REPRODUCTION

Associations among individual gilt birth weight, litter birth weight phenotype, and the efficiency of replacement gilt production

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Abstract

Selection for larger litter size has increased the number of low individual birth weight (BW_i) pigs and produced sows with a repeatable low average litter birth weight phenotype (BWP). Using an average of 3.6 litters records per sow, BWP was established in 644 nucleus-multiplication sows producing replacement gilts in a large commercial operation and classified as low (L-BWP, <1.18 kg, *n* = 85), medium (M-BWP, ≥1.18 to ≤1.35 kg, *n* = 250), or high (H-BWP, >1.35 kg, *n* = 309) on the basis of a BW_i of 1.18 kg below which there was a high risk of early mortality and the average BW_i (1.35 kg) for the population. In subsequent litters, potential replacement gilts born to these sows (*n* = 7,341) received a unique identification tag that allowed the impact of BW_i, BWP, and their interactions on the efficiency of replacement gilt production to be evaluated. Negative effects of BW_i on mortality until day 4 after birth were confirmed (*P* < 0.05) and cumulative losses to weaning, to day 70 of age, and to final pre-selection at 165 d of age were affected (*P* ≤ 0.05) by the interaction between BWP and BW_i. Among the 2,035 gilts for which records for selection efficiency and production to fourth parity were available, a lower BW_i decreased the probability of gilts reaching pubertal estrus (*P* < 0.05) after 21 and 28 d of boar stimulation starting at 180 d of age, with no effect of BWP. Overall, neither BW_i, BWP, nor their interaction affected age at puberty. After breeding, only the main effect of BWP affected productivity and retention in the sow herd. In parities 1 and 2, percent stillborn was higher in litters born to gilts from H-BWP compared with L-BWP dams (*P* < 0.05), and in parity 2, total born and born alive were lower in sows derived from H-BWP compared with other BWPs. There were no differences in retention based on BWP classes until parity 2, after which retention tended (*P* ≤ 0.09) to be lower in sows derived from H-BWP compared with L-BWP dams. These results provide evidence that sow BWP is an important factor in the overall efficiency of replacement gilt management. This study also confirms that effective gilt selection and pre-breeding management protocols support excellent sow lifetime productivity and mitigate the risk of a high BWP in the litter of origin affecting retention in the breeding herd.

Key words: birth weight, gilts, litter of origin, sow lifetime productivity

Abbreviations

AUC	area under the ROC curve
BWi	individual birth weight
BWP	birth weight phenotype
FR	farrowing rate
GDU	gilt development unit
H-BWP	high birth weight phenotype
L-BWP	low birth weight phenotype
M-BWP	medium birth weight phenotype
ROC	receiver operating characteristic

Introduction

Sow lifetime productivity is a complex trait that is influenced by both sow productivity (quality pigs weaned per sow per year) and longevity (Sasaki and Koketsu, 2008; Koketsu et al., 2017; Rohrer et al., 2017; Kang et al., 2018). Numerous factors impact sow productivity, including sow fertility and prolificacy, preweaning mortality, nutrition, management, housing and environment, herd health, and stockmanship (Kraeling and Webel, 2015; Koketsu et al., 2017). However, the successful introduction of high-quality, breeding-eligible gilts into the sow herd is often underrecognized as an important driver of sow productivity and retention in the breeding herd (Bortolozzo et al., 2009; Patterson et al., 2010; Patterson and Foxcroft, 2019). At the level of a commercial genetic nucleus-multiplication unit, the number and quality of replacement gilts that a sow produces in her lifetime are also an important measure of lifetime performance in terms of the contribution that each sow makes to efficient genetic transfer from the nucleus to terminal-line level of production.

Decades of selection for high prolificacy in sows have successfully increased the total number of pigs born. However, an associated increase in the proportion of low birth weight pigs, and in preweaning mortality, has been linked to this gradual increase in sow prolificacy (Foxcroft et al., 2009; Smit et al., 2013; Yuan et al., 2015; Da Silva et al., 2016, 2018; Magnabosco et al., 2015). Individual low birth weight gilts are at risk for increased mortality, lower retention, and poor growth from birth until selection into the breeding herd (Almeida et al., 2015; Magnabosco et al., 2015). Moreover, gilts weighing less than 1.0 kg at birth had fewer total pigs born alive at first farrowing, fewer pigs produced over three parities, and increased removal due to anestrus, compared with gilts weighing above 1.0 kg (Magnabosco et al., 2016). When “litter of origin” is explored in the context of the increasing number of low birth weight pigs produced in contemporary sow populations, it becomes apparent that a large percentage of low birth weight offspring come from a minority of sows with an extreme and repeatable low litter birth weight phenotype (BWP). Gilts born to sows with this low BWP are hypothesized to carry all the same risks described above for individual low birth weight gilts but as a “litter” trait (Foxcroft, 2012). This trait is repeatable over consecutive parities in terminal-line sows and arises from interactions among ovulation rate and the dynamics of early embryonic survival, which in turn lead to excessive intrauterine crowding in early gestation and limited placental development (Foxcroft et al., 2009; Smit et al., 2013; Da Silva et al., 2018). Later in gestation, a low BWP is associated with characteristics of intrauterine growth retardation and negatively affects birth weight, body composition, postnatal survival, and growth performance of terminal-line offspring, independent of the size of the litter born (Smit et al., 2013). The

impact of a low BWP on the efficient production of replacement gilts from commercial nucleus/multiplication sows has not been reported.

The present study was part of a coordinated National Pork Board research strategy to understand key factors limiting sow lifetime productivity and was based on the hypothesis that a repeatable sow BWP would affect the efficiency of replacement gilt production at the production nucleus-multiplication level and have lasting effects on the performance of gilts selected for breeding. Consequently, the first objective of this study was to characterize sow BWP in a population of sows at the commercial nucleus-multiplication level of a large commercial production system. The next objective was to determine the effect of sow BWP on the efficiency of replacement gilt production using 1) agreed criteria for non-selection and 2) the application of proven protocols for final gilt selection involving both direct and fence-line contact daily with mature boars in purpose-designed facilities (Patterson et al., 2016). Finally, the effects of sow BWP on the productivity and retention of selected replacement gilts were determined. The design of the study permitted an in-herd comparison of the effects of individual birthweight (BW_i) of gilt, sow BWP, and their interactions on gilt performance.

Materials and Methods

This study was performed in accordance with the guidelines of Pork Quality Assurance Plus and Holden Farms Inc. ethical guidelines and with approval of the Faculty Animal Care and Use Committee—Livestock, University of Alberta (AUP00001767).

Animals and location

The primary study locations were the production nucleus-multiplication farm ($n = 2,400$) Line 03 (L03) sows (PIC, Hendersonville, USA) of Holden Farms Inc. (HFI) located near Northfield, Minnesota, USA and associated downstream gilt development units (GDUs) and commercial sow farms located near Northfield, MN, USA and Waukon, IA, USA within the HFI system. The study was conducted between March 2014 and October 2018.

Management of multiplication sows

Data collected in the preliminary phase of the study were used to establish a repeatable sow BWP using a similar approach to that described by Smit et al. (2013). Parities 1 to 5 nucleus and multiplication sows were initially allocated to the trial. Within 24 h after birth and before cross-fostering, sow identification, parity, date of birth, total number of piglets born, number of piglets born alive, number of stillborn, and the BW_i and sex of all pigs born were recorded. The same measurements were taken after every subsequent farrowing during the experimental period (1 to 5 consecutive litter measurements taken). Litter data were recorded irrespective of the litter sire (either an L03 boar for the production of L03 replacement gilts within the production nucleus or L02 boars at the production multiplication level to produce potential Camborough (a trademark from GENUS; replacement gilts for commercial production). Cross-fostering between litters was kept to a minimum and completed within 24 h after birth.

Management of gilts from birth to final pre-selection

Postnatal care involved drying each piglet at birth and adherence to a split-suckling protocol to ensure colostrum ingestion of all piglets after birth. Tail docking and iron injections were

completed no later than 6 d after birth. Within 24 h after the birth of the third or subsequent litters (at which time sow BWP had been established), all live potential replacement gilts were individually identified with an ear tag in both ears. Detailed protocols were implemented to enable the tracking of individual gilts from birth to culling. From birth to the end of the nursery stage, gilts performance was recorded in the genetic database PICtraq (PIC) and from nursery exit to culling or the termination of the study in the swine management software Porcitech (Agritech Software, Barcelona, Spain). At the time of death or non-selection as a replacement female, ear tags were removed and the reason for culling or non-selection was recorded. Records were continually monitored to ensure all gilts were accounted for.

