ABSTRACT

MORRISON, MATTHEW DAVID ALLEN. Estimates of Variance Components for Gilt Retention Traits. (Under the direction of Dr. Todd See and Dr. Mark Knauer.)

The objective of this study was to estimate variance components among traits of importance to gilt retention in modern swine production. The study used 6,282 gilts with Large White dams and Landrace sires, distributed among 11 different sow farms within the State of North Carolina, from Smithfield Premium Genetics Group. Gilts were on average 262 d (SD=25) of age at first mating and 377 d (SD=25) at first farrowing. Traits considered were piglet birth weight (BWT), age at first service (AFS), age at first farrowing (AFF), whether a gilt farrowed a first litter (STAY), whether a gilt was culled for reproductive reasons (CFR) and whether a gilt was culled for nonreproductive reasons (CFO). Variance components were calculated using an animal model with THRGIBBS1F90 for categorical traits and GIBBS2F90 for linear traits. Heritability estimates for CFR and CFO were 0.19 and 0.05, respectively, while the heritability for STAY was 0.11. Age at first service and age at first farrowing had heritability estimates of 0.24 and 0.20, respectively, while having a genetic correlation of 0.995. The estimated genetic correlation between STAY and AFS was 0.78. Based on the results of this study genetic improvement for gilt retention appears possible. Improvements in gilt retention may be possible by genetically decreasing age at first service.

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Estimates of Variance Components for Gilt Retention Traits

by
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DEDICATION

First to my parents for teaching me the value of hard work. To Marvin Johnson and Dan Hoge for continuing to push me forward. Last but not least, my fiancé Tamara Wessels for your unwavering support.

BIOGRAPHY

Matthew Morrison, the son of Margie and David Morrison grew up with one older brother, Martin in Conwango Valley New York. He helped with the family farm and was actively involved with the Pine Valley FFA and Chautauqua County 4-H program. His passion for livestock drove him to obtain his associates from Black Hawk East community college and Bachelor's of science from Western Illinois University.

During his undergraduate career he served on the National Junior Swine Association's junior board of directors. Matthew was a member of competitive livestock judging teams at both Black Hawk East and Western Illinois University. During this time he was employed by several show pig and commercial swine operations that fueled his interest in working in animal agriculture. His time working for the Western Illinois University bull test started the transition of thinking about animal breeding and genetics in a more scientific manner.

After graduation, Morrison interned with Smithfield Premium Genetics group (SPG). This experience confirmed his interest in animal breeding and genetics and helped lead him to his Masters research project of estimating variance components of gilt retention traits. During his Masters studies he has had the opportunity to continue his passion for livestock evaluation by assisting with the NCSU colligate livestock judging team.

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LITERATURE REVIEW

Introduction

Improving reproductive fitness is an area of interest within the swine industry where producers wish to capitalize on the value of breeding females. Authors have reported the importance of quality replacement gilts (Christenson, 1986; Nelson et al., 1990; Tárres et al., 2006a; Hoge and Bates, 2011). Studies have evaluated sow longevity and traits that impact sow longevity (Le Cozler et al., 1998; Lucia et al., 2000; Serenius and Stalder, 2004; Tárres et al., 2006a; Tárres et al., 2006b; Serenius et al., 2008; Knauer et al., 2010; Hoge and Bates, 2011; Amér et al., 2014). However fewer studies have evaluated gilt retention, defined as the ability of a replacement gilt to farrow a litter (Knauer et al., 2011; Lewis and Bunter, 2011). The investigation of gilt retention can be separated into two categories, genetics and environment. The following review has been organized to analyze scientific articles that discuss pertinent information to the success of gilt retention into 11 sections; first of which covers the underlying challenge and economics involved with replacement rates, followed by nongenetic factors associated with gilt retention and finally a summarization of the genetics behind gilt retention.

Economics of gilt and sow retention

High female culling rates increase the need for replacement gilts and have a negative effect on profits (Christenson, 1986; Stalder et al., 2003; Serenius and Stalder, 2004). Within the swine industry replacement rates are reported between 42% and 59% (Dagorn and Aumaitre, 1979; Dijkhuizen et al., 1989; Lucia et al., 2000; Tárres et al., 2006b) with an average parity at culling between 3.1 and 3.7 (Lucia et al., 2000; Stalder et al., 2003). Of sows that are removed from the herd, most are culled for reproductive reasons (Dagorn and Aumaitree, 1979; Lucia et al., 2000; Patterson et al., 2010; Sasakie and Koketsu, 2011). Hence, improving female retention can enhance the economic efficiency of the swine industry and increase profits by reducing expenses associated with replacement gilts (Nikkila et al., 2013).

The introduction of new breeding females into the sow herd represents an important financial investment (Dyck, 1988; Lucia et al., 2000; Tárres et al., 2006b). The percent of gilts that farrow a first litter ranges from 61% to 92% (Moeller et al., 2004; Knauer et al., 2011; Lewis and Bunter, 2011). This makes replacement gilts a highly inefficient investment, as those gilts that do not farrow are generally heavier than optimal market weight (Dyck, 1988). An increased number of low parity sows in a breeding herd is also associated with reduced reproductive throughput (Lucia et al., 2000).

There are direct and indirect costs associated with replacement gilts whether they are purchased or retained through a breeding program (Lucia et al., 1999; Tárres et al., 2006b). The methodology used by Stalder et al. (2003) placed the direct costs associated with a replacement gilt at ninety dollars over market hog price, awarding a premium for genetic merit. The introduction of high numbers of replacement gilts adds indirect costs associated with increased disease risk (Tárres et al., 2006b). Capital is also needed to rear replacement gilts until they are ready to be mated, incurring feed, facility and management costs (Stalder et al., 2003).

Stalder et al. (2003) states that net present value (NPV) can be used to estimate when a sow pays for her initial cost and becomes a profitable asset. In that study, the authors used

NPV to determine that the average gilt needs to farrow three parities before becoming a positive asset. Since the average cull sow parity ranges from 3.1 to 3.7 (Lucia et al., 2000; Stalder et al., 2003), on average sows are culled just after reaching a positive NPV. The authors further prove a reduction in gilt replacement costs by 12% would result in a positive NPV at parity two vs. parity three. Hence under the authors' parameters a reduction of gilt replacement costs by 12% would allow the average gilt to attain a positive NPV a full parity before culling.

Nutrition and the developing gilt

The impact of restricting gilt feeding level in relation to subsequent reproduction has produced variable findings (Klindt et al., 2001; Johnson et al., 2008; Knauer et al., 2012). Klindt et al. (2001) fed gilts 1 of 3 different feeding levels (74% of ad libitum, 90% of ad libitum, ad libitum) from 13 to 25 weeks of age. The authors reported gilts that were limited to 74% of ad libitum had reduced feed consumption from 13 weeks of age to farrowing when compared to gilts fed 90% of ad libitum or ad libitum. Yet this did not limit piglet production as the differences between groups for number of piglets born per gilt assigned to ad libitum, 90% of ad libitum and 74% of ad libitum were not statistically significant (6.47, 7.26 and 6.38, respectively). The same authors reported gilts that were restrictively fed 74% of ad libitum consumed 12% less feed and had one percent less body weight at farrowing compared to those fed 90% of ad libitum. The feed efficiency differences between the 74% and 90% restricted treatments reported by Klindt et al. (2001) suggests restricted gilts experienced compensatory gain during the flushing stage prior to breeding when compared to those fed ad libitum. Johnson et al. (2008) fed gilts 75% of ad libitum or ad libitum beginning at 123 days of age until entering the breeding farm. The authors reported gilts fed restrictively had a reduced probability of exhibiting estrus when compared to those fed as libitum (85 vs. 95%, respectively); however, restrictively feeding gilts numerically improved the probability of surviving through three parities (30 vs. 26%, respectively). Knauer et al. (2012) restricted gilts to 2.05 kg at a later stage of development, from 200 to 270 days of age. Results showed gilts that were restricted exhibited a longer length of estrus (2.18 vs. 2.03 days), stronger standing reflex (15.4 vs. 14.0) and younger age at puberty (219 vs. 225 days of age) when compared to those fed ad libitum. The authors further stated that developing gilts might benefit from ad libitum feeding through 200 days of age and then being placed on a limited ration. Perhaps the differences in timing of diet restrictions between studies accounts for the variation in previous findings. Yet Stalder et al. (2000) points out restrictively feeding replacement gilts is challenging to implement given the design of many modern production systems.

