross-fostering that should be considered to maximize preweaning growth and survival, including the optimum litter size after cross-fostering. Most of the studies that reported on the effects of litter size after cross-fostering used litter sizes that were small (i.e., ≤ 12 piglets per litter) compared to current levels in commercial herds (Stewart and Diekman, 1989; Deen and Bilkei, 2004; English and Bilkei, 2004). In addition, results of these studies have been highly variable, which in part reflects large differences in study design and methodology. A number of studies used survey data collected from commercial farms (Roehe and Kalm, 2000; Zindove, 2011; KilBride et al., 2012) which also had different management protocols. Such an approach results in confounding of many of the factors of interest such as the range in piglet birth weight within litters after cross-fostering. However, these studies have generally shown that decreasing litter size early after birth reduced piglet PWM and/or increased weaning weights.

There has been limited controlled research comparing the effects of different litter sizes after cross-fostering on the preweaning performance of piglets, and even fewer that compared litter sizes after cross-fostering relative to the functional teat number of the sow. With historical cross-fostering studies using litter sizes between 6 and 12 piglets, the number of functional teats on the sows was unlikely to limit teat access for piglets or impact the study results. However, with the large litter sizes that are common today, it is critical to understand the relationship between teat number, litter size, and piglet preweaning survival and growth. Therefore, the objective of this study was to compare litter sizes after cross-fostering ranging from below to in excess of sow functional teat number for effects on piglet preweaning growth and mortality.

MATERIALS AND METHODS

This study was carried out on a commercial sow facility of The Maschhoffs, LLC, located near Beardstown, IL, USA. Protocols for this 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 (19.5 ± 0.50 d of age) using a total of 39 sows/litters. These sows were from 9 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 × 2.07 m long (total pen floor space of 3.15 m^2), and pens had solid side walls and woven metal floors. 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°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 day 112 of gestation. All sows within a farrowing room had been inseminated on the same day and were induced on day 114 to farrow on day 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 room until farrowing, sows were given 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 (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.

Pretreatment Allocation Data Collection

Sow parity, genetic line, body condition score, and number of teats and teat functionality score were determined on all sows two days prior to treatment allocation. 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 = functional and ideal, elongated and pointed with no visible defects; 2 = functional, but 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 or 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; sows within a block had the same farrowing date, similar parity (± 1; no first parity gilts were used), similar body condition score (± 1), and the same number of functional teats (total number of teats with scores 1 or 2). Sow genetic line was balanced across treatments over the entire study period; all piglets were cross-fostered. Three Litter Size treatments were compared: Decreased (two piglets less than sow functional teat number), Control (same number of piglets as sow functional teat number), and Increased (two piglets more than sow functional teat number). Sows used in the study had 13, 14, or 15 functional teats, therefore, litter sizes after cross-fostering ranged from 11 to 17 piglets, depending on block and Litter Size treatment.

Treatment Allocation Process

Treatment allocation was carried out on the day after farrowing immediately after the piglets had been weighed. The allocation process was carried out in two stages; firstly, piglets were allocated to Litter Size treatments and secondly, sows were allocated to litters. Each litter within a block had no more than three littermates, similar proportions of piglets from each gender (±1), and similar mean (±0.05 kg) and CV (±2.5%) of piglet birth weight. This was accomplished by forming outcome groups of three piglets of the same gender and similar birth weight and randomly allotting each piglet from the outcome group to one of the Litter Size treatments. This process was repeated until all litters in the block had two piglets more than the sow functional teat number. Subsequently, two and four piglets were removed from the Control and Decreased treatment litters, respectively, such that the final litters in each block met the allocation restrictions described above. After the piglets were allocated to litters, three sows were selected on the basis of the sow blocking factors previously described and randomly allocated to the three litters to form a block.