At weaning, agreed study protocols stipulated that all healthy gilts should be transferred to the nursery, irrespective of apparent differences in weaning weight. After weaning, selected gilts were relocated to a single nursery facility and pen-housed in groups of 16 to 20 gilts on plastic flooring in 2.7×5.5 m pens, providing 1.5 to 1.8 m² per animal, where they remained for approximately 6 to 7 wk. All females were reared using industry standard protocols and fed a gilt developer diet ad libitum (see [Supplementary Table S1](#)). At approximately 70 d of age, gilts were transferred to one of seven rearing facilities. Acceptable criteria for initial culling or non-selection using visual appraisal at nursery exit included under-condition, a hairy appearance, physical defects, and extreme runting, but not relative growth performance. During the rearing phase, gilts were housed in group pens of 18 to 30 gilts on fully slatted floors until approximately 160 d of age, and a final pre-selection process at approximately 165 d of age then identified gilts acceptable for entry to the final selection program. Non-selection criteria at this final pre-selection stage were similar to those not only described above, but also included non-selection for poor structure, poor conformation, and a lifetime growth rate less than 0.55 kg/d. Retention data were recorded for all gilts until the final pre-selection stage of development. However, in the final analysis of the effects of BWi or sow BWP on gilt development and pre-selection outcomes, removals due to known health incidents ($n = 110$), or gilts that were inadvertently allocated to a different flow within the system ($n = 46$), were not included.

All pre-select gilts were considered to be part of the HFI sow herd inventory when they commenced boar exposure at approximately 180 d of age within their respective GDU and received an HFI production identification tag that was cross-referenced to the birth identification tag. Gilt acclimation and vaccination programs followed standard HFI protocols and included vaccination against reproductive pathogens (porcine parvovirus, leptospirosis caused by *Leptospira canicola*, *L. grippityphosa*, *L. hardjo*, *L. icterohaemorrhagiae*, *L. Pomona*, and *Erysipelothrix rhusiopathiae*), porcine circovirus type 2, and influenza A virus. For specific farms, vaccination via commercial modified live vaccines against porcine reproductive and respiratory syndrome virus may have been included. Vaccinations were scheduled to be completed before the start of the puberty induction program. Analysis of data on final selection outcomes and on gilt performance until the fourth parity of gilts selected was restricted to three farms within the HFI system that had established on-site gilt development programs and purpose-built handling facilities that allowed standardized and objective measures of puberty induction in response to daily exposure to a full range of boar stimuli. The production data collected from these farms also covered periods during which there were no health issues that would

confound the project objectives. The final selection program involved standardized protocols for daily direct stimulation with mature boars, as described previously ([Patterson et al., 2016](#)), and “selection” for entry to each breeding herd was based on records of a standing pubertal estrus. A stipulated period of gilt acclimation to individual stalls after reaching pubertal estrus resulted in gilts being bred at second or third estrus with a targeted breeding weight range of 135 to 160 kg.

Female performance in the sow herd

Gilts and sows were managed according to standard HFI protocols, and farm staff had no knowledge of the origin of the gilts. Records for service, farrowing and culling dates, litter size, and culling reasons were retrospectively collected from herd production records reported in Porcitech (Agritech Software, Barcelona, Spain).

For the purposes of the present paper, associations among both the BWi of potential replacement gilts and the established sow BWP (gilt litter of origin) and gilt retention to the point of final pre-selection around 165 d of age were first established to explore factors contributing to the efficiency of replacement gilt production by nucleus-multiplication sows. Associations among BWi and BWP, and final selection for breeding (a recorded pubertal standing estrus) and performance within the breeding herd until fourth parity for gilts bred, were then established for a subset of pre-select gilts representative of all three BWPs to determine key factors affecting productivity at commercial sow farm level.

Statistical analyses

Prior to analyses, the raw data underwent rigorous data verification. All data were analyzed using the software Statistical Analysis System (SAS) version 9.4. Differences were considered significant at $P \leq 0.05$ and a tendency at probabilities between 0.05 and ≤ 0.10 . Numerical data are expressed as LS means $\pm$ SEM or as percentages.

Using the same approach as [Magnabosco et al. \(2015\)](#), gilt BWi was used as a continuous variable to determine the predicted probability for mortality 4 d after birth using logistic regression models in SAS (GLIMMIX procedure): birth dam, parity of the dam, season, and total size of the birth litter were used as random variables in the model. The predicted probabilities were used to obtain receiver operating characteristic (ROC) curves (LOGISTIC procedure). The optimal cutoff value for predicting mortality within 4 d after birth for BWi was determined. Model accuracy was assessed by calculating the area under the ROC curve (AUC) and interpreted as described by [Greiner et al. \(2000\)](#).

Litter average birth weight was determined on each litter born to a sow by averaging BWi for all pigs born within a single litter (male, female, born live, and stillborn). To ensure the integrity of the BWP data, litter data in the experimental records recorded on-site were compared with data recorded in the sow farm database, and in the few instances, where these records differed by more than 15%, the data were not used in the determination of average litter birth weight and sow BWP. Although there were excellent consistency and integrity in the HFI records system, in the less than 2% of cases where inconsistency of records was identified, these inconsistent data were removed from the data set before analysis. The mean of the litter average birth weights of sows producing at least two litter records with >10 total born based on the experimental records ($n = 644$: overall mean litter average birth weight = 1.35 kg; mean number of litter used to establish the

BWP = 3.6) was then used to establish three sow BWPs with respect to the critical threshold of birth weight for increased mortality established (1.18 kg), and the overall population mean average birth weight of 1.35 kg as follows: low BWP (L-BWP: <1.18 kg; $n = 85$), medium BWP (M-BWP: ≥ 1.18 to ≤ 1.35 kg; $n = 250$), and high BWP (H-BWP: >1.35 kg; $n = 309$).

Having applied the standardized selection/culling criteria described above, cumulative losses by death or health at 4 d after birth, until weaning, at 70 d of age, and at pre-selection into the breeding herd at approximately 165 d of age were determined in 7,341 gilts. The percentages of gilts in estrus within 14, 21, 28, and 35 d of starting boar stimulation and farrowing rates (FRs) and retention rates of gilts selected to be bred were analyzed in a subset of gilts ($n = 2,035$) using logistic regression models (GLIMMIX procedure). In these models, BWi, BWP, and their interaction were considered as fixed effects to investigate whether gilts with different BWi would respond differently among BWP classifications. Random effects consisted of season, farm, birth dam, parity of dam, and total size of the birth litter. The GLIMMIX procedure was used to analyze total born piglets, total born alive pigs, and gilts born alive at the multiplication sow level. At the replacement gilt level, birth weight, age, weight, and growth rate (at pre-selection, puberty, final selection, and service), subsequent total born piglets and total born alive piglets were analyzed. The GLIMMIX procedure, fitted with the assumption that the data exhibited a binomial distribution, was used to analyze the percentages of piglets weighing less than 1.18 kg at birth, the number of gilts tagged at multiplication sow level, and the number of stillborn pigs at the replacement gilt level.

If the interaction between BWP and BWi was significant, the post-linear modeling procedure was used to obtain the overall comparison of slopes among BWPs or to make specific comparisons at different levels of BWi. In models in which BWi was significant but with no interaction effect, the predicted probabilities concerning the effect of continuous BWi on variables with binary response were used to obtain ROC curves and optimal cutoff values, as described earlier. When neither BWi nor the BWi by BWP interaction were significant, the model

was run considering only the fixed effect of BWP and LSmeans were compared using the Tukey–Kramer test.

Results

Figure 1 shows the relationship between litter average birth weight and litter size in the 644 sows for which a BWP phenotype was established. Across all litter sizes with more than 10 pigs born, there was a negative relationship between total litter size born and the litter average birth weight of that litter ($y = -0.036x + 1.89$, $R^2 = 0.13$, $P < 0.0001$; Figure 1). The litter average birth weight of the most prolific sows was lower than the population litter average birth weight of 1.35 kg, and as litter size increased, there was an associated decrease in the proportion of sows producing litters with a high litter average birth weight.

The overall phenotypic characteristics of the 644 multiplication sows assigned a BWP and their gilt offspring are shown in Table 1. The L-BWP sows represented the 13.2% of sows producing litters with the greatest risk of increased deaths in the immediate postnatal period. The average total litter sizes born in the litters used to establish the L- and M-BWPs were similar but were higher than in H-BWP sows ($P < 0.001$); nevertheless, the litter average birth weight was different between L-, M-, and H-BWP sows ($P < 0.001$). Between three and four litter records were generally used to establish sow BWP, and the average number of litter records used was similar among the three BWPs ($P > 0.05$). Within each phenotype, the proportion of L-, M-, and H-BWP litters varied substantially. For L-BWP sows, 71.0%, 28.7%, and 0.3% of litters were classified as low, medium, and high, respectively, and in L-BWP sows, a greater percentage of piglets had individual birth weights <1.18 kg compared with M-BWP and H-BWP sows ($P < 0.001$). Despite differences in total born, the number of gilts born alive and gilts tagged did not differ among BWP classifications ($P > 0.05$), but fewer gilts born alive born to L-BWP sows were tagged at birth compared with H-BWP sows, reflecting additional death losses immediately after birth ($P \leq 0.05$).