Stalder et al. (2000) fed three gilt development diets that varied in energy and crude protein levels to gilts from five genetic lines (A, B, C, D, E) representative of the industry. In the authors study, diet 1 consisted of 18% crude protein, 0.96% lysine and 2.97% crude fat, diet 2 contained 13% crude protein, 0.60% lysine and 8.14% crude fat. Both diets 1 and 2 were fed at ad libitum from 68 kg to 113 kg of body weight. Gilts that were fed diet 3 received 1.81 kg of feed containing 23% crude protein, 1.30% lysine and 2.52% crude fat after reaching 82 kg of body weight. The variation in composition of diets succeeded in creating differences in growth and fat reserves; where, gilts fed diet 1 were faster growing and had more fat deposition than those fed diet 3. Gilts that were fed diet 2 in the study had a higher ADG and more fat deposits than gilts fed ether diet 1 or 3; while gilts fed diet 3 were smallest at 200 days of age. The authors further reported gilt development diet did not have a significant effect on reproductive performance in parity one; however, there was a significant diet by genetic line interaction for total number born and number born alive in parity one. Yet the amount of variation accounted for by the diet by genetic line interaction was not consistent across each genetic line. Stalder et al. (2000) found none of the reproductive traits measured at 21 days were impacted by the interaction of gilt developing diet and genetic line suggesting that there was little to no difference in lactation performance based on the interaction. The authors suggested that producers give gilts ad libitum access to a moderate protein diet; however, this was not based on changes in reproductive performance, but rather with the consideration of convenience and economics.

In another attempt to change body composition, Calderón Díaz et al. (2015a) fed gilts one of six diets with different ME levels ad libitum. The six diets in the study ranged from 18.0 to 21.8% crude protein, 0.97 to 1.28% lysine and 2.9 to 3.6 ME (Mcal/kg). The only resulting change between diets was a slight increase in backfat, gilts that were fed the high ME (3.6 Mcal/Kg) diet had an increase of 2.2 mm of backfat when compared to gilts fed the low ME diet (2.9 Mcal/Kg). The authors further reported gilts that were fed diets low in ME had greater feed consumption than gilts fed the intermediate or high ME diets (7.3 and 14.9 kg, respectively). The authors stated the lack of change in body composition was thought to be a consequence of gilts changing their intake patterns according to ME density of the diet fed. Gilts in the study were first exposed to boars for estrous detection at day 160 and then were harvested at approximately 260 days of age and the reproductive tracts were collected

(Calderón Díaz et al., 2015b). The authors counted corpus lutea, measured uterine horn length and scored reproductive tracts on a four point scale based on the stage of development. Results showed gilt development diet did not impact age at puberty or reproductive tract measurements.

Nutritional requirements for developing gilts are reported in the National Swine Nutrition Guide (Whitney et al., 2010). Suggested amino acid, calcium and phosphorus levels for proper gilt development are listed in Table 1. Recommended ranges of salt, trace minerals and vitamin profiles for replacement breeding swine are shown in Table 2. Table 3 contains guidelines for optimum levels of trace minerals and vitamins for inclusion in replacement swine diets. The National Swine Nutrition Guide further suggests that gilts for breeding purposes should be fed differently than market swine once they reach 180 pounds by increasing minerals, calcium and phosphorus to build body reserves (Whitney et al., 2010).

Backfat

Gilt backfat and its role in sow longevity and sow lifetime performance has been thoroughly studied (Brisbane and Chesnais, 1996; Rozeboom et al., 1996; Yazdi et al., 2000a; Stalder et al., 2005; Tárres et al., 2006b; Knauer et al., 2010; Hoge and Bates, 2011). Brisbane and Chesnais (1996) reported gilts with greater than 18 mm of backfat had a 30% increase in longevity when compared to those with less than 10 mm of backfat across herds. Yet within herds, fatter gilts (>18 mm) had a 4 to 7% increase in longevity when compared to leaner gilts (<10 mm) indicating across farm results were biased due to herd management. In agreement, Tárres et al. (2006b) reported that low levels of backfat (<16 mm) were associated with increased culling of gilts. Similarly, Stalder et al. (2005) reported the fattest gilts (≥ 25 mm) had a greater lifetime number of piglets than those in the leanest group where backfat was ≤ 9 mm (27.6 vs. 20.1). The difference in lifetime piglets was influenced by an increased number of parties for fat gilts (3.1 vs. 2.3). In perhaps the only study with standardized culling criteria, Knauer et al. (2010) reported gilt backfat impacted sow longevity in three of the six genetic lines tested. In three genetic lines where backfat was significant, an increase in backfat increased the likelihood of farrowing a fourth litter. In contrast, Rozeboom et al. (1996) and Yazdi et al. (2000a) reported gilt backfat was not related to sow longevity. The effect of gilt backfat on sow longevity remains debatable; however, differing results may be related to differences in genetics or the location and/or timing of backfat measurements (Stalder et al., 2005). It has been suggested that a threshold of acceptability in terms of backfat may increase the retention of replacement gilts (Stalder et al, 2005).

The effect of backfat on age at puberty, age at first mating, or the age at first farrowing has been investigated (Nelson et al., 1990; Eliasson et al., 1991; Stalder et al., 2005; Tárres et al., 2006b). Nelson et al. (1990) reported fatter gilts were more likely to exhibit a normal estrous cycle when compared to leaner gilts. This supports the idea that gilts with more backfat at 90 kg will attain puberty at younger ages than leaner gilts (Eliasson et al., 1991). Stalder et al. (2005) reported the fattest gilts (≥ 25 mm) were 10 days younger at first farrowing than the leanest gilts (≤ 9 mm). Hence, lower levels of backfat can delay puberty and perhaps reduce gilt retention if herds give gilts a fixed time to exhibit estrus.

Growth rate and weight

The impact of growth on sow longevity and lifetime productivity has been examined (Rozeboom et al., 1996; Yazdi et al., 2000a; Stalder et al., 2005; Tárres et al., 2006b). Slow growing gilts are less likely to be culled (Hoge and Bates, 2011) and have a greater number of total lifetime pigs produced (Stalder et al., 2005). Knauer et al. (2010) reported that in three of six genetic lines average daily gain had a significant effect on sow longevity, with reduced growth being favorable for longevity. Tholen et al. (1996) reported a negative genetic correlation between average daily gain and sow longevity, particularly in early parities (r_g=-0.16). In contrast, Yazdi et al. (2000a) reported no association between average daily gain up to 170 days of age and sow longevity. The timing of growth measurements may impact gilt reproduction; gilts that had rapid growth after the developmental stage until breeding were more at risk for culling (Tárres et al., 2006b).