Procedures and Measurements

Piglets were weighed at 24 h after birth and at the end of the test period (day 19 or 20; weaning weight; WW), and average daily gain (ADG) was calculated. Weigh scales (Brecknell LPS-15 bench scale; Avery Weigh-Tronix; Fairmont, MN) for measurement of piglet birth and weaning weights were validated prior to each collection of weights using 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 4-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 adequate body fat, was not lethargic, and was able to suckle). Piglets with a vitality score 1 were euthanized; those with a score of 2 were removed from the litter and placed on a nontest sow; those with a score of 3 were treated with antibiotics according to farm protocol but remained on-test; those with a score 4 were not treated and remained on-test. All piglets removed during the study period due to low vitality score (score 1 or 2) or death were considered as preweaning mortality (PWM) and 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 during the study period to determine cause of death. Necropsies were carried out by the principal investigator, who was fully trained and experienced in necropsy procedure 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 13 blocks/replicates, each consisting of three sows/litters, one of each Litter Size treatment; the experimental unit was the litter. 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 after 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 effect of Litter Size treatment and the random effect of block and sow within block. Least-squares means 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.

An analysis was carried out to evaluate the effects of birth weight on subsequent performance using piglet as the experimental unit and assigning each to a Birth Weight Category (BWC): Light = 0.5 to 1.0 kg; Medium = 1.0 to 1.5 kg; Heavy = > 1.5 kg. The model used accounted for the fixed effects of Litter Size treatment, BWC, and the interaction, and the random effect of block and sow within block. Degrees of freedom were adjusted for unequal numbers of piglets from each BWC using a Kenward–Roger adjustment. In addition, regression analyses were carried out to estimate relationships for each of the Litter Size treatments between piglet birth weight and WW and PWM, and between day of the study period and the average number of piglets per litter. For the analysis for WW and the number of piglets per litter, PROC MIXED of SAS was used, and PROC GLIMMIX was used for the analysis involving PWM. The model for the number of piglets per litter included Litter Size treatment, day of study, and the interaction of day of study with Litter Size treatment. The model for WW included Litter Size treatment, linear and quadratic terms for birth weight and interactions of these terms with Litter Size treatment. The model for PWM included Litter Size treatment, birth weight, the interaction of birth weight with Litter Size treatment. All models included the random effect of block. For both WW and PWM, analyses were carried out to estimate the regression terms for the Decreased treatment, and adjustments to these coefficients were determined for the other two Litter Size treatments. Adjustments were considered different to zero at $P \leq 0.05$, indicating differences between Litter Size treatments for the respective term. The regression equations for the log odds of PWM were used to estimate the predicted probability of PWM across the range of piglet birth weights (between 0.7 and 2.3 kg) for each Litter Size treatment, using the formulas:

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

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

RESULTS AND DISCUSSION

A summary of sow parameters for each of the Litter Size treatments is presented in Table 1. The parity, body condition score, and teat number of sows were similar ($P > 0.05$) across treatments, and were comparable to those reported in studies carried out with commercial populations (Maes et al., 2004; Vande Pol et al., 2021a, 2021b). Recent studies have reported similar teat numbers to those found in the current study. For example, Kim et al. (2005) showed that the total number of teats for Landrace and Yorkshire gilts averaged 14.9 and 13.7, respectively, and Vande Pol et al. (2021a, 2021b) reported that total teat numbers of commercial sows were between 14.4 and 14.7. Using the same teat functionality scoring system as in the current study, Vande Pol et al. (2021a) reported that 78.5%, 21.5%, and 2.8% of teats had functionality scores of 1, 2, and 3, respectively, and Vande Pol et al. (2021b) reported values of 84.3%, 13.8%, and 2.0%, respectively. In the current study, these percentages were 81.8%, 14.2%, and 4.0%, respectively.

Least-squares means for the effect of Litter Size treatment on piglet numbers and weights, and PWM are presented in Table 2. There were no differences ($P > 0.05$) between Litter Size treatments for piglet birth weight, WW, or ADG (Table 2). However, there was a tendency ($P = 0.07$) for piglet WW to be greater for the Decreased compared to

Table 1. Summary of sow parameters by Litter Size treatment

	Litter Size[1]				
Item	Decreased	Control	Increased	SEM	*P*-value
Total number of sows	13	13	13	–	–
Sow parity[2]	3.9	2.7	3.0	0.51	0.22
Sow body condition score[3]	3.38	3.77	3.69	0.151	0.18
Number of teats[4]					
Score 1	12.4	12.5	12.0	0.28	0.46
Score 2	2.0	2.0	2.4	0.25	0.46
Score 3	0.8	0.5	0.5	0.19	0.61
Functional (Score 1 + 2)	14.4	14.5	14.4	0.18	0.94
Total (Score 1 + 2 + 3)	15.2	15.0	14.9	0.23	0.77

[1]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

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

[3]On a 5-point scale (1 = extremely thin, 5 = extremely fat).