Figure 1. Relationship between litter size (as total number of pigs born) and litter average birth weight in 644 sows. The average litter birth weight over the population is 1.35 kg (solid black line). The dashed black line indicates the birth weight of 1.18 kg, below which sows were classified as having a low birth weight phenotype.

Table 1. Summary statistics of measured traits (LS means $\pm$ SEM) in sows with low, medium, and high BWPs

	Sow BWP			P-value
	Low (< 1.18 kg)	Medium (≥ 1.18 to ≤ 1.35 kg)	High (> 1.35 kg)	
Number of sows	85	250	309	
Proportion of total, %	13.2	38.8	48.0	
Average total born	15.3 $\pm$ 0.2 ^a	15.2 $\pm$ 0.1 ^a	14.2 $\pm$ 0.1 ^b	<0.0001
Average litter birth weight, kg $\pm$ g	1.12 $\pm$ 9 ^a	1.28 $\pm$ 5 ^b	1.49 $\pm$ 5 ^c	<0.0001
Nos. litters per phenotype ¹	3.6 $\pm$ 0.1	3.7 $\pm$ 0.1	3.6 $\pm$ 0.1	0.1417
Percentage of litters within BWP classified as:				
L-BWP	71.0	24.2	3.4	
M-BWP	28.7	70.4	56.0	
H-BWP	0.3	5.3	40.6	
Nos. potential replacement gilts	985	2,882	3,474	
Pigs <1.18 kg, %	58.0 $\pm$ 0.7 ^a	36.8 $\pm$ 0.4 ^b	19.4 $\pm$ 0.3 ^c	<0.0001
Gilts born alive per litter	6.9 $\pm$ 0.2	6.9 $\pm$ 0.1	6.7 $\pm$ 0.1	0.3759
Gilts tagged per litter ²	5.8 $\pm$ 0.2	6.0 $\pm$ 0.1	5.9 $\pm$ 0.1	0.6294
Gilts born alive tagged, %	84.0 $\pm$ 1.5 ^a	87.2 $\pm$ 0.8 ^{ab}	88.4 $\pm$ 0.8 ^b	0.0204

¹The average number of litters used to establish each sow BWP.

²Not all gilts born alive were tagged, reflecting additional death losses immediately after birth.

^{a-c}Within row, significant difference between phenotype classification ($P < 0.05$).

Figure 2. Predicted probabilities of mortality and losses until 4 d of age (A), weaning (B), 70 d of age (C), and final pre-selection (D) by BWi and BWP estimated using logistic regression models. L-BWP: piglets with a BWi < 1.18 kg; M-BWP: piglets with a BWi ≥ 1.18 to ≤ 1.35 kg; H-BWP: piglets with a BWi > 1.35 kg. The dashed arrow indicates the best cutoff point of BWi for survival until 4 d of age. Solid black line, solid gray line, and dotted black line indicate the 95% confidence limits for H-, M-, and L-BWP, respectively.

Selection efficiency

Mortality until day 4 after birth was affected ($P \leq 0.05$) by BWi (Figure 2A) but not affected by BWP (L-BWP: $3.8 \pm 0.9\%$, M-BWP: $4.0 \pm 0.5\%$, and H-BWP: $4.6 \pm 0.5\%$) nor by the BWi by BWP

interaction. A lower BWi was associated with increased gilt losses and the best cutoff point estimation for survival at day 4 was 1.18 kg (AUC = 0.76%; $P < 0.0001$; Figure 2A). Cumulative losses to weaning, to day 70 of age, and to final pre-selection

at approximately 165 d of age were affected ($P \leq 0.05$) by the interaction between BWP and BWi (Figure 2). At weaning (Figure 2B), the probability of mortality was similar between BWP classes until BWi exceeded 1.4 kg; above a BWi of 1.4 kg, mortality increased ($P \leq 0.05$) in H-BWP compared with M-BWP gilts. At day 70 of age (Figure 2C), gilts born to sows with an H-BWP and with a BWi of <0.7 kg had a lower probability of being lost or culled compared with gilts born to M-BWP gilts. When BWi exceeded 1.4 and 1.5 kg, the probability of losses at day 70 was greater ($P \leq 0.05$) in H-BWP compared with M-BWP and L-BWP, respectively. At the final pre-selection at around 165 d of age (Figure 2D), H-BWP gilts had a lower probability ($P \leq 0.05$) of cumulative losses at BWi below 0.9 and 1.1 kg, respectively, compared with L-BWP and M-BWP gilts. Gilt retention was then similar between BWP classes until BWi exceeded 1.5 kg, after which the probability of losses was higher ($P \leq 0.05$) in H-BWP compared with M-BWP gilts.

Growth performance

Gilts were weighed at final pre-selection at 164.8 ± 15.0 d of age. A significant two-way interaction was detected for weight and growth rate at final pre-selection and weight at pubertal estrus ($P \leq 0.06$). The slope of the L-BWP class was different compared with M-BWP and H-BWP, and both weight (data not shown) and growth rate (Figure 3A) at pre-selection were

lower in L-BWP compared with M-BWP and H-BWP classes until BWi exceeded 1.0 kg and 1.1 kg in H-BWP and M-BWP gilts, respectively ($P \leq 0.05$). For weight at first estrus, L-BWP gilts were lighter ($P \leq 0.05$) than H-BWP and M-BWP gilts until BWi exceeded 0.9 and 1.2 kg, respectively (Figure 3B). Low BWi was associated with a decreased growth rate at first estrus and estimated weight at service ($P \leq 0.05$), with weak and very weak correlation coefficients, respectively ($r = 0.27$ and $r = 0.18$; $P < 0.0001$).

Responses to puberty induction in the GDU

Gilts were first exposed to boars for puberty stimulation at 178.3 ± 10.4 d of age. In the first 14 d of boar stimulation, the probability of gilts reaching pubertal estrus was not affected (Figure 4A; $P > 0.05$) by BWP (L-BWP: $50.0 \pm 1.4\%$, M-BWP: $48.9 \pm 1.3\%$, and H-BWP: $47.8 \pm 1.3\%$), by BWi, or their two-way interaction. There was also no significant effect of BWP on the pubertal response by 21 d (L-BWP: 68.8 ± 8.9 , M-BWP: 68.4 ± 7.8 , and H-BWP: 66.4 ± 8.1 d), 28 d (L-BWP: 79.6 ± 6.9 , M-BWP: 80.3 ± 5.8 , and H-BWP: 77.3 ± 6.4 d), or 35 d (L-BWP: 82.7 ± 5.3 , M-BWP: 83.6 ± 4.1 , and H-BWP: 81.5 ± 4.4 d) nor were there significant two-way interactions between BWi and BWP. However, a low BWi was associated with a decreased probability of achieving puberty after 21 d ($P = 0.009$) and 28 d ($P = 0.029$) of boar exposure (Figure 4B and C). The best cutoff point estimation for puberty attainment was 1.20 kg (AUC = 0.75%) and 1.23 kg (AUC = 0.79%) by days 21 and 28, respectively. A low BWi tended ($P = 0.074$) to be associated with a decreased probability of achieving puberty within 35 d (Figure 4D), and the best cutoff point estimation for puberty attainment by 35 d was 1.36 kg (AUC = 0.76%). Overall, no differences were detected in age at puberty ($P > 0.05$) when the main effect of BWP was examined (L-BWP: 193.6 ± 3.6 d, M-BWP: 193.9 ± 3.4 d, and H-BWP: 194.3 ± 3.4 d of age).

Post-selection performance

Further analysis of litter birth weight effects on breeding performance, retention rate in the breeding herd, and productivity was restricted to data from three sow farms that produced the selection response data and remained free of major health incidents during the accumulation of production data until removal from the herd or until sows farrowing their fourth litter. Although more restrictive, these analyses still included production data on over 1,749 gilts whose performance could be linked back to their litter of origin.

Overall, for gilts served, 87% ($n = 1,525$) reached puberty before 210 d of age, 99% ($n = 1,730$) had a recorded pubertal estrus, 82% ($n = 1,438$) had an estimated service weight of less than 160 kg, and 90% ($n = 1,569$) were less than 240 d of age at first service. There was no effect of BWP on the probability of pre-selected gilts being served (L-BWP: $87.4 \pm 3.1\%$, M-BWP: $87.8 \pm 1.3\%$, and H-BWP: $85.4 \pm 1.4\%$) or the probability of being served with a target weight of less than 160 kg (L-BWP: $89.2 \pm 4.1\%$, M-BWP: $87.5 \pm 3.6\%$, and H-BWP: $84.1 \pm 4.4\%$). A lower BWi was associated with a lower probability ($P = 0.007$) of pre-selected gilts being served (Figure 5A), and the best cutoff point estimation was 1.27 kg (AUC = 0.68%). A higher BWi was associated with a lower probability ($P = 0.010$) of being served within a targeted weight of less than 160 kg (Figure 5B), and the best cutoff point estimation was 1.55 kg (AUC = 0.76%).