The growth of developing gilts and its impact on age at puberty, age at first mating or age at first farrowing has been thoroughly studied (Eliasson et al., 1991; Rozeboom et al., 1996; Stalder et al., 2005; Patterson et al., 2010; Filha et al., 2010; Hoving et al., 2010). Stalder et al. (2005) reported gilts that took longer than 210 days to reach 114 kg were older at first farrowing than those gilts that reached 114 kg in less than 150 days (405 vs. 386 days). In agreement, Eliasson et al. (1991) reported that an increase in growth rate of 100 grams per day reduced age at puberty by three days. In contrast, Patterson et al. (2010) reported that growth rate during the first 100 days of a gilts life did not impact age at puberty. Filha et al. (2010) divided gilts into three growth rate groups 600 to 700 (I), 701 to 770 (II) and 771 to 880 g per day (III). The authors reported no difference in farrowing rate between growth rate groups I, II and III (91.3, 91.6 and 92.6%, respectively).

Weight at breeding is thought to be an important factor in gilt retention (Hoving et al., 2010). In Hoving et al. (2010), gilts that were 10 kg heaver at breeding had a 15.5% increased chance of rebreeding after weaning their first litter. The authors suggest that heavier gilts are better able to rebreed after their first litter because they have more body reserves. Young, light sows have the highest feed costs, as they require more energy to reach mature size (Amér et al., 2014). Williams et al. (2005) observed the impact of weight on subsequent reproduction of 1,674 gilts in a commercial sow unit. Results of a cost benefit analysis showed that the optimum weight for mating was between 135 and 150 kg. The same study showed that gilts weighing under 135 kg at mating had less total pigs born after three parties when compared to gilts weighing over 135 kg at mating (31.1 vs. 32.8). Newton and Mahan (1993) fed 114 Yorkshire × Landrace F1 cross gilts three different diets to vary weight at breeding without confounding age. The study did not find an impact of breeding weight on puberty onset or number of pigs born through three parties. The authors recommended a breeding weight of 135 kg based on multiple factors. First, the authors observed a numerical increase in the percent of gilts that failed to conceive or were anestrous in the 120 kg breeding group when compared to the 135 kg and 150 kg (52.8 vs. 42.5 and 31.6%, respectively). Next, gilts in the heaviest group had a higher incidence of piglet mortality in parities 1, 2 and 3 when compared to gilts from the 120 kg or 135 kg group.

Gilt housing

Literature tends to be in agreement that group size can have an impact on mating and regular estrous cycles (Cronin et al., 1983; Christenson, 1984). Christenson (1984) followed the estrous cycles of gilts raised in pens of 3, 9, 17 and 27 with a constant stocking density of 1.1 m^2 per gilt. The study checked gilts daily from 7 to 9 months of age for estrus. At nine months of age, pens of 3 had fewer normal cycling gilts than pens of 9, 17 or 27 (56.9 vs. 78.0, 80.4 and 80.7%, respectively). Cronin et al. (1983) analyzed failure to mate between 29 and 35 weeks of age in Australian Large White, Landrace and Large White × Landrace cross females. Results showed gilts reared in pens of 50 or more had a greater percentage of females not mated when compared to gilts reared in pens of less than 50 (12.9 vs. 8.6%). The authors reported that 77% of unmated gilts at 35 weeks of age had a silent estrus meaning they had low or no response to the back-pressure test. The rate of silent estrus was double for gilts in pens of 50 or more when compared to gilts in a pen size of less than 50 (8.0 vs. 3.6%). Perhaps this was caused by increased difficulties in observing the standing estrus due to a large number of gilts (Cronin et al., 1983; Eliasson et al., 1991).

The impact of stocking density on gilt development has produced mixed results (Ford and Teague, 1978; Rahe et al., 1987; Young et al., 2008). Rahe et al. (1987) raised gilts in two treatments; the first reared with 1.06 m^2 per gilt from 30 to 65 kg of body weight and then 1.25 m^2 per gilt from 65 to 100 kg; the second treatment of gilts was raised in half the stocking density by doubling the number of gilts per pen. Upon reaching 100 kg of body weight, gilts were harvested and the brain, adrenals, pituitary, uterus and ovaries were collected. The study resulted in lighter reproductive and endocrine organs for those gilts raised under crowded conditions. Specifically, gilts reared in the higher stocking density had lighter uterus weights (166 vs. 196 g) and pituitary gland weights (314 vs. 325 g) when compared to gilts raised in lower stocking densities. The authors reported fewer gilts in high stocking rate treatment ovulated prior to harvest when compared to the low stocking density group (13 vs. 32%). In agreement, Young et al. (2008) reported more gilts raised with a stocking density of 1.13 m^2 per gilt reached puberty than those reared with a stocking density of 0.77 m^2 per gilt (32.7 vs. 30.3%). Besides enhanced puberty attainment, those reared in a stocking density of 1.13 m^2 per gilt were younger at puberty compared to those in the 0.77 m^2 treatment (182 vs. 184 days). In contrast to the findings of Rahe et al. (1987) and Young et al. (2008), Ford and Teague (1978) showed no differences in puberty based on stocking density. In that study, gilts in the control stocking density were provided with 0.37 m^2 per female until average weight reached 34 kg at which time pigs were given 0.09 m^2 per pig more room. As gilts continued to grow they were given an additional 0.09 m^2 per pig for every 13.6 kg increase in weight. Besides the control group, gilts were also reared under two treatment conditions receiving 50 and 75% of the control space, respectively. No differences were detected in the proportion of gilts that reached puberty by eight months of age for the control, 50 or 75% stocking densities (97, 100, and 100%, respectively). However, pigs in the 50% treatment showed decreased average daily gain, poorer feed efficiency, and increased weight variation.

Studies have been conducted on stocking density and its effects on sow retention (Young et al., 2008; Estienne et al., 2015). Young et al. (2008) raised gilts with ether a stocking density of 0.77 m^2 or 1.13 m^2 per gilt. Rearing space did not impact a component trait of sow retention, weaning-to-estrus interval, as analyzed for parities 1, 2 or 3. Wean-to-estrus intervals for parities 1, 2, and 3 for gilts raised in a stocking density of 0.77 m^2 were 11.4, 6.5, and 6.7 days, respectively, and for 1.13 m^2 were 10.8, 7.0, and 6.0 days, respectively. The authors report gilts raised with a stocking density of 0.77 m^2 per gilt had similar removal rates for parities 1, 2 and 3 when compared to gilts raised with 1.13 m^2 per gilt stocking density (27.4, 40.2 and 48.2%, respectively) vs. (25.0, 28.8 and 44.6%, respectively). In Estienne et al. (2015) gilts were allocated to three nursery stocking densities of 0.17 m^2, 0.25 m^2 and 0.33 m^2 per gilt. A higher percentage of gilts raised in a stocking density of 0.17 m^2 farrowed a first litter when compared to those reared at 0.33 m^2 per gilt (97.1 vs. 93.6%, respectively). The same authors reported no differences between stocking densities of 0.17, 0.25 and 0.33 m^2 per gilt in the percentage of gilts that farrowed a second litter (77.4, 73.2 and 73.9%, respectively) or third litter (66.2, 63.8 and 62.3%, respectively). Collectively, results suggest that gilt stocking density during development does not impact culling rate at parity two and three. Yet the results of Estienne et al. (2015) suggest that nursery stocking density impacts gilt culling at parity one.