[4]On a 3-point scale (1 = ideal, elongated and pointed with no visible defects; 2 = not ideal, teat less elongated, but no visible defects; 3 = nonfunctional, teat severely damaged or visibly defective).

the other two Litter Size treatments. Preweaning mortality was lower ($P \leq 0.05$) for the Decreased than the Increased treatment, with the Control treatment being intermediate and not different ($P > 0.05$) from the other treatments (Table 2).

By design, the number of piglets per litter after cross-fostering was lowest ($P \leq 0.05$) for the Decreased treatment, and greatest ($P \leq 0.05$) for the Increased treatment, with Control treatment being intermediate to and different ($P \leq 0.05$) from the other two treatments (Table 2). As expected, the number of piglets per litter decreased during lactation for all three treatments and was greater ($P \leq 0.05$) for the Increased than the Decreased treatment at all times during the study period (Table 2). Litter size for the Control treatment was intermediate to and not different ($P > 0.05$) from the other treatments at 14 d or at weaning. Increasing litter sizes by two piglets from the Decreased to the Control treatment and also from the Control to the Increased treatment resulted in increases in the number of piglets weaned by 1.3 and 0.7, respectively (Table 2). Due to the differences in litter size, total litter weight was greater ($P \leq 0.05$) at the start of the study period for the Increased compared to the Control and Decreased treatments. However, there was no difference ($P > 0.05$) between treatments for total litter weight at weaning (Table 2).

Table 2. Least-squares means for the effect of Litter Size treatment on piglet and litter weights, pre-weaning average daily gain, preweaning mortality, and the causes and timing of mortality

	Litter Size[1]				
Item	Decreased	Control	Increased	SEM	*P*-value
Number of piglets	161	187	213	–	–
Litter size					
After cross-fostering	12.1[c]	14.1[b]	16.1[a]	0.30	<0.0001
At 7 d after birth	11.8[b]	13.4[a]	14.6[a]	0.81	<0.0001
At 14 d after birth	11.7[b]	12.8[ab]	13.8[a]	0.44	0.01
At weaning	11.3[b]	12.6[ab]	13.3[a]	0.51	0.03
Litter weight, kg					
Birth	16.1[b]	19.0[b]	22.0[a]	1.41	0.0001
Weaning	69.8	73.8	78.0	10.09	0.41
Piglet weight, kg					
Birth	1.46	1.46	1.46	0.058	0.97
Weaning	6.17	5.86	5.84	0.184	0.07
Pre-weaning average daily gain, kg	0.243	0.225	0.223	0.0083	0.20
Preweaning mortality, %	7.7[b]	11.5[ab]	17.9[a]	–	0.04
Number of mortalities	14	23	40	–	–
Cause of mortality, % of total mortality within treatment					
Crushing	64.3	47.8	47.5	–	0.56
Starvation	28.6	52.2	45.0	–	0.52
Other	7.1	0.0	7.5	–	0.99
Time of mortality, % of total mortality within treatment					
Day 1 to 2	14.3	8.7	5.0	–	0.55
Day 1 to 7	50.0	52.2	55.0	–	0.94
Day 8 to weaning	50.0	47.8	45.0	–	0.94
Age at death, d[2]	8.6	7.9	8.0	1.50	0.96

[1]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

[2]Data were transformed prior to analysis using a square transformation to correct for normality and homogeneity of variance of the residuals.

[a,b,c]Means with differing superscripts differ at $P \leq 0.05$.

A number of studies have conducted retrospective analyses of commercial farrowing and lactation data which have generally also shown that increases in litter size are associated with increased PWM and decreased WW (Roehe and Kalm, 2000; Andersen et al., 2011; KilBride et al., 2012).