Production performance up to fourth parity

Neither BWi nor the BWi by BWP interaction was associated with differences in FR, total born, or total born alive over four parities ($P > 0.05$). The main effects of BWP were established and

Figure 3. Growth rate at final pre-selection at 165 d of age (A) and weight at puberty (B) by BWi and BWP. L-BWP: piglets with an individual birth weight < 1.18 kg; M-BWP: piglets with an individual birth weight ≥ 1.18 to ≤ 1.35 kg; H-BWP: piglets with an individual birth weight > 1.35 kg. Solid black line, solid gray line, and dotted black line indicate the 95% confidence limits for H-, M-, and L-BWP, respectively.

Figure 4. Predicted probabilities of attaining puberty by 14 (A), 21 (B), 28 (C), and 35 d (D) after the initiation of boar exposure according to BWi and BWP, estimated using logistic regression models. L-BWP: piglets with a BWi < 1.18 kg; M-BWP: piglets with a BWi $\geq$ 1.18 to $\leq$ 1.35 kg; H-BWP: piglets with a BWi > 1.35 kg. Dashed arrows indicate the best cutoff points of BWi for puberty attainment. Solid black line, solid gray line, and dotted black line indicate the 95% confidence limits for H-, M-, and L-BWP, respectively.

are reported in Table 2. In parity 2, total born was lower in gilts derived from H-BWP compared with M-BWP dams, and total born alive was lower in gilts from H-BWP compared with L-BWP and M-BWP dams (Table 2, $P < 0.05$). In parity 1, the percent stillborn was higher in litters born to gilts from H-BWP compared with L-BWP and M-BWP dams, whereas gilts from M-BWP and H-BWP dams had a higher percent stillborn than from L-BWP in parity 2 (Table 2, $P < 0.05$). In parity 3, the percent stillborn was higher in sows derived from M-BWP, compared with L-BWP and H-BWP dams (Table 2, $P < 0.05$).

Retention of Sows in the breeding herd

Overall, BWi and the BWi by BWP interaction were not associated with differences in retention nor with reasons for culling up to parity 4, and the main effects of BWP established are reported in Table 3. There were no differences in retention between BWP classes until parity 2 ($P \geq 0.15$), after which retention tended ($P \leq 0.09$) to be lower in sows derived from H-BWP compared with L-BWP dams. An analysis of removal patterns for the effect of dam BWP showed no effect on the incidence of reproductive and locomotor problems or downer sows ($P \geq 0.44$). However, more sows derived from H-BWP than M-BWP dams tended to be removed due to sudden death and prolapses ($P < 0.08$).

Discussion

The present study was part of a coordinated strategy to understand key factors limiting the efficiency of replacement gilt

production and was based on the hypothesis that a repeatable sow BWP would affect both the efficiency of replacement gilt production at the production nucleus-multiplication level and have lasting effects on the performance of gilts selected for breeding. Because nearly 60% of the gilts produced from sows with a low BWP are in the low BWi category (see Table 1), many of the associations between a low BWi and low BWP, and measures of gilt performance, will be similar. However, a proportion of low birth weight gilts come from sows with a medium or high BWP, and the biological origin of these low birth weight gilts is different. Although small at birth, these gilts may simply be “small for gestational age” and not carry the developmental imprint seen in low BWi gilts born to sows with the extremely low BWP. Any interactions seen between BWi and BWP are particularly intriguing and suggest that for some measures of gilt performance, sow BWP can change the relationship between BWi and other traits. Furthermore, sow BWP affected measures of gilt performance in the absence of BWi or an interaction effect, suggesting “litter of origin effects.”

The data presented in Table 1 involving a much larger population of sows than used in the studies of Smit et al. (2013), and using an average of more than three consecutive litters of at least 10 pigs born to establish sow BWP, confirm the repeatability of the extreme L-BWP. Given the very low proportion of high birth weight gilts in the litters born to the L-BWP sows, the early culling of this 15% of multiplication sows would have little impact on the overall production of quality replacement gilts, as these are largely born to the M- and H-BWP sows in the population. However, an early culling

Figure 5. Predicted probabilities of pre-selected gilts being served (A) and being served at less than 160 kg (B) according to BWi and BWP estimated using logistic regression models. L-BWP: piglets with a BWi < 1.18 kg; M-BWP: piglets with a BWi ≥ 1.18 to ≤ 1.35 kg; H-BWP: piglets with a BWi > 1.35 kg. Dashed arrows indicate the best cutoff points of BWi for being served after selection and being served within the targeted weight. Solid black line, solid gray line, and dotted black line indicate the 95% confidence limits for H-, M-, and L-BWP, respectively.

strategy would address the considerable costs of maintaining extreme L-BWP sows in the multiplication population for very little benefit in terms of replacement gilts entering terminal-line production. The data in Table 1 and Figure 1 also confirm that the extreme L-BWP occurs across all litter size categories and is consistent with the underlying hypothesis that this phenotype is driven by interactions among key reproductive traits early in gestation that have lasting consequences for litter birth weight and developmental potential irrespective of the final size of the litter born. These data also confirm that sow hyperprolificacy per se, in the sense of the total number of pigs born, is not the major driver of a low BWP. Rather, we suggest that some of the component reproductive traits that underlie the gradual increase in total pigs born (ovulation rate and early embryonic survival) are consistently interacting in the small population of extreme L-BWP sows to create extreme intrauterine crowding in early gestation, thus setting up a pattern of intrauterine growth retardation due to limited placental development in all littermates.

Gilt postnatal development and selection efficiency

The results of the current study confirm that BWi is a risk factor for loss or removal of gilts at all stages of postnatal development.

Significant differences in survival are already present by day 4 and at weaning and likely reflect the early crushing and poorer preweaning survival of pigs born to low BWP sows previously seen at the commercial level of production [Smit et al. \(2013\)](#). Also consistent with the present results, [Magnabosco et al. \(2015\)](#) reported that gilts with low birth weights have lower survival to finishing and thus may be compromised as future replacement females. At weaning, and at 70 and 165 d of age in the present study, significant interactions between BWP and BWi affected gilt retention, such that the death, culling, or non-selection of gilts with a BWi greater than 1.4 to 1.5 kg in the H-BWP phenotype was greater than in gilts derived from the M- and L-BWPs. At weaning, we cannot rule out that there may be sow-level factors that may be compromised in H-BWP dams that lead to increased mortality. At 70 d of age or at final pre-selection around 165 d, the increased growth rate of the heavier weight gilts derived from H-BWP dams may be negatively impacting mortality and culling. Some studies have reported an association between high growth rate in gilts and osteochondrosis and lameness ([van Grevenhof et al., 2012](#); [Fabà et al., 2019](#)), but other studies have reported no such associations ([Tóth et al., 2016](#)). Although it was not one of the listed reasons for non-selection, extremely high body weights at the time of final pre-selection may still have resulted in a non-selection decision.

Growth and reproductive performance

In terms of birth weight effects on postnatal growth, the first and expected conclusion is that BWi is linked to postnatal growth potential, again reflecting results from studies at the terminal-line level of production ([Smit et al., 2013](#)) and in comparable replacement gilt studies ([Almeida et al., 2014](#); [Magnabosco et al., 2015](#); [Supakorn et al., 2019b](#)). However, the interactions between BWi and BWP were interesting. The lower weight and slower growth rates of BWi gilts less than 1.0 and 1.1 kg in the L-BWP, compared with the M- and H-BWP, respectively, may reflect the limited developmental potential of gilts derived from L-BWP dams. As reviewed by [Foxcroft et al. \(2006\)](#), intrauterine growth retardation results in fetal reprogramming and a change in the number and type of muscle fibers which limit the growth rate potential of piglets after birth (see reviews of [Foxcroft et al., 2006](#); [Rehfeldt and Kuhn, 2006](#)).

However, in the present study, most pre-selected gilts at 165 d of age had adequate growth for achieving sexual maturity in response to stimulation with boars at the final selection stage of gilt development. The study of [Beltranena et al. \(1991\)](#) defined a threshold growth rate to puberty of 0.55 kg/d below which the attainment of puberty was delayed. As with most recent surveys of gilt growth performance in systems that use feeding to appetite throughout gilt development ([Calderón Díaz et al., 2015](#)), the present data confirm that low birth weight gilts that are retained to the final pre-selection stage of development have sufficient growth performance to express their inherent sexual precocity, at least after 28 d of exposure to puberty-inducing boar stimuli. This raises questions about existing selection strategies that do not favor the retention of gilts with relatively low growth performance amongst their birth cohort. However, taking into account the cost of feed, nonproductive days, numbers of born alive, stillborns, and litter uniformity at breeding, [Amaral Filha et al. \(2010\)](#) recommended that gilts should achieve a growth rate of between 600 and 770 g/d for optimal performance.