The impact of heat stress on the onset of puberty, a component of gilt retention, was investigated by Flowers et al. (1989) and Flowers and Day (1990). In both Flowers et al. (1989) and Flowers and Day (1990) gilts were housed in environmentally controlled chambers under one of two environments. Control gilts were housed at 15.6 °C and 35% relative humidity and heat stressed gilts at 33 °C and 35% relative humidity, typical high temperatures of summer pork production. In both Flowers and Day (1990) and Flowers et al. (1989) there was not a significant difference in growth and feed intake between stressed gilts and control gilts. Both studies report heat stressed gilts had higher respiration rates and water consumption when compared to control gilts. Flowers et al. (1989) reported fewer heat stressed gilts (20 vs. 90%) reached puberty. Heat stressed gilts were on average 9 days older at puberty when compared to gilts in the control environment. The authors suggest that the delay in puberty was a consequence of lowered levels of gonadotropin secretion and not a function of variation in growth and feeding patterns. Flowers et al. (1989) clearly shows that heat stress negatively impacts puberty attainment; therefore, heat stress can negatively impact gilt retention.

In continuing efforts to understand the effects of heat stress, Flowers and Day (1990) studied gilts that underwent a bilateral, unilateral or sham ovariectomy. The ovariectomy procedures in that study allowed for increases in plasma concentrations of LH and FSH along with the examination of ovaries. Results showed that heat stressed gilts secreted less LH and FSH than gilts in the control environment (51 and 32%, respectively). The authors further reported gilts in heat stress conditions were more prone to having cystic follicles and exhibited fewer small follicles (< 6.0 mm) than those that were raised in the control environment. Specifically, gilts that underwent sham and unilateral ovariectomy surgeries in the heat stressed group had 29.4 and 31.5 small follicles, respectively, and control gilts had 42.6 and 46.1 small follicles, respectively. Collectively, results suggest that gilts raised in heat stress conditions have decreased follicular activity and a reduction in hormone secretions needed for the onset of puberty; thus further supporting that heat stress can negatively impact gilt retention.

Feet and leg soundness of developing gilts

Dijkhuizen et al. (1989) reported the highest economic loss from culling sows was due to lameness or leg weakness. D'Allaire et al. (1987) reported that feet and leg issues are common in young sows with 20, 16 and 11% being culled in parties 1, 2 and 3, respectively. Feet and leg problems have further complications as they may limit those gilts that can be used as replacements. Therefore leg weakness can decrease selection intensity and slow the amount of progress that can be made by swine breeding programs (Tárres et al. 2006a). As gilts transition from parity one to parity two, feet and leg issues become increasingly important in relation to culling (Sasaki and Koketsu, 2011).

Studies have investigated the effect of feet and leg soundness on sow longevity (Barczewski et al., 1990; Yazdi et al., 2000b; Serenius and Stalder, 2004; Tárres et al., 2006a). Tárres et al. (2006a) used a hazard function to analyze the effects of feet and leg traits on sow longevity. The authors scored rear legs, side view angle of rear legs, angle of rear pasterns, and size of inner claws on rear leg. Feet and leg traits were assigned a score ranging from 1 to 7 with a score of four being optimum. Gilts with extreme rear leg scores were 1.4 times more likely to be culled when compared to gilts with an intermediate rear leg score (4). The same study reported that gilts with the ideal score for inner claw length on rear legs were 0.83 times less likely to be culled than those with more extreme scores. The authors reported replacement rate decreased approximately 5% when sows had optimum feet and leg scores. Barczewski et al. (1990) studied the effect of feet and leg traits on reaching parity three. The study photographed gilts as they walked on a treadmill to objectively score feet, leg and locomotion traits. The authors reported gilts with weak front and rear pasterns tended to be more likely to reach parity 3. Having a smaller rear hock angle was less desirable, gilts that were culled at 192 days of age or after farrowing parity one had statistically smaller rear hock angle scores then those that survived. The authors further reported gilts that reached parity three had greater rib width when compared to females culled before parity three. Grindflek and Sehested (1996) studied the effect of feet and leg traits on longevity in Norwegian Landrace and Yorkshires. The authors recorded feet and leg traits prior to farrowing and reported gilts with straight pasterns, sickle-hocks or rear legs standing under had the highest probabilities of poor locomotion. Results found that sows with poor locomotion were 21% less likely to farrow their second litter.

Osteochondrosis, or the abnormality of bone and cartilage due to high growth or injury, can also impact retention of breeding swine (Goedegebuure et al., 1988; Yazdi et al., 2000b). Yazdi et al. (2000b) studied the effect of osteochondrosis on sow longevity in Yorkshire and Landrace pigs, reporting a low genetic correlation between sow longevity and osteochondrosis (r_g = 0.07). Hence, osteochondrosis tended to increase the culling of sows in the study. Geodegebuure et al. (1988) divergently selected Duroc swine for changes in front leg soundness. Front leg structure was scored on a scale of 1 (worst) to 9 (best). The authors reported gilts with high front leg measurements had decreased osteochondrosis; hence, selection for feet and leg traits may help minimize complications due to osteochondrosis.

Studies have shown that selection and improvement for feet and leg traits are possible (Rothschild and Christian, 1988; Serenius and Stalder, 2004; Knauer et al., 2011; Nikkila et al., 2013). It has been suggested that gilt retention and longevity can be improved through indirect selection on feet and leg traits (Lopez-Serrano et al., 2000; Serenius and Stalder, 2004; Knauer et al., 2011). Rothschild and Christian (1988) studied the response to selection after five generations of divergent selection for front leg structure in Duroc swine. Heritability estimates for front leg structure of the improved genetic line and worsened genetic line were 0.29 and 0.42, respectively. Serenius and Stalder (2004) estimated the heritability of overall leg action in Finish Landrace and Large White pigs to be 0.06 and 0.07, respectively. Knauer et al. (2011) reported relatively greater heritability estimates for front leg side view, rear leg side view, front leg front view and rear leg rear view of 0.37, 0.11, 0.25 and 0.18, respectively. Nikkila et al. (2013) produced heritability estimates for 11 feet and leg traits ranging from 0.07 to 0.31. The same authors reported overall leg action had a heritability of 0.12. Given associations between structural conformation and locomotion with gilt and sow retention, indirect selection for feet and leg traits would likely improve gilt retention in populations with average or below average structural conformation.

Boar exposure

It is a common practice to expose gilts to mature boars to induce estrus and detect heat in swine (Young et al., 1990; Patterson et al., 2010; Knauer et al., 2010). Patterson et al. (2010) exposed gilts to mature boars at an average of 140 days of age resulting in 73% of gilts showing identifiable signs of puberty before 180 days of age. In studies by Young et al. (1990) and Patterson et al. (2010), gilts that were exposed at an early age to boar stimulation did not have any reductions in subsequent reproductive throughput. Patterson et al. (2010) reported that early boar exposure can be used to observe age at puberty and identify 50 to 75% of gilts that will have a longer reproductive life.