Increases in litter size at birth generally result in decreases in average piglet birth weight and increases in within-litter variation in birth weight (Roehe and Kalm, 2000; Andersen et al., 2011), factors that have been shown to increase PWM and decrease WW of piglets (Roehe and Kalm, 2000; Herpin et al., 2002; Mesa et al., 2006). Therefore, it is probable that the effects of litter size observed in these population studies may be partly due to effects of piglet birth weight rather than litter size *per se*. Interestingly, three studies (Sharpe, 1966; Cecchinato et al., 2008; KilBride et al., 2014) found negative effects of rearing piglets in small (4 to 8, < 6, or ≤ 7 piglets, respectively) compared to larger (9 to 11, > 6, or 8 to 11 piglets, respectively) litters on preweaning mortality, although the reasons for these results are not clear. Cecchinato et al. (2008) suggested that this effect may be due to physiological deficiencies in sows that farrow small litters. However, the litter sizes in the study of Sharpe (1966) were reported after cross-fostering, and further research is necessary to determine the biological causes of this negative effect. In the current study, both average piglet birth weight and variation in birth weight were equalized across Litter Size treatment to remove these as potential confounding factors. Most of the cross-fostering studies that have used such an approach have generally found that reducing litter size increased piglet WW and/or decreased PWM (Stewart and Diekman, 1989; Auldist et al., 1998), which is similar to the results of the current study.

Changes in litter size within the three Litter Size treatments over the study period were evaluated using regression analysis and these results are presented in Table 3 and illustrated in Figure 1. As expected, the intercepts for the regression relationships differed ($P \leq 0.05$) between Litter Size treatments, reflecting the differences created by cross-fostering at the start of the study period. In addition, litter size decreased linearly ($P \leq 0.05$) over the study period for all three treatments, however, the rate of decline was greater ($P \leq 0.05$) for the Increased than the Decreased treatment (−0.16 vs. −0.05 piglets per day), with the slope for the Control treatment (−0.09 piglets per day) being intermediate and different ($P \leq 0.05$) to those for the other two treatments (Table 3). Interestingly, for the Increased treatment, the average number of piglets per litter remained above the average number of functional teats on the sows on this treatment (14.3) up until day 9 of the study period (Figure 1). This suggests that, on average, piglets in excess of the number of teats can survive for several days after birth. This may provide options for rearing extra piglets through creating large litters in early lactation combined with other management approaches, such as subsequent cross-fostering of the extra piglets and/or complimentary rearing of large litters using liquid milk replacer (Kobek-Kjeldager et al., 2020a, 2020b). Given that in current commercial production the total number of piglets born alive is often greater than the number of teats available on the sows, further research in this area is warranted.

Table 3. Regression terms for the relationship between day of study and litter size for the three Litter Size treatments

Item[1,2]	Coefficient[3]	Adjustment[4]	SE	*P*-value[5]
Intercept, number of piglets				
Decreased	11.85	–	0.187	<0.0001
Adjustment for Control	–	1.89	0.232	<0.0001
Adjustment for Increased	–	3.70	0.232	<0.0001
Slope, number of piglets per day				
Decreased	−0.05	–	0.015	0.002
Adjustment for Control	–	−0.04	0.021	0.03
Adjustment for Increased	–	−0.11	0.021	<0.0001
Model R^2	0.55	–	–	–

[1]The regression model included Litter Size treatment, day of study, the interaction of day of study with Litter Size treatment, and the random effect of block.

[2]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

[3]Intercept or slope for the Decreased treatment.

[4]Adjustment to intercept or slope for the Control or Increased treatments.

[5]For the Decreased treatment, *P*-values indicate whether the intercept or slope are different to 0. *P*-values for the Control and Increased treatments indicate differences for intercept or slope compared to the Decreased treatment.

The effect of Litter Size treatment on the causes and timing of PWM are presented in Table 2. The average age of piglets at death was between 7.9 and 8.6 d, and did not differ ($P > 0.05$) between treatments (Table 2). Also, there was no effect ($P > 0.05$) of Litter Size treatment on the causes of PWM. The main causes of PWM were starvation and crushing, which, in combination, accounted for 92.9%, 100.0%, and 92.5% of all mortality within the Decreased, Control, and Increased treatments, respectively (Table 2). This is in agreement with previous research, which has shown that crushing and starvation are the main causes of piglet mortality (Dyck and Swierstra, 1987; Marchant et al., 2000). The study of Kobek-Kjeldager et al. (2020b) also reported the causes of piglet mortality according to litter size treatment, however, these were not