At the other end of the growth rate spectrum, the excellent growth performance of gilts born to H-BWP sows may be an increasing problem for the industry, as individual gilts are achieving growth rates to puberty in excess of 700 g/d.

Table 2. Reproductive performance over four parities for gilts served and classified according to their dams BWP

	Sow BWP			P-value
	Low (< 1.18 kg)	Medium (≥ 1.18 to ≤ 1.35 kg)	High (>1.35 kg)	
Parity 1	173	657	808	
FR to first service, %	90.9 $\pm$ 3.3	89.9 $\pm$ 2.9	87.6 $\pm$ 3.4	0.2543
FR with 1 reserve, %	94.8 $\pm$ 2.5	94.6 $\pm$ 2.1	93.9 $\pm$ 2.3	0.7940
Total born ¹ , n	14.0 $\pm$ 0.5	14.1 $\pm$ 0.5	14.1 $\pm$ 0.5	0.8569
Born alive ¹ , n	12.9 $\pm$ 0.4	13.0 $\pm$ 0.4	12.9 $\pm$ 0.4	0.8261
Stillborn ² , %	4.4 $\pm$ 0.6 ^a	5.2 $\pm$ 0.6 ^a	6.5 $\pm$ 0.7 ^b	<0.0001
Parity 2	160	580	708	
FR to first service, %	91.5 $\pm$ 2.4	88.1 $\pm$ 1.8	87.0 $\pm$ 1.8	0.2640
FR with 1 reserve, %	96.6 $\pm$ 1.6	93.8 $\pm$ 1.8	94.9 $\pm$ 1.5	0.2733
Total born ¹ , n	14.5 $\pm$ 0.4 ^{ab}	14.6 $\pm$ 0.3 ^a	14.0 $\pm$ 0.3 ^b	0.0107
Born alive ¹ , n	13.7 $\pm$ 0.5 ^a	13.6 $\pm$ 0.4 ^a	12.9 $\pm$ 0.4 ^b	0.0012
Stillborn ² , %	3.9 $\pm$ 0.4 ^a	5.4 $\pm$ 0.3 ^b	5.7 $\pm$ 0.3 ^b	0.0031
Parity 3	146	512	613	
FR to first service, %	93.3 $\pm$ 2.2	88.7 $\pm$ 1.8	90.0 $\pm$ 1.6	0.2705
FR with 1 reserve, %	96.3 $\pm$ 1.8	92.2 $\pm$ 2.0	93.3 $\pm$ 1.7	0.2406
Total born ¹ , n	15.1 $\pm$ 0.4	15.4 $\pm$ 0.3	15.1 $\pm$ 0.3	0.4047
Born alive ¹ , n	13.9 $\pm$ 0.5	13.8 $\pm$ 0.4	13.8 $\pm$ 0.4	0.9161
Stillborn ² , %	6.1 $\pm$ 0.7 ^a	8.1 $\pm$ 0.6 ^b	6.6 $\pm$ 0.5 ^a	0.0003
Parity 4	128	440	519	
FR to first service, %	89.2 $\pm$ 2.8	88.1 $\pm$ 1.6	88.3 $\pm$ 1.5	0.9459
FR with 1 reserve, %	92.7 $\pm$ 2.4	91.3 $\pm$ 1.4	90.8 $\pm$ 1.4	0.7826
Total born ¹ , n	16.0 $\pm$ 0.4	15.5 $\pm$ 0.3	15.4 $\pm$ 0.3	0.3143
Born alive ¹ , n	13.8 $\pm$ 0.7	13.5 $\pm$ 0.7	13.4 $\pm$ 0.7	0.6071
Stillborn ² , %	9.4 $\pm$ 1.2	9.2 $\pm$ 1.1	8.8 $\pm$ 1.0	0.5770

¹Total born and born alive include maximum of one re-breeding.²Analyzed as a binomial response.^{a,b}Within a row, different letters indicate significant difference between BWP classes ($P < 0.05$).**Table 3.** Retention rate, removals by parity, and reason for removal to fourth parity of gilts initially bred and classified according to the BWP of their litter of origin

	Sow BWP			P-value
	Low (< 1.18 kg)	Medium (≥ 1.18 to ≤ 1.35 kg)	High (>1.35 kg)	
Retention rate				
Gilts served, % (n)	100 (183)	100 (700)	100 (866)	
Farrow P1, %	94.8 $\pm$ 2.5	94.6 $\pm$ 2.1	93.9 $\pm$ 2.3	0.7940
Weaned P1 served, %	90.9 $\pm$ 2.6	89.5 $\pm$ 2.0	86.8 $\pm$ 2.3	0.1521
Farrow P2, %	87.1 $\pm$ 3.5	83.0 $\pm$ 3.4	81.4 $\pm$ 3.6	0.1817
Weaned P2 served, %	82.7 $\pm$ 3.7 ^x	79.7 $\pm$ 3.0 ^{xy}	76.1 $\pm$ 3.3 ^y	0.0939
Farrow P3, %	79.8 $\pm$ 4.6 ^x	73.6 $\pm$ 4.4 ^{xy}	71.1 $\pm$ 4.6 ^y	0.0791
Weaned P3 served, %	74.9 $\pm$ 4.9 ^x	69.1 $\pm$ 4.4 ^{xy}	65.7 $\pm$ 4.6 ^y	0.0623
Farrow P4, %	69.2 $\pm$ 5.1 ^x	63.4 $\pm$ 4.3 ^{xy}	59.8 $\pm$ 4.4 ^y	0.0747
Reason for removal				
Reproductive ¹ , %	14.5 $\pm$ 4.0	15.5 $\pm$ 3.4	15.0 $\pm$ 3.3	0.9332
Locomotion ² , %	2.7 $\pm$ 1.3	5.0 $\pm$ 1.0	4.6 $\pm$ 0.9	0.4392
Sudden death, %	2.7 $\pm$ 1.4 ^{xy}	2.7 $\pm$ 1.0 ^x	4.7 $\pm$ 1.6 ^y	0.0662
Downer sow, %	1.4 $\pm$ 1.0	1.9 $\pm$ 0.9	2.3 $\pm$ 1.0	0.6756
Prolapse ³ , %	1.5 $\pm$ 1.1 ^{xy}	0.9 $\pm$ 0.5 ^x	2.5 $\pm$ 1.2 ^y	0.0759
Other ⁴ , %	6.5 $\pm$ 2.5	9.5 $\pm$ 2.5	9.1 $\pm$ 2.4	0.4887

¹Return to estrus, anestrous, and abortion.²Locomotor disorders, arthritis, and leg conformation.³Rectal, vaginal, and uterine prolapses.⁴Disease, poor body condition, low farrowing productivity, and no recorded reason.^{xy}Different letters within a row indicate a trend in the difference between BWP classes ($P < 0.10$).

Confirming the extensive results reported by [Calderón Díaz et al. \(2015\)](#), because there was no link between high growth rates and age at first estrus, some later-maturing gilts achieved

weights at pubertal estrus and at breeding that are above industry benchmarks. If the efficiency of inducing pubertal estrus is low, or the pre-stimulation management or health

status of replacement gilts at the time of final selection is not optimal, our data support the conclusion that retention of gilts born to sows with a high BWP will become an increasing problem for the industry. Similarly, gilts that were heavier at first service had a decrease in FR in parity 2 and those gilts bred at >170 kg were at risk of low retention and locomotion problems over three parities (Amaral Filha et al., 2008), are heavier at farrowing, and have increased maintenance requirements over their productive life (Bortolozzo et al., 2009). However, Faccin et al. (2017) reported that for gilts growing >700 g/d and not overweight at breeding, neither productivity nor longevity was adversely impacted. Collectively, these data suggest that weight at service, rather than growth rate per se, affects future performance. Therefore, the implementation of an effective gilt stimulation program as a means of controlling the weight at breeding is a critical component of any gilt development program.

Responses to puberty induction in the GDU

Analysis of responses of pre-select gilts to standardized puberty induction protocols was restricted to data from three farms with a proven record of implementing good gilt selection programs. Two of these sow farms had established on-site GDUs and purpose-built facilities, allowing the efficient use of boars for inducing pubertal estrus. The third sow farm received known pubertal gilts from the same off-site GDU for which detailed production data were presented previously (Patterson et al., 2016). All three farms were largely free of any major disease breaks during the period of the study encompassing gilt selection and the recording of selected gilt performance in the sow herd until culling or farrowing the fourth litter.