Proper estrous detection may be a factor in gilt retention. Methods of boar exposure to insure maximum effectiveness of estrous detection have been studied (Hemsworth et al., 1984; Hemsworth et al., 1986; Patterson et al. 2002). Hemsworth et al. (1986) determined that applying the back-pressure test to gilts in the presence of a boar was more effective in detecting estrus than without the presence of a boar (95 vs. 81%). In Hemsworth et al. (1984) and Hemsworth et al. (1986) gilts were either housed with constant direct boar contact or were housed with a one meter aisle separating them from boars. Results showed that detecting estrus using the back-pressure test was less efficient when gilts were housed with direct contact to boars compared to when gilts were separated from boars by an aisle one meter in width. These results suggest gilts should not be housed in direct contact to boars in order to maximize the effectiveness of the male during estrous detection. Patterson et al. (2002) studied three methods of boar exposure and its impacts on the onset of puberty in gilts. The three methods used in the study were direct boar contact with pens of gilts being moved to boars (DGB), direct boar contact with the boar being moved to the gilt pens (DBG) and fence-line contact with gilts being housed in individual stalls (FBG). The authors reported gilts with direct contact to boars (DGB and DBG) reached puberty at an earlier age and had a shorter interval between first boar exposure and puberty attainment when compared to gilts with fence-line contact (181 and 184 vs. 191 days, respectively, and 21.8 and 24.0 vs. 32.0 days, respectively). Yet the percent of gilts that obtained puberty by 215 days was not statistically different between groups in the study. Boar exposure methods DGB, DBG and FBG resulted in 96, 82, and 81% of gilts obtaining puberty, respectively. These results contrast with those of Hemsworth et al. (1984) who utilized two methods of boar exposure. In the first method gilts were placed in the alleyway adjacent to boar pens for five minutes. The second method of boar exposure gilts were checked for estrus in their own pens separated from boars by an alleyway one meter in width. Results showed that boar exposure methods impacted estrous detection as more gilts were detected when they were exposed to boars in the alleyway compared to boar exposure in their own pen (90 vs. 52%, respectively). Collectively, these studies suggest proper boar exposure methods can be thought of as an important component of gilt retention.

The impact of age at first boar exposure on age at puberty and puberty obtainment, component traits of gilt retention, has been investigated (Brooks and Smith, 1980; Cronin et al., 1983; Flowers, 2009). Flowers (2009) exposed 3,180 gilts to boars at either 140 or 170 days of age. In that study, a mature boar was put in pens of gilts daily for 15 to 20 minutes. Gilts were followed through 6 parities of production. A higher percentage of gilts that were exposed to boars at 140 days of age obtained puberty when compared to gilts that were exposed to boars at 170 days of age (88.5 vs. 82.3%). At parity 6, more gilts that were exposed at 140 days of age remained in production compared to gilts exposed at 170 days of age (35 vs. 17%). These results are in agreement with Cronin et al. (1983) who studied the impact of age at boar exposure in Australian swine production. Gilts (n=2,912) were divided into two groups; those receiving boar exposure at 23 weeks of age and those receiving boar exposure at 28 weeks of age. In the study gilts that were unmated after 35 weeks were culled so that ovaries could be examined for signs of puberty. Fewer gilts exposed to boars at 23 weeks did not reached puberty when compared to those exposed at 28 weeks (1.5 vs. 3.0%). The production system in the study used natural matings and after 35 weeks of age fewer gilts from the 23 week group failed to mate when compared to the 28 week group (6.1 vs. 9.5%). A greater percentage of gilts that were exposed to boars at 23 weeks were mated compared to gilts that were exposed at 28 weeks of age (70.1 vs. 66.0%, respectively). However, after 35 weeks there was not a significant difference between gilts exposed at 23 or 28 weeks of age that had reached puberty and were not mated (11.9 vs. 11.5%, respectively). In contrast to Flowers (2009) and Cronin et al. (1983), Brooks and Smith (1980) reported no impact of age at boar exposure on gilt retention. Gilts (n=64) were exposed to boars at either 160 or 200 days of age and bred on second estrus. Average age at first mating for gilts exposed at 160 and 200 days of age was 197.8 and 237.2 days, respectively. Brooks and Smith (1980) report that 17 gilts from each boar exposure group reached parity 5. Perhaps the difference in results is a function of age at boar exposure used. In Flowers (2009), the late group was exposed to boars at 170 days of age while in Brooks and Smith (1980) the early group was given boar exposure at 160 days of age.

Age at puberty

Age at first service and age at first farrowing have been used as comparable traits to age at puberty (Tummaruk et al., 2001; Holm et al., 2004; Holm et al., 2005; Knauer et al., 2011). Tummaruk et al. (2001) and Holm et al. (2004) agree that age at first mating is perhaps not the exact biological representation of age at puberty, but is a practical way of analyzing field data. Holm et al. (2005) reported age at first service had a genetic correlation with age at first farrowing of 0.98 indicating they are very similar traits. Knauer et al. (2010) investigated factors that impact a sow's ability to reach 6 parities. In the study, when undergoing model selection the authors found that age at first farrowing was significant;

however, when age at first farrowing was not included in the model age at puberty became significant in a similar manner. This implies that age at first farrowing is at least a representation of age at puberty.

Many studies have concluded that a younger age at puberty, age at first farrowing or age at first service improves sow longevity (Schukken et al., 1994; Le Cozler et al., 1998; Knauer et al., 2010; Patterson et al., 2010; Hoge and Bates, 2011). Using survival analysis, Hoge and Bates (2011) found that as age at first farrowing decreased by 10 days the risk for being culled was reduced by 2%. In agreement, Knauer et al. (2010) reported a younger age at puberty or first farrowing improved sow longevity. The authors reported age at first farrowing explained 6% of the variation in sow retention to parity 4. Similarly, Schukken et al. (1994) found gilts that were younger at breeding had a longer productive life span than those that were bred at an older age. Gilts that conceived at 200 days of age were 6.5% less likely to be culled for reproductive failure when compared to gilts that conceived at 320 days of age. These results are supported by Moeller et al. (2004) who reported a genetic line that reached puberty on average 13 days faster had 15% more gilts farrow a litter when compared to the average of the remaining genetic lines. In a study by Patterson et al. (2010), gilts were grouped based on the age that they exhibited puberty; early puberty (EP) less than 143 days of age, intermediate puberty (IP) 154 to 167 days, late puberty (LP) 168 to 180 days and non-select (NS) gilts being those that did not show the standing reflex before 180 days of age. Results showed that NS gilts were less likely to be bred when compared to EP, IP and LP gilts (73.0 vs. 97.7, 93.2 and 93.0%, respectively). Of the gilts that were mated in the study, there was not a significant difference between age at puberty groups and their ability to reach three parities. However, culling per parity tended to be highest for NS when compared to EP, IP and LP (17.2 vs. 12.4, 15.6 and 14.2% respectively).

The results of Le Cozler et al. (1998) tend to be in contrast with studies reporting a younger age at puberty enhancing retention. Le Cozler et al. (1998) analyzed 171,178 litters from 38,349 Large White × Landrace sows from 976 French swine herds. The authors grouped sow herds based on the herd average for age at first farrowing; early (337 days), usual (356 days) and late (371 days). Age at first farrowing impacted sow longevity as gilts in the late group farrowed more parties when compared to the early group (4.95 vs. 4.85). The study further reported gilts from the late group had an older age at culling when compared to the early group (1024 vs. 982 days). When the herd average age at first farrowing exceeded 371 days the authors report a decrease in sow longevity. The results suggest that there maybe be an optimum range for age at first farrowing.

P.G. 600

The use of P.G. 600, a combination of 400 IU of pregnant mare serum and 200 IU of human gonadotropin, has been tested and proven to be effective in inducing puberty in gilts (Britt et al., 1989; Knox et al., 2000). In a study by Britt et al. (1989), 678 gilts were split into a control group (exposed to mature boars for estrous detection) and a treatment group (received P.G. 600 prior to boar exposure). The authors reported that P.G. 600 increased the percent of gilts that exhibited estrus within 7 days (57.5 vs. 40.9%) and the percent of gilts that exhibited estrus within 28 days (72.9 vs. 59.5%). These results are in agreement with Knox et al. (2000) who compared three groups of gilts; those given P.G. 600 subcutaneously (SC), those given P.G. 600 intramuscularly (IM) and a control group not given P.G. 600.