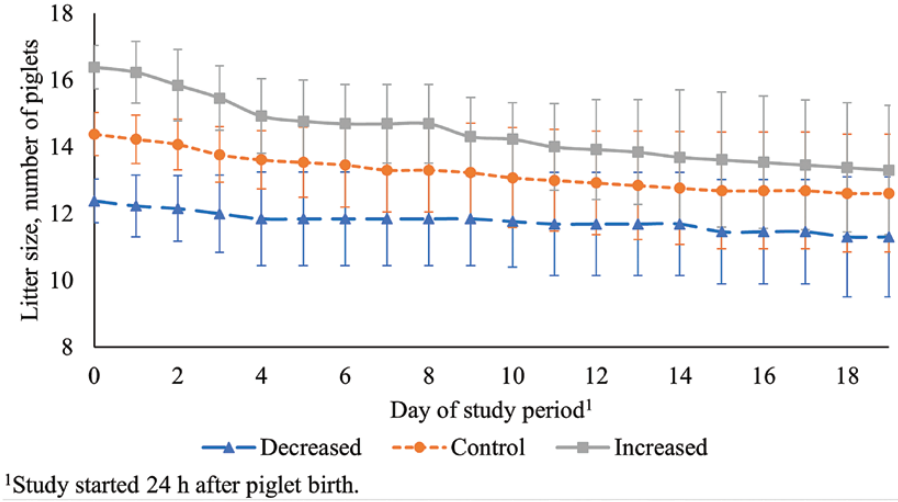

Figure 1. Mean and standard deviation of litter size by day of study within Litter Size[2] treatment. [2]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

statistically analyzed. There were no other studies found that related the causes or timing of piglet mortality with litter size after cross-fostering.

There were no interactions ($P > 0.05$) between Litter Size and BWC treatments for any measurement (data not reported), therefore, the main effects of BWC on piglet preweaning growth, PWM, and timing and causes of PWM are presented in Table 4. By definition, Light piglets had the lowest ($P \leq 0.05$) birth weights, Heavy piglets had the greatest ($P \leq 0.05$), and Medium piglets were intermediate and different ($P \leq 0.05$) to the other two BWC. Similarly, Light piglets had lower ($P \leq 0.05$) ADG and WW compared to Heavy piglets; Medium piglets were intermediate and different ($P \leq 0.05$) than the other two BWC for both parameters (Table 4). Light piglets also had greater ($P \leq 0.05$) PWM than the other two BWC, which were similar ($P > 0.05$) for this measurement. There was no effect ($P > 0.05$) of BWC on the causes and timing of piglet PWM (Table 4). The main causes of PWM were starvation and crushing, which, in combination, accounted for 100.0%, 93.5%, and 90.9% of all mortality within Light, Medium, and Heavy BWC, respectively (Table 4).

In agreement with the results of the current experiment, many studies have shown that heavier piglet birth weights are favorably associated with both WW and PWM (Roehe and Kalm, 2000; Herpin et al., 2002; Mesa et al., 2006). In the present study, there were no differences between BWC for the causes or timing of PWM, or the age of piglets at death. These results are at variance with the results of two cross-fostering studies that were carried out in the same facilities and using the same BWC as the current experiment (Vande Pol et al., 2021a, 2021b). However, the effects of birth weight on PWM in these two studies were inconsistent. Vande Pol et al. (2021a) found that age at death generally increased with birth weight and that Medium piglets had greater mortality due to crushing than

Table 4. Least-squares means for the effect of Birth Weight Category on piglet weights, average daily gain, preweaning mortality, and the causes and timing of mortality