Individual birth weight affected the response to puberty induction stimuli: Gilts with a BWi less than 1.20 and 1.23 kg showed a delayed response to puberty attainment after 21 and 28 d, respectively, of intensive boar contact. As discussed above, the attainment of puberty may be delayed in gilts with lower growth rates, and achieving a minimum body weight or a particular metabolic state may also be prerequisites for puberty to occur. The lower birth weight and slower-growing gilts in the present study may not have met these thresholds. However, by 35 d of stimulation, BWi only showed a tendency to delay the onset of puberty. This is not surprising, because when gilts continue to be stimulated and monitored for longer periods (up to 260 d of age), most will eventually have a recorded estrus (Calderón Díaz et al., 2015). Generally, the results of the present study confirm the work of Almeida et al. (2014) and Magnabosco et al. (2016) who reported no effect of birth weight on age at puberty or the percent of gilts reaching puberty within 30 d of boar exposure. Overall, within the strict time limits imposed in the induction protocol (35 d after initial exposure to the boar), just over 80% of all pre-selected gilts had a recorded pubertal estrus, indicating the effective use of the stimulation protocols across the three farms used at this stage of the study. These results are consistent with previously reported results and confirm the positive impact of using effective commercial-based gilt development and selection programs (Amaral Filha et al., 2009; Patterson et al., 2016; Patterson and Foxcroft, 2019). In our earlier study using the same off-site facility (Patterson et al., 2016), an overall response of 77.6% of successful puberty induction was achieved. The 5% improvement in puberty induction in the present study may be related to the increase in age at the implementation of the boar stimulation protocols. As reported by van Wettere et al. (2006), delaying the start of puberty stimulation results in a more synchronous response to boar stimulation.

A comparison of mean age at puberty and mean age at service (a difference of around 27 d across all gilts) suggests good compliance with a protocol that provides known cyclic gilts to the breeding farm/breeding room for mating at second observed estrus. As reviewed by Patterson and Foxcroft (2019), delaying breeding to the second estrus has a positive effect on litter size and future performance. Again, given the good growth performance of contemporary commercial replacement gilts, implementation of an effective gilt development program is critical if overweight gilts at breeding are not to become a risk factor for retention in the breeding herd. Greater than 80% of gilts that had a pubertal estrus within 35 d of the initiation of boar exposure in the present study were eventually bred. However, a BWi lower than 1.27 kg was associated with a decreased proportion of gilts bred. Selection of gilts with the greatest reproductive potential is a critical step in improving sow lifetime production (Patterson and Foxcroft, 2019) and takes advantage of the known link between early sexual maturity and improved sow lifetime productivity (Tart et al., 2013; Koketsu et al., 2017; Li et al., 2018).

Post-selection performance

These results illustrate excellent adherence to gilt development protocols, and these farms met proposed industry targets for age at puberty (Tart et al., 2013; Koketsu et al., 2017; Li et al., 2018), estrus at breeding (Aherne et al., 1991; Levis, 2000), and weight (Williams et al., 2005; Amaral Filha et al., 2008, 2010) and age at service (Tani and Koketsu, 2016; Koketsu et al., 2017, 2020). However, a greater proportion of gilts with a BWi greater than 1.55 kg exceeded the upper targeted weight for breeding of 160 kg. Therefore, even with efficient gilt selection and gilt development protocols in place, the overweight gilt at breeding was a potential risk for sow lifetime productivity.

Litter size born over four successive parities

As confirmed by Faccin et al. (2017), in gilts having at least one estrus before mating, and meeting the minimum requirement for growth rate (>0.55 kg/d), weight and age (>180 d of age) at mating, subsequent litter size, FR, and retention rate were not adversely impacted. Therefore, given the excellent adherence to gilt development protocols achieved on the farms used in the present study, it is not surprising to see a lack of effect of the litter of origin on many of the measures of sow lifetime productivity in the population of select gilts that entered the breeding herd.

However, a trend for increased stillborn in H-BWP gilts was detected. These results reflect a reported increased risk of stillborns in gilts with higher growth rates or excessive body weights (Amaral Filha et al., 2008; Bortolozzo et al., 2009). In addition, having more than one stillborn piglet in the first and second litter increases the risk of a sow being removed in later parities (Bergman et al., 2018). Our earlier research on the associations between the metabolic state of weaned parity 1 sows and their subsequent reproductive performance (Patterson et al., 2011; Foxcroft, 2012) might suggest a negative impact of the higher maintenance costs of these heavier sows during lactation on the amount of tissue catabolism needed to meet their requirements for continued growth and milk production. The results from the current study indicate that second litter size was compromised in gilts from H-BWP dams compared with M-BWP dams, and increased catabolism during lactation may again be a related factor.

Retention of sows in the breeding herd

Overall, there were no significant differences in retention between BWP classifications, and the industry benchmark of greater than 70% retention of gilts through three parities was met. In contrast, once selected and bred, the trend for the rate of attrition of sows derived from H-BWP dams to increase with successive parities is consistent with the reported link between heavier weights at selection and breeding and removal due to lameness and locomotion problems (Amaral Filha et al., 2008). However, in the current study, there was no difference in loss attributed to locomotion; rather, more sows tended to be culled as sudden deaths and prolapses, which may indicate a more complex set of issues underlying the poorer retention of gilts born to sows with the H-BWP. This is of particular relevance to current industry trends as sow mortality and prolapses (Iida et al., 2019; Supakorn et al., 2019a, 2019c) are an increasing concern.

Practical implications of this study

The lifetime number of quality pigs weaned is an accepted measure of individual sow productivity and is influenced by a number of factors, including pigs weaned/sow/year, litter size, preweaning mortality, lactation length, and nonproductive days (Koketsu et al., 2017). The lifetime efficiency of nucleus-multiplication sows in producing quality weaned gilts is also important, and these gilts will pass on the genetic superiority of their dams for important commercial traits. However, the number of replacement gilts that actually enter commercial production is also critical and affects the efficiency of the genetic transfer program. Therefore, the impact of commercial nucleus-multiplication sow BWP on gilt retention rates to pre-selection and then the ongoing proportion of gilts actually selected and bred are critical issues for the industry. One of the critical hypotheses underlying the present study is that sow BWP is determined by an interaction among key reproductive traits that have responded to decades of selection for numbers of total piglets born. However, these traits are not subject to direct selection, and sow BWP will bear little relationship to the ascribed genetic index of nucleus-multiplication sows. Significant differences in the overall retention rate of gilts to the pre-selection stage were established in the present study. At the production nucleus level, a low BWP would be associated with a lower production of gilts from these litters as pure-line replacements, either because the gilts born fail to meet growth requirements or because of potential negative developmental impacts of a low BWP on reproductive performance (Almeida et al., 2017). At the production multiplier level, although sows with a low BWP may produce few productive replacement gilts in their entire lifetime, this association between BWP and the efficiency of genetic transfer through the production nucleus-multiplication system is essentially unrecognized. Ladinig et al. (2014) reported a transgenerational effect of birth weight in pigs; consequently, those gilts born to L-BWP multiplication sows that do enter commercial production would be expected to pass on the low BWP to their slaughter generation progeny. Removing the 10% to 15% of nucleus-multiplication sows with an established L-BWP, and management practices to further improve gilt retention rates in the remaining sows, would lead to more efficient genetic transfer from nucleus sow to terminal line production in the smaller population of multiplication sows remaining. Indeed, if culling was based on litter birth weight data of the first two litters farrowed, even purebred nucleus replacement gilts could be removed as potential pure-line

replacements at the pre-selection 2 stage of development, at which time their birth dams would already have produced a second litter and a reliable and extreme L-BWP would have been established.

From a genetic transfer perspective, the production of very few replacement gilts in the productive lifetime of some sows in the production nucleus-multiplication herd represents a poor genetic investment. These sows only “earn” their genetic premium if their genetic potential is effectively passed on to the replacement gilts used for terminal line production. The disconnect between a high genetic merit for genetic traits included in the estimated breeding value of some nucleus/multiplication sows, and their poor reproductive performance in terms of replacement gilt production, emphasizes the need to measure and manage important phenotypic traits in contemporary sow populations. This is analogous to similar issues with investing in high-indexing artificial insemination boars with unproven fertility. Investing in high indexing boars that are determined to have relatively low fertility when used for artificial insemination, either in single-sire matings, or when used in pooled semen doses out of which the less fertile (uncompetitive) boars sire very few progenies, has been identified as a weakness in the management of many commercial boar studs (Dyck et al., 2018). Investing in high indexing nucleus-multiplication sows that are found to have a low litter BWP phenotype and thus the limited potential for supplying replacement gilts for commercial production suggest another inefficiency in the genetic transfer that could be avoided in well managed, in-house, breeding programs. In the larger production enterprises that manage both their own boar studs and production nucleus/multiplication sow farms, the opportunity to optimize genetic transfer to the level of terminal line production offers significant economic benefits. In both cases, the additional replacement costs of early culling of unproductive boars and sows are very largely offset by the enhanced performance of the boars and nucleus sows remaining in production. In terms of replacement gilt costs, a smaller but higher-quality supply of potential replacement gilts into the gilt development program would provide further economic benefits.