More SC and IM gilts ovulated when compared to the control group (86 and 77 vs. 18%, respectively). The authors further reported the interval to estrous expression was shorter for P.G. 600 gilts when compared to the control group (4.6 vs. 5.9 days). The method of P.G. 600 administration resulted in a difference in the percent of gilts that exhibited estrus, as control and IM were lower than SC (15 and 52 vs. 76%, respectively). Collectively, these studies suggest that P.G. 600 can be an effective tool to increase the percent of gilts that obtain puberty, a component trait of gilt retention.

Kirkwood et al. (2000) analyzed the effects of P.G. 600 on replacement gilts. The study divided gilts into three groups based on mating method; mated at first observed spontaneous estrus (Control, n=132), mated on spontaneous estrus after skipping a gonadotropin induced estrus (Skip, n=60) and mating on the gonadotropin induced estrus (Bred, n=140). Gilts in the Bred group were younger at first mating when compared to Skip and the Control (185, 215 and 197 days, respectively). No differences were detected for the average number of parities produced by Bred, Skip and Control (3.47, 3.17 and 3.39, respectively). The farrowing rate for Bred was statistically lower than that of Skip or Control (70.0 vs. 89.8 and 89.4%, respectively). The authors partly attributed the high gilt retention rate of 89% and increased longevity to parity four as excellent swine farm management.

Eckhardt et al. (2014) investigated the impacts of P.G. 600 on subsequent sow longevity to parity three. The authors divided gilts in to two groups, the first contained 60 gilts that were treated with P.G. 600 and then 72 hours later were administered Lutropin (HOR). The second group of 59 gilts were not treated and represented a control group (CON). In contrast to Britt et al. (1989) and Knox et al. (2000) there was not a significant difference in age at puberty or percent of gilts that obtained puberty. Eckhardt et al. (2014) reported HOR and CON groups reached puberty at 179 and174 days of age, respectively. The authors further showed that there was not a statistical difference in the percent of gilts obtaining puberty for the HOR and CON groups (91.7 and 94.9%, respectively). However, numerically fewer HOR gilts were culled after parity one when compared to CON (18.3 vs. 32.2%). Although culling at parity three was similar for HOR and CON (12.9 vs. 10.3%, respectively), numerically fewer HOR sows were culled throughout the entire study (48.9 vs. 67.6%). The authors further reported that fewer HOR gilts were culled for reproductive reasons when compared to CON gilts (34.7 vs. 50.2%).

Maternal effects on reproduction

Intrauterine maternal effects of sex ratio, proximity of females to males in utero and number of fetuses have been shown to influence subsequent gilt reproduction (Lamberson et al., 1988; Drickamer et al., 1997; Tummaruk et al., 2001). Drickamer et al. (1997) investigated the effects of litter sex ratio on gilt fertility. Gilts were distributed into three groups based on ratio of males to females in their birth litter. Each group contained one third of the litters, group one contained the lowest proportion of males, group two was the middle range of sex ratio and group three had the highest proportion of males. The authors used farrowing records to confirm the success of matings. Gilts that did not conceive after the first insemination were then mated up to four more times. The authors used these records to calculate a success ratio. Success ratio was the number of successful matings divided by total number of attempts. Results showed that gilts born into the group with the highest portion of males had a lower success ratio than those born into the middle or lowest third (35, 55 and

70%, respectively). Therefore, as the proportion of males increased it significantly reduced the probability that the first insemination would result in farrowing a litter. The authors suggest that the reduction of insemination success in litters with high numbers of males was a function of the proximity of male fetuses to gilt fetuses in the uterus. In agreement, Lamberson et al. (1988) showed the effect of sex ratio on age at puberty. An increase in proportion of gilts caused a decrease in age at puberty with the effect being stronger in smaller litters. While the impacts of maternal effects are clear, the use of this information in swine breeding is more conflicted (Lamberson et al., 1988). The authors report that modeling sex ratio, fraternity size (number born) and the interaction of sex ratio and fraternity size only accounted for 1.3% of the variation in age at puberty, suggesting that maternal effects are perhaps not needed for the genetics of gilt retention.

The postnatal maternal effect of litter size nursed on retention and sow longevity has been investigated (Nelson and Robison, 1976; Flowers, 2009). In Nelson and Robison (1976), litters were cross-fostered into either small (6 piglets) or large litters (14 piglets). The study resulted in little variation for mean age at first estrus between gilts raised in small litters and large litters (208 vs. 206 days, respectively). The authors note that the number of gilts farrowing was not large enough to provide strong statistical tests. In Flowers (2009), gilts (n=3,180) were allocated into either small litters (7 or less piglets) or large litters (10 or more piglets) by cross-fostering between 24 and 48 hours of age. Gilts were then followed through six parties. Nurse litter size impacted puberty obtainment after boar exposure. Results showed 20% more gilts from small litters reached puberty within 28 days of boar exposure when compared to gilts from large litters. The author further showed sow retention through six parities was greatly improved when compared to those raised in large litters (35 vs. 17%). The author explained that 15% of the increases in sow longevity were due to improved rebreeding of young sows (parity one and parity two). Gilts raised in small litters had a 5% higher farrowing rate in parties 1 to 6 when compared to gilts from large litters. Flowers (2009) suggests that by limiting the competition for resources prior to weaning replacement gilts are likely to have greater longevity and reproductive performance.

Genetics of gilt retention

Differences in gilt retention rates have been reported between genetic lines (Moeller et al., 2004; Johnson et al., 2009; Knauer et al., 2012). Knauer et al. (2012) reported numerical differences in gilt retention rates for Landrace, Large White, Landrace × Large White F_1 and composite Landrace × Large White females of 67, 72, 69 and 77, respectively. Johnson et al. (2009) reported a higher proportion of gilts from the Nebraska Index Line farrowing a parity 1 litter when compared to Large White × Landrace cross gilts (69 vs. 56%).

Moeller et al. (2004) studied six different maternal lines in the National Pork Producers Council Maternal Line National Genetic Evaluation Program. The six genetic lines included; American Diamond Swine Genetics (ADSG), Danbred (DB), DeKalb-Monsanto DK44 (DK), DeKalb-Monsanto GPK347 (GPK347), National Swine Registry (NSR) and Newsham Hybrids (NH). The ADSG, DB, DK and NH lines were commercially available Landrace × Large White F_1 crossbreds. The NSR female was a Landrace × Yorkshire F_1 cross. The GPK347 female consisted of F_1 Dekalb-Monsanto Genepacker Line 34 boars mated to University of Nebraska Index Line sows. Each line entered at least 590 weaned gilts into the test. Gilt retention rates for the ADSG, DB, DK, GPK347, NSR and NH lines were 77, 77, 75, 92, 78 and 76, respectively. Perhaps retention differences between the lines can be explained by differences in age at puberty. The GPK347 gilts were 13 days younger at puberty than the other genetic lines combined. The authors note that a 15% differences in gilt retention rates could have a large impact on profits. Gilt retention differences between genetic lines reported by Moeller et al. (2004) support the relationships between age at puberty, gilt retention and sow longevity.