	Birth Weight Category[1]				
Item	Light	Medium	Heavy	SEM	P-value
Number of piglets	61	238	262	–	–
Piglet weight, kg					
Birth	0.90[c]	1.27[b]	1.76[a]	0.016	<0.0001
Weaning	3.99[c]	5.38[b]	6.76[a]	0.145	<0.0001
Average daily gain, kg	0.159[c]	0.211[b]	0.258[a]	0.0073	<0.0001
Preweaning mortality, %	37.7[a]	11.8[b]	7.5[b]	–	<0.0001
Number of mortalities	24	31	22	–	–
Cause of mortality, % of total mortality within treatment					
Crushing	37.5	54.8	54.5	–	0.40
Starvation	62.5	38.7	36.4	–	0.15
Other	0.0	6.5	9.1	–	0.94
Time of mortality, % of total mortality within treatment					
Day 1 to 2	0.0	9.7	13.6	–	0.91
Day 1 to 7	66.7	51.6	40.9	–	0.23
Day 8 to weaning	33.3	48.4	59.1	–	0.23
Age at death, d[2]	7.0	8.0	9.3	1.17	0.30

[1]Light = birth weights between 0.5 and 1.0 kg; Medium = birth weights between 1.0 kg and 1.5 kg; Heavy = birth weights > 1.5 kg.

[2]Data transformed using a square transformation to correct for normality and homogeneity of variance of the residuals.

[a,b,c]Means with differing superscripts differ at $P \leq 0.05$.

the other two BWC. In contrast, Vande Pol et al. (2021b) found that age at death was greater for Medium than Light and Heavy birth weight piglets, and that mortality due to crushing was similar for the three BWC. Further research would be needed to clarify the effect of birth weight on the causes and timing of mortality.

The absence of Litter Size by BWC interactions in the current study suggests that the effects of the Litter Size treatments were similar for piglets of all birth weights. However, other studies have suggested that the effect of litter size on PWM could vary depending on the birth weight distribution in the litter. For example, PWM of low birth weight pigs was unaffected by litter size when they were reared in litters of uniform birth weight but increased with litter size when they were reared with heavier littermates (Milligan et al., 2002; Deen and Bilkei, 2004; English and Bilkei, 2004). However, these studies used relatively small litter sizes, and did not include piglets of all birth weights or relate litter size treatments to sow teat number. Only one other study has utilized such an approach. Kobek-Kjeldager et al. (2020b) compared the growth and mortality of piglets reared in litter sizes that were either equal to functional teat number (approximately 14 piglets) or in larger litters of a fixed size of 17 piglets. In that study, PWM was 13.5 percentage units lower and average piglet WW (at 28 d of age) was 1.3 kg greater for the smaller litter size treatment. The smaller litter size treatment in the study of Kobek-Kjeldager et al. (2020b) was similar to the Control treatment of the current study, and the larger litter size treatment had approximately one more piglet per litter than the Increased treatment. The difference in PWM between the Control and Increased treatments in the current study was 6.4 percentage units, which was less than the difference between litter size treatments in PWM for Kobek-Kjeldager et al. (2020b); this difference is most likely because of greater number of piglets in the larger litter size treatment of that study.

In the current study, the relationships between piglet birth weight and WW and PWM within each Litter Size treatment was further explored using regression analyses. The results for WW are presented in Table 5 and illustrated in Figure 2. The relationship with birth weight was quadratic, and the intercept, linear, and quadratic terms for the Decreased treatment were different ($P \leq 0.05$) to zero (Table 5). The intercept adjustments for the Control and Increased treatments were similar ($P > 0.05$) and both less than zero ($P \leq 0.05$), indicating that the intercepts for these treatments were lower than that of the Decreased treatment. The linear and quadratic term adjustments for the Control and Increased treatments were not different ($P > 0.05$) than zero (Table 5), indicating that the shapes of the curves were similar for the three Litter Size treatments. These results suggest that WW was greater for the Decreased than the other treatments at all birth weights, and that WW increased at a similar rate with increases in birth weight for the three treatments. However, predicted differences in WW between the Litter Size treatments across the range in birth weights were relatively small (Figure 2).