In conclusion, the results of this study provide evidence that sow BWP is an important factor in the overall efficiency of replacement gilt management. Sows with the L-BWP are largely composed of low individual birth weight gilts, and the current result confirms that low individual birth weight is a primary concern for early losses of potential replacement gilts before weaning. For those gilts that are pre-selected for entry to the breeding herd, ensuring that gilts meet the key eligibility requirements for age at puberty, and weight and estrus at service, will support good lifetime productivity.

Supplementary Data

Supplementary data are available at *Journal of Animal Science* online.

Acknowledgments

This work was funded by the National Pork Checkoff Sow Lifetime Productivity Project #18-138 and with financial support from Genus-PIC, Hendersonville, USA. We would like to thank Holden Farms, Inc. for their in-kind support and collaboration during this project.

Conflict of interest statement

The authors have no conflicts to declare.

Literature Cited

- Aherne, F. X., I. H. Williams, and R. H. Head. 1991. Nutrition – reproduction interactions in swine. Available from <http://livestocklibrary.com.au/handle/1234/19634>. Accessed October 19, 2020.
- Almeida, M. de, M. L. Bernardi, A. P. Motta, F. P. Bortolozzo, and I. Wentz. 2014. Effect of birth weight and litter size on the performance of landrace gilts until puberty. *Acta Sci. Vet.* 42:1182. Available from <http://www.ufrgs.br/actavet/42/PUB%201182.pdf>. Accessed October 19, 2020.
- Almeida, F., A. A. Dias, L. P. Moreira, A. T. L. Fiúza, and H. Chiarini-Garcia. 2017. Ovarian follicle development and genital tract characteristics in different birthweight gilts at 150 days of age. *Reprod. Domest. Anim.* 52:756–762. doi:10.1111/rda.12976
- Almeida, F. R. C. L., B. Laurensen, L. X. Pereira, K. J. Teerds, and N. M. Soede. 2015. Effects of birthweight on reproductive system development and onset of puberty in gilts. *Reprod. Fertil. Dev.* 29:254–261. doi:10.1071/RD15036
- Amaral Filha, W. S., M. L. Bernardi, I. Wentz, and F. P. Bortolozzo. 2009. Growth rate and age at boar exposure as factors influencing gilt puberty. *Livest. Sci.* 120:51–57. doi:10.1016/j.livsci.2008.04.009
- Amaral Filha, W. S., M. L. Bernardi, I. Wentz, and F. P. Bortolozzo. 2010. Reproductive performance of gilts according to growth rate and backfat thickness at mating. *Anim. Reprod. Sci.* 121:139–144. doi:10.1016/j.anireprosci.2010.05.013
- Amaral Filha, W. S., A. C. Schenkel, E. Seidel, M. L. Bernardi, I. Wentz, and F. P. Bortolozzo. 2008. Sow productivity over three parities according to weight at first service. In: Proceedings of the 20th IPVS Congress; June 22 to 26, 2008; Durban, South Africa, Produced by the Organising Committee of the 20th IPVS. Durban, South Africa: Hein Jonker Media Management; p. 442.
- Beltranena, E., F. X. Aherne, G. R. Foxcroft, and R. N. Kirkwood. 1991. Effects of pre- and postpubertal feeding on production traits at first and second estrus in gilts. *J. Anim. Sci.* 69:886–893. doi:10.2527/1991.693886x
- Bergman, P., Y. T. Gröhn, P. Rajala-Schultz, A. M. Virtala, C. Oliviero, O. Peltoniemi, and M. Heinonen. 2018. Sow removal in commercial herds: patterns and animal level factors in Finland. *Prev. Vet. Med.* 159:30–39. doi:10.1016/j.prevetmed.2018.08.010
- Bortolozzo, F. P., M. L. Bernardi, R. Kummer, and I. Wentz. 2009. Growth, body state and breeding performance in gilts and primiparous sows. In: H. Rodríguez-Martínez, J. L. Vallet, and A. J. Ziecik, editors. Control of pig reproduction VIII: Proceedings of the 8th International Conference on Pig Reproduction, May 31–June 4th, 2009, Alberta, Canada. Nottingham: Nottingham University Press.
- Calderón Díaz, J. A., J. L. Vallet, C. A. Lents, D. J. Nonneman, J. R. Miles, E. C. Wright, L. A. Rempel, R. A. Cushman, B. A. Freking, G. A. Rohrer, et al. 2015. Age at puberty, ovulation rate, and uterine length of developing gilts fed two lysine and three metabolizable energy concentrations from 100 to 260 d of age. *J. Anim. Sci.* 93:3521–3527. doi:10.2527/jas.2014-8522
- Da Silva, C. L., H. van den Brand, B. F. Laurensen, M. L. Broekhuijse, E. F. Knol, B. Kemp, and N. M. Soede. 2016. Relationships between ovulation rate and embryonic and placental characteristics in multiparous sows at 35 days of pregnancy. *Animal* 10:1192–1199. doi:10.1017/S175173111600015X
- Da Silva, C. L. A., H. A. Mulder, M. L. W. J. Broekhuijse, B. Kemp, N. M. Soede, and E. F. Knol. 2018. Relationship between the estimated breeding values for litter traits at birth and ovarian and embryonic traits and their additive genetic variance in gilts at 35 days of pregnancy. *Front. Genet.* 9:1–11. doi:10.3389/fgene.2018.00111
- Dyck, M. K., N. E. Diether, J. L. Patterson, and G. R. Foxcroft. 2018. AI management to optimize sow productivity. In: M. K. Dyck, and B. P. Willing, editors. *Advances in Pork Production*. Vol. 29. Edmonton, Canada: University of Alberta, Agriculture Food and Nutritional Science. p. 183–191.
- Fabà, L., J. Gasa, M. D. Tokach, M. Font-i-Furnols, E. Vilarasa, and D. Solà-Oriol. 2019. Effects of additional organic micro-minerals and methionine on carcass composition, gait score, bone characteristics, and osteochondrosis in replacement gilts of different growth rate. *Anim. Feed Sci. Technol.* 256:114262. doi:10.1016/j.anifeedsci.2019.114262
- Faccin, J. E. G., F. Laskoski, P. E. Lesskui, A. F. Lopes Paschoal, A. L. Mallmann, M. L. Bernardi, A. P. Gonçalves Mellagi, I. Wentz, and F. Pandolfo Bortolozzo. 2017. Reproductive performance, retention rate, and age at the third parity according to growth rate and age at first mating in the gilts with a modern genotype. *Acta Sci. Vet.* 45:1452. doi:10.22456/1679-9216.80034
- Foxcroft, G. R. 2012. Reproduction in farm animals in an era of rapid genetic change: will genetic change outpace our knowledge of physiology? *Reprod. Domest. Anim.* 47 (Suppl 4):313–319. doi:10.1111/j.1439-0531.2012.02091.x
- Foxcroft, G. R., W. T. Dixon, M. K. Dyck, S. Novak, J. C. Harding, and F. C. Almeida. 2009. Prenatal programming of postnatal development in the pig. In: H. Rodríguez-Martínez, J. L. Vallet, and A. J. Ziecik, editors. Control of pig reproduction VIII: Proceedings of the 8th International Conference on Pig Reproduction, May 31–June 4th, 2009, Alberta, Canada. Nottingham: Nottingham University Press.
- Foxcroft, G. R., W. T. Dixon, S. Novak, C. T. Putman, S. C. Town, and M. D. A. Vinsky. 2006. The biological basis for prenatal programming of postnatal performance in pigs. *J. Anim. Sci.* 84:E105–E112. doi:10.2527/2006.8413_supplE105x
- Greiner, M., D. Pfeiffer, and R. D. Smith. 2000. Principles and practical application of the receiver-operating characteristic analysis for diagnostic tests. *Prev. Vet. Med.* 45:23–41. doi:10.1016/S0167-5877(00)00115-x
- van Grevenhof, E. M., H. C. M. Heuven, P. R. van Weeren, and P. Bijma. 2012. The relationship between growth and osteochondrosis in specific joints in pigs. *Livest. Sci.* 143: 85–90. doi:10.1016/j.livsci.2011.09.002
- Iida, R., C. Piñeiro, and Y. Koketsu. 2019. Incidences and risk factors for prolapse removal in Spanish sow herds. *Prev. Vet. Med.* 163:79–86. doi:10.1016/j.prevetmed.2018.12.016
- Kang, J. H., E. A. Lee, K. C. Hong, and J. M. Kim. 2018. Regulatory gene network from a genome-wide association study for sow lifetime productivity traits. *Anim. Genet.* 49:254–258. doi:10.1111/age.12640
- Koketsu, Y., R. Iida, and C. Piñeiro. 2020. Increased age at first-mating interacting with herd size or herd productivity decreases longevity and lifetime reproductive efficiency of sows in breeding herds. *Porcine Health Manag.* 6:2. doi:10.1186/s40813-019-0142-9
- Koketsu, Y., S. Tani, and R. Iida. 2017. Factors for improving reproductive performance of sows and herd productivity in commercial breeding herds. *Porcine Health Manag.* 3:1. doi:10.1186/s40813-016-0049-7
- Kraeling, R. R., and S. K. Webel. 2015. Current strategies for reproductive management of gilts and sows in North America. *J. Anim. Sci. Biotechnol.* 6:3. doi:10.1186/2049-1891-6-3
- Ladinig, A., G. Foxcroft, C. Ashley, J. K. Lunney, G. Plastow, and J. C. Harding. 2014. Birth weight, intrauterine growth retardation and fetal susceptibility to porcine reproductive and respiratory syndrome virus. *PLoS One.* 9:e109541. doi:10.1371/journal.pone.0109541
- Levis, D. 2000. Housing and management aspects influencing gilt development and longevity: a review. In: Proceedings of the 2000 Allen D. Leman Conference; St. Paul, Minnesota; p. 117–131. Available from <https://conservancy.umn.edu/handle/11299/147364>. Accessed October 19, 2020.
- Li, Q., X. Yuan, Z. Chen, A. Zhang, Z. Zhang, H. Zhang, and J. Li. 2018. Heritability estimates and effect on lifetime