Few studies have estimated variance components for gilt retention (Knauer et al., 2011; Lewis and Bunter, 2011). The study by Knauer et al. (2011) used THRGIBBS1F90 to estimate variance components between whether a gilt farrowed a first litter (STAY) with gilt estrous, growth, body composition and structural conformation traits. The authors reported a heritability estimate of 0.14 for STAY. In contrast, Lewis and Bunter (2011) reported a relatively lower heritability estimate for STAY (0.04) using ASReml. Interestingly, Knauer et al. (2011) estimated a common litter effect of 0.08 for STAY. In contrast, Lewis and Bunter (2011) reported that a common litter effect was not significant for farrowing a first litter. The substantial common litter effect reported by Knauer et al. (2011) indicates maternal effects can influence gilt retention. One noticeable difference between the studies by Knauer et al. (2011) and Lewis and Bunter (2011) was the percentage of gilts that farrowed. Knauer et al. (2011) reported 72% of gilts farrowed a first litter while Lewis and Bunter (2011) found 61% of gilts reached parity 1. This appeared to be a function of study design as Lewis and Bunter (2011) selected a large number of gilts initially to account for culling due to structural soundness. The authors reported culling 32% percent of gilts before they had the opportunity to be mated. Taken together, the heritability estimate for gilt retention by Knauer et al. (2011) indicates sufficient genetic variation for selection; however, Lewis and Bunter (2011) describe gilt retention as a non-heritable trait. Hence more studies are needed to clarify the existence of genetic variation for gilt retention.

Knauer et al. (2011) estimated genetic and phenotypic correlations between gilt retention (STAY) with gilt estrous, growth, body composition and structural conformation traits. The authors reported genetic correlations between STAY with length of estrus, standing reflex traits, age at puberty, days to 114 kg and backfat of 0.34, 0.34 to 0.74, -0.27, 0.52, and -0.29, respectively. These genetic correlations imply that greater gilt retention was associated with a longer length of estrus, stronger standing reflex, early age at puberty, slower growth and increased backfat. Hence, selection for a stronger strength of standing reflex may be useful strategy to improve gilt retention rates.

Knauer et al. (2011) estimated the phenotypic and genetic correlations between feet and leg traits and farrowing a first litter. Results generally showed low phenotypic correlations between structure scores and farrowing a first litter (-0.06 to 0.08). However, estimated genetic correlations between gilt retention with rib girth, front leg structure, and rear leg structure were 0.34, 0.17, and 0.49 respectively. These correlations imply that wider ribbed gilts were more likely to farrow and splay-footed and cow hocked gilts were less likely to farrow a first litter. Serenius and Stalder (2004) reported the genetic correlations between leg conformation and length of productive lifetime for Large White and Landrace were 0.17 and 0.32, respectively. Lopez-Serrano et al. (2000) reported genetic correlations between leg conformation scores and retention to parity three for Large White and Landrace were 0.02 and 0.36, respectively. Collectively, the results of these studies suggest that leg conformation has a higher correlation with sow longevity in Landrace compared to Large White.

Conclusion

Through the review of literature several implications and conclusions can be drawn on factors that impact gilt retention and sow longevity. Improving gilt retention rates and sow longevity within the swine industry can represent economic gains and should be important traits of interest for swine breeding companies. Studies suggest that management of gilt growth and diet after 200 days of age can improve retention rates. Gilt retention is impacted by age at puberty or age at first service, which can be manipulated through boar exposure or genetic selection. Gilts selected for breeding should come from genetically superior lines with ideal feet and leg conformation. Few studies have specifically focused on the genetics of gilt retention and pertinent component traits. The results of the two studies that have estimated the heritability of gilt retention tend to disagree. Further research is needed to solidify the heritability of gilt retention for its use in selection programs. Hence, the purpose of the current study (chapter two) was to estimate the genetic variance and heritability for gilt retention and associated component traits.

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Table 1 Amino acid, calcium and phosphorus recommendations for maternal line replacement gilts (Whitney et al., 2010).

Type of diet	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6F**	**Phase 6L**
Body weight, lb	**45 to 90**	**90 to 135**	**135 to 180**	**180 to 225**	**225 to 270**	**270 to breeding**	**270 to flush**
Assumed feed intake, lb/day	**3.1**	**4.0**	**4.7**	**5.3**	**5.7**	**5.9**	**5.0**
Dietary metabolizable energy, Mcal/lb	**1.52**	**1.52**	**1.52**	**1.52**	**1.52**	**1.52**	**1.52**
	% of diet						
Lysine, total	1.15	1.04	0.95	0.85	0.74	0.65	0.77
Standardized ileal digestible							
Lysine	1.02	0.92	0.84	0.74	0.64	0.56	0.67
Threonine	0.64	0.58	0.54	0.48	0.43	0.38	0.46
Methionine	0.30	0.27	0.24	0.22	0.19	0.17	0.21
Methionine + cysteine	0.59	0.53	0.50	0.45	0.40	0.35	0.42
Tryptophan	0.16	0.15	0.13	0.12	0.10	0.09	0.11
Isoleucine	0.56	0.51	0.46	0.41	0.35	0.31	0.37
Valine	0.66	0.60	0.54	0.48	0.42	0.36	0.44
Arginine	0.41	0.35	0.30	0.25	0.22	0.19	0.23
Histidine	0.33	0.29	0.27	0.24	0.21	0.18	0.21
Leucine	1.02	0.92	0.84	0.74	0.64	0.56	0.67
Phenylalanine + tyrosine	0.96	0.86	0.79	0.70	0.61	0.54	0.64
Phenylalanine	0.61	0.55	0.50	0.45	0.39	0.34	0.40
Calcium	0.81	0.75	0.71	0.67	0.65	0.65	0.75
Phosphorus, total[c]	0.81	0.75	0.71	0.67	0.65	0.65	0.75
Phosphorus, available	0.38	0.34	0.32	0.29	0.29	0.29	0.34
Phosphorus, digestible	0.35	0.32	0.29	0.26	0.26	0.26	0.32
	g/Mcal ME[d]						
Lysine, total	3.43	3.10	2.83	2.54	2.21	1.94	2.30
Standardized ileal digestible							
Lysine	3.04	2.74	2.50	2.22	1.92	1.67	2.00
Threonine	1.92	1.73	1.60	1.44	1.29	1.14	1.36
Methionine	0.88	0.80	0.72	0.64	0.58	0.52	0.62
Methionine + cysteine	1.77	1.59	1.50	1.33	1.19	1.05	1.26
Tryptophan	0.49	0.44	0.40	0.36	0.31	0.27	0.32
Isoleucine	1.67	1.51	1.37	1.22	1.06	0.92	1.10
Valine	1.98	1.78	1.62	1.44	1.25	1.09	1.30
Arginine	1.22	1.04	0.90	0.76	0.65	0.57	0.68
Histidine	0.97	0.88	0.80	0.71	0.61	0.54	0.64
Leucine	3.04	2.74	2.50	2.22	1.92	1.67	2.00
Phenylalanine + tyrosine	2.86	2.58	2.35	2.09	1.82	1.61	1.92
Phenylalanine	1.83	1.65	1.50	1.33	1.15	1.00	1.20
Calcium	2.42	2.24	2.12	2.00	1.94	1.94	2.24
Phosphorus, total[c]	2.42	2.24	2.12	2.00	1.94	1.94	2.24
Phosphorus, available	1.13	1.01	0.95	0.87	0.87	0.87	1.01
Phosphorus, digestible	1.04	0.95	0.87	0.78	0.78	0.78	0.95

Table 2. Ranges for recommended dietary additions of salt, trace minerals and vitamins from concentrate, base mixes or premixes for replacement gilts and boars (Whitney et al., 2010).