The results of the regression analysis for PWM are presented in Table 6 and illustrated in Figure 3. The area under the receiver operating characteristic curve for the model was 0.71, indicating that the model was moderately accurate for predicting PWM (Table 6). The log odds of PWM decreased linearly ($P \leq 0.05$) for the Decreased treatment across the range of piglet birth weights with both

Table 5. Regression terms for the relationship between piglet birth weight[1] and weaning weight within Litter Size treatment

Item[1,2]	Coefficient[3]	Adjustment[4]	SE	P-value[5]
Intercept, kg				
Decreased	6.33	–	0.135	<0.0001
Adjustment for Control	–	−0.35	0.134	0.01
Adjustment for Increased	–	−0.38	0.133	0.004
Linear term, kg weaning weight per kg birth weight				
Decreased	2.88	–	0.284	<0.0001
Adjustment for Control	–	−0.36	0.389	0.36
Adjustment for Increased	–	−0.45	0.385	0.24
Quadratic term, kg weaning weight per kg birth weight squared				
Decreased	−1.16	–	0.356	0.001
Adjustment for Control	–	−0.07	0.910	0.94
Adjustment for Increased	–	−0.11	0.902	0.90
Model R^2	0.39	–	–	–

[1]Using centered birth weight, with a mean of 1.46 kg. The regression model included Litter Size treatment, linear and quadratic birth weight, the interactions of birth weight with Litter Size treatment, and the random effect of block.

[2]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

[3]Intercept and slope for the Decreased treatment.

[4]Adjustment to intercept or slope for the Control or Increased treatments.

[5]For the Decreased treatment, P-values indicate whether the intercept or slope are different to 0. P-values for the Control and Increased treatments indicate differences for intercept or slope compared to the Decreased treatment.

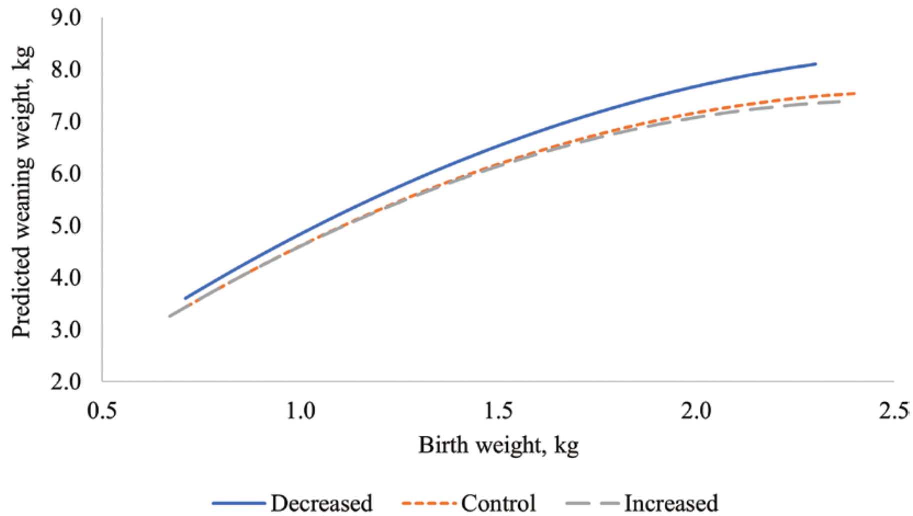

Figure 2. Regression relationships between piglet birth weight and predicted weaning weight for each Litter Size[1] treatment. [1]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

Table 6. Regression terms for the relationship between piglet birth weight and the log odds of preweaning mortality (PWM) within Litter Size treatment

Item[1,2]	Coefficient[3]	Adjustment[4]	SE	P-value[5]
Intercept, log odds PWM				
Decreased	−2.56	–	0.354	<0.0001
Adjustment for Control	–	0.32	0.418	0.45
Adjustment for Increased	–	0.90	0.377	0.02
Slope, log odds PWM per kg birth weight				
Decreased	−1.85	–	0.876	0.03
Adjustment for Control	–	-0.51	1.134	0.65
Adjustment for Increased	–	−0.38	1.035	0.71
Model AUROC[6]	0.71	–	–	–

[1]Using centered birth weight, with a mean of 1.46 kg. The regression model included Litter Size treatment, birth weight, the interaction of birth weight with Litter Size treatment, and the random effect of block.

[2]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

[3]Intercept and slope for the Decreased treatment.

[4]Adjustment to intercept or slope for the Control or Increased treatments.

[5]For the Decreased treatment, P-values indicate whether the intercept or slope are different to 0. P-values for the Control and Increased treatments indicate differences in intercept or slope compared to the Decreased treatment.