- reproductive performance of age at puberty in sows. *Anim. Reprod. Sci.* **195**:207–215. doi:[10.1016/j.anireprosci.2018.05.025](https://doi.org/10.1016/j.anireprosci.2018.05.025)
- Magnabosco, D., M. L. Bernardi, I. Wentz, E. C. P. Cunha, and F. P. Bortolozzo. 2016. Low birth weight affects lifetime productive performance and longevity of female swine. *Livest. Sci.* **184**:119–125. doi:[10.1016/j.livsci.2015.12.008](https://doi.org/10.1016/j.livsci.2015.12.008)
- Magnabosco, D., E. C. Pereira Cunha, M. L. Bernardi, I. Wentz, and F. P. Bortolozzo. 2015. Impact of the birth weight of Landrace × Large White dam line gilts on mortality, culling and growth performance until selection for breeding herd. *Acta Sci. Vet.* **43**:1–8. Available from <http://www.ufrgs.br/actavet/43/PUB%201274.pdf>. Accessed October 19, 2020.
- Patterson, J. L., E. Beltranena, and G. R. Foxcroft. 2010. The effect of gilt age at first estrus and breeding on third estrus on sow body weight changes and long-term reproductive performance. *J. Anim. Sci.* **88**:2500–2513. doi:[10.2527/jas.2008-1756](https://doi.org/10.2527/jas.2008-1756)
- Patterson, J., and G. Foxcroft. 2019. Gilt management for fertility and longevity. *Animals* **9**:434. doi:[10.3390/ani9070434](https://doi.org/10.3390/ani9070434)
- Patterson, J. L., M. N. Smit, S. Novak, A. P. Wellen, and G. R. Foxcroft. 2011. Restricted feed intake in lactating primiparous sows. I. Effects on sow metabolic state and subsequent reproductive performance. *Reprod. Fertil. Dev.* **23**:889–898. doi:[10.1071/RD11015](https://doi.org/10.1071/RD11015)
- Patterson, J., E. Triemert, B. Gustafson, T. Werner, N. Holden, J. C. Pinilla, and G. Foxcroft. 2016. Validation of the use of exogenous gonadotropins (PG600) to increase the efficiency of gilt development programs without affecting lifetime productivity in the breeding herd. *J. Anim. Sci.* **94**:805–815. doi:[10.2527/jas.2015-9705](https://doi.org/10.2527/jas.2015-9705)
- Rehfeldt, C., and G. Kuhn. 2006. Consequences of birth weight for postnatal growth performance and carcass quality in pigs as related to myogenesis. *J. Anim. Sci.* **84** Suppl:E113–123. doi:[10.2527/2006.8413_supple113x](https://doi.org/10.2527/2006.8413_supple113x)
- Rohrer, G. A., A. J. Cross, C. A. Lents, J. R. Miles, D. J. Nonneman, and L. A. Rempel. 2017. 026 Genetic improvement of sow lifetime productivity. *J. Anim. Sci.* **95**:11–12. doi:[10.2527/asasmw.2017.026](https://doi.org/10.2527/asasmw.2017.026)
- Sasaki, Y., and Y. Koketsu. 2008. Sows having high lifetime efficiency and high longevity associated with herd productivity in commercial herds. *Livest. Sci.* **118**:140–146. doi:[10.1016/j.livsci.2007.12.029](https://doi.org/10.1016/j.livsci.2007.12.029)
- Smit, M. N., J. D. Spencer, F. R. Almeida, J. L. Patterson, H. Chiarini-Garcia, M. K. Dyck, and G. R. Foxcroft. 2013. Consequences of a low litter birth weight phenotype for postnatal lean growth performance and neonatal testicular morphology in the pig. *Animal* **7**:1681–1689. doi:[10.1017/S1751731113001249](https://doi.org/10.1017/S1751731113001249)
- Supakorn, C., M. I. Christianson, J. Howard, K. A. Gray, and K. J. Stalder. 2019a. Heritability estimates for sow prolapse. *Livest. Sci.* **227**:111–113. doi:[10.1016/j.livsci.2019.07.006](https://doi.org/10.1016/j.livsci.2019.07.006)
- Supakorn, C., C. A. Lents, X. Martinez, J. Vallet, R. Dean Boyd, A. DeDecker, and K. J. Stalder. 2019b. 351 Neonatal birth weight effects on gilt development growth and first parity reproductive efficiency. *J. Anim. Sci.* **97**:146–147. doi:[10.1093/jas/skz122.259](https://doi.org/10.1093/jas/skz122.259)
- Supakorn, C., G. Moeller, J. Stock, A. Johnson, and K. J. Stalder. 2019c. A review of aetiology and risk factors affecting sow mortality. *Animal Science Publications*; p. 529. Available from https://lib.dr.iastate.edu/ans_pubs/529. Accessed October 19, 2020.
- Tani, S., and Y. Koketsu. 2016. Factors for culling risk due to pregnancy failure in breeding-female pigs. *J. Agric. Sci.* **9**:109–117. doi:[10.5539/jas.v9n1p109](https://doi.org/10.5539/jas.v9n1p109)
- Tart, J. K., R. K. Johnson, J. W. Bundy, N. N. Ferdinand, A. M. McKnight, J. R. Wood, P. S. Miller, M. F. Rothschild, M. L. Spangler, D. J. Garrick, et al. 2013. Genome-wide prediction of age at puberty and reproductive longevity in sows. *Anim. Genet.* **44**:387–397. doi:[10.1111/age.12028](https://doi.org/10.1111/age.12028)
- Tóth, F., J. L. Torrison, L. Harper, D. Bussieres, M. E. Wilson, T. D. Crenshaw, and C. S. Carlson. 2016. Osteochondrosis prevalence and severity at 12 and 24 weeks of age in commercial pigs with and without organic-complexed trace mineral supplementation. *J. Anim. Sci.* **94**:3817–3825. doi:[10.2527/jas.2015-9950](https://doi.org/10.2527/jas.2015-9950)
- van Wettter, W. H., D. K. Revell, M. Mitchell, and P. E. Hughes. 2006. Increasing the age of gilts at first boar contact improves the timing and synchrony of the pubertal response but does not affect potential litter size. *Anim. Reprod. Sci.* **95**:97–106. doi:[10.1016/j.anireprosci.2005.09.009](https://doi.org/10.1016/j.anireprosci.2005.09.009)
- Williams, N. H., J. L. Patterson, and G. R. Foxcroft. 2005. Non-negotiables in gilt development. In: *Advances in Pork Production*. Vol. **16**; Edmonton, California: University of Alberta, Agriculture Food and Nutritional Science; p. 281–289.
- Yuan, T. L., Y. H. Zhu, M. Shi, T. T. Li, N. Li, G. Y. Wu, F. W. Bazer, J. J. Zang, F. L. Wang, and J. J. Wang. 2015. Within-litter variation in birth weight: impact of nutritional status in the sow. *J. Zhejiang Univ. Sci. B.* **16**:417–435. doi:[10.1631/jzus.B1500010](https://doi.org/10.1631/jzus.B1500010)