[6]AUROC = Area under the receiver operating characteristic curve, a measure of the percentage of piglet mortality outcomes correctly predicted by the model.

the intercept and linear terms for this treatment being different ($P \le 0.05$) to zero (Table 6). The intercept adjustment was greater ($P \le 0.05$) than zero for the Increased treatment but not ($P > 0.05$) for the Control treatment (Table 6). In addition, the linear term adjustments for the Control and Increased treatments were not different ($P > 0.05$) to zero. These results indicate that the intercept for the Increased treatment was greater than that of the other two treatments, however, the linear terms were similar for all three treatments (Table 6). These linear regression relationships for the log odds of PWM were used to calculate the predicted probability of PWM for each Litter Size treatment (Figure 3). As piglet birth weight decreased, the predicted probability of PWM increased for all Litter Size treatments. However, the extent of this change was greatest for the Increased, lowest for Decreased, and intermediate for the Control treatment. This is illustrated by the increase in the probability of PWM with decreasing birth weight across the range of birth weights observed in this study (i.e., from 2.3 to 0.7 kg) which was 22.0, 37.0, and 49.6 percentage units for the Decreased, Control, and Increased treatments, respectively (Figure 3).

These results suggest that the greater PWM for the Increased treatment (Table 2) was mainly due to increased mortality in lower birth weight piglets rather than in heavier littermates. For example, the predicted probability of PWM for a 1.0 kg piglet would be 15.3%, 24.3% and 34.7% for the Decreased, Control, and Increased treatments, respectively, whereas for a 2.0 kg piglet, this would be 2.8%, 2.9%, and 5.4%, respectively (Figure 3). Previous research has shown that rearing piglets in litters of mixed compared to uniform birth weight resulted in lower PWM for heavier piglets and greater PWM for lighter piglets

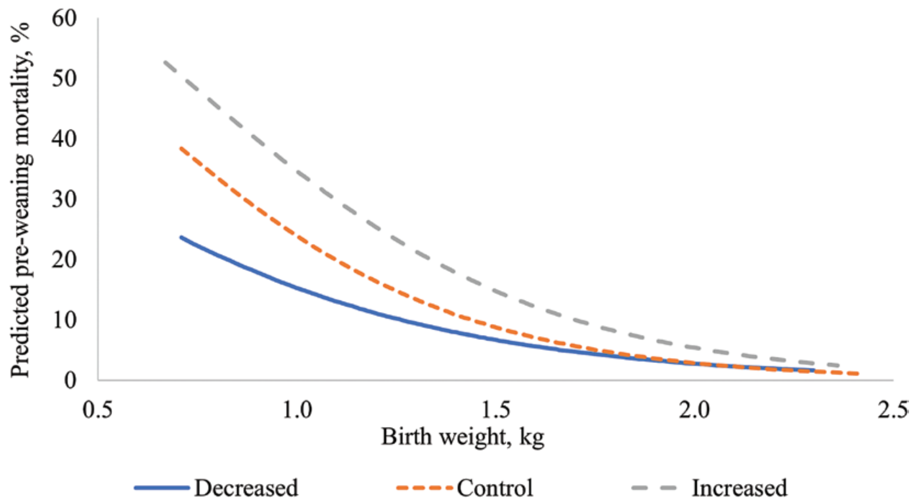

Figure 3. Regression relationships between piglet birth weight and predicted preweaning mortality for each Litter Size[1] treatment. [1]Decreased = 2 piglets less than the sow functional teat number; Control = the same number of piglets as the sow functional teat number; Increased = 2 piglets more than the sow functional teat number.

(Vande Pol et al., 2021a, 2021b). In the current study, all litters were of mixed birth weight, which may explain why PWM levels increased to a greater extent for lighter than heavier birth weight piglets.

In conclusion, the results of this study highlight that sow functional teat number is an important factor that should be considered in the development of cross-fostering protocols. Increasing litter size in excess of sow functional teat number was detrimental for piglet preweaning survival and reducing litter size below functional teat number improved preweaning survival and, to a lesser extent, piglet growth. Selection of the optimum litter size to use after cross-fostering for commercial production may vary depending on the specific situation, as many other management factors need to be considered. The results of this study provide relationships that can be used in formulating such decisions.

Conflict of interest statement. The authors declare no real or perceived conflicts of interest.

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