Type of diet	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Body weight, lb	**45 to 90**	**90 to 135**	**135 to 180**	**180 to 225**	**225 to 270**	**270 to breeding**
Assumed feed intake, lb/d	**3.2**	**3.9**	**4.8**	**5.4**	**5.7**	**5.9**
Dietary metabolizable energy, Mcal/lb	**1.52**	**1.52**	**1.52**	**1.52**	**1.52**	**1.52**
Minerals						
Salt, %	0.2 to 0.4	0.2 to 0.4	0.2 to 0.4	0.2 to 0.4	0.2 to 0.4	0.4 to 0.6
Sodium, %	0.1 to 0.2	0.1 to 0.2	0.1 to 0.2	0.1 to 0.2	0.1 to 0.2	0.15 to 0.25
Chloride, %	0.08 to 0.2	0.08 to 0.2	0.08 to 0.2	0.08 to 0.2	0.08 to 0.2	0.12 to 0.3
Copper, ppm	4 to 20	4 to 20	3 to 20	3 to 20	3 to 20	5 to 20
Iodine, ppm	0.14 to 0.4	0.14 to 0.4	0.14 to 0.4	0.14 to 0.4	0.14 to 0.4	0.15 to 0.5
Iron, ppm	60 to 180	60 to 180	50 to 180	40 to 180	40 to 180	80 to 200
Manganese, ppm	2 to 30	2 to 30	2 to 30	2 to 30	2 to 30	20 to 45
Selenium, ppm[c]	0.15 to 0.3	0.15 to 0.3	0.15 to 0.3	0.15 to 0.3	0.15 to 0.3	0.15 to 0.3
Zinc, ppm	60 to 180	60 to 180	50 to 180	50 to 180	50 to 180	50 to 200
Vitamins						
Vitamin A, IU/lb	600 to 4000	600 to 4000	600 to 4000	600 to 4000	600 to 4000	1800 to 7000
Vitamin D_3, IU/lb	70 to 400	70 to 400	70 to 400	70 to 400	70 to 400	90 to 700
Vitamin E, IU/lb	5 to 20	5 to 20	5 to 20	5 to 20	5 to 20	20 to 40
Vitamin K, mg/lb[d]	0.25 to 2	0.25 to 2	0.25 to 2	0.25 to 2	0.25 to 2	0.25 to 3
Riboflavin, mg/lb	1 to 10	1 to 10	1 to 10	1 to 10	1 to 10	2 to 8
Niacin, mg/lb	5 to 25	5 to 25	3 to 25	3 to 25	3 to 25	5 to 35
Pantothenic acid, mg/lb	4 to 20	4 to 20	3 to 20	3 to 20	3 to 20	5 to 20
Choline, mg/lb[e]	0	0	0	0	0	250 to 500
Biotin, mg/lb[f]	0	0	0	0	0	0.1 to 0.3
Vitamin B_{12}, mg/lb	0.005 to 0.02	0.005 to 0.02	0.002 to 0.02	0.002 to 002	0.002 to 0.02	0.007 to 0.02
Folic acid, mg/lb[g]	0	0	0	0	0	0.6 to 1.8
Vitamin B_6, mg/lb[h]	0	0	0	0	0	0 to 2.25

Table 3. Specific recommended dietary additions of trace minerals and vitamins from concentrates, base mixes or premixes for replacment gilts and boars (Whitney et al., 2010).

Type of diet	Grower	Finisher-1	Finisher-2	Finisher-3
Body weight, lb	**45 to 135**	**135 to 225**	**225 to 270**	**270 to breeding**
Dietary metabolizable energy, Mcal/lb	**1.52**	**1.52**	**1.52**	**1.52**
Minerals				
Sodium, %[a,b]	0.15	0.15	0.15	0.2
Chloride, %[a,b]	0.15	0.15	0.15	0.2
Copper, ppm	12	10	8	16
Iodine, ppm	0.25	0.20	0.15	0.30
Iron, ppm	125	100	75	165
Manganese, ppm	6	5	4	30
Selenium, ppm[c]	0.25	0.20	0.15	0.3
Zinc, ppm	125	100	75	165
Vitamins				
Vitamin A, IU/lb	2500	2000	1500	4000
Vitamin D_3, IU/lb	250	200	150	300
Vitamin E, IU/lb	15	12	9	30
Vitamin K, mg/lb[d]	1	0.8	0.6	2
Riboflavin, mg/lb	4	3	2	4
Niacin, mg/lb	11	9	7	15
Pantothenic acid, mg/lb	7	6	5	10
Choline, mg/lb	0	0	0	250
Biotin, mg/lb	0	0	0	0.1
Vitamin B_{12}, mg/lb	0.01	0.008	0.006	0.01
Folic acid, mg/lb	0	0	0	0.75
Vitamin B_6, mg/lb	0	0	0	0

CHAPTER 2

Estimates of Variance Components for Gilt Retention Traits

Introduction

Many studies have addressed sow retention and longevity (Le Cozler et al., 1998; Lucia et al., 2000; Serenius and Stalder, 2004; Tárres et al., 2006a; Tárres et al., 2006b; Serenius et al., 2008; Knauer et al., 2010; Hoge and Bates, 2011; Amér et al., 2014). Yet less research has focused on improving gilt retention rates. Perhaps this is because gilt data is normally not recorded on sow farms unless the female is mated. Hence studies evaluating sow longevity typically do not include gilts that do not farrow a litter. We propose that sow longevity starts with selection of gilts for the breeding herd as a substantial portion of gilts selected to be bred do not farrow. Knauer et al. (2011) and Lewis and Bunter (2011) reported the percentage of gilts that farrowed a litter was between 61 and 72%. Hence strategies are needed to improve the percentage of gilts that farrow.

Increasing replacement gilt retention would be economically beneficial for swine producers. According to Stalder et al. (2003), replacement gilts that are raised or purchased have a premium value of ninety dollars over market hog price. Keeping a large number of replacement gilts may result in economic losses, as those gilts that are not retained into the breeding herd are heavier than ideal market hog weight (Dyck, 1988). Increased management, feed, facility and labor costs associated with high number of replacement gilts enhances the importance of improving gilt retention rates.

Few studies have directly investigated the genetics of gilt retention (Knauer et al., 2011; Lewis and Bunter, 2011). Therefore further studies are needed to examine associations among commonly recorded gilt traits in production systems. Hence, the objective of this study was to estimate variance components among gilt retention, development and removal traits.

Materials and Methods

Data

Data on 6,282 gilts were provided by Smithfield Premium Genetics (Rose Hill, NC). Crossbred females were from Large White dams (n=1,649) mated to Landrace sires (n=98). Gilts were farrowed at two multiplication farms in eastern North Carolina between June 2012 and November 2012. Farrowing rooms at both farms were ventilated and temperature was automatically controlled. Birth weights, weaning weights, sex ratio of birth litter (proportion of females) and cross-fostering between litters was recorded at multiplication farms. Following weaning gilts were moved to an onsite nursery with controlled temperature and ventilation. After a seven week nursery period, gilts were moved to finishing facilities in South Carolina. Finishing floors were slatted, naturally ventilated and provided gilts ad libitum access to feed and water. Gilts from the finishing sites were distributed among 11 commercial sow farms in eastern North Carolina. Sow farms were partially slatted with breeding stalls, farrowing stalls and mechanical ventilation. Gestating gilts were limit fed based on body condition. Data obtained from the commercial sow farms included; sow farm entry date, service date, farrow date, litter size, preweaning mortality and number weaned.

Binary traits constructed included whether a gilt farrowed a litter (STAY), whether a gilt was culled for reproductive reasons (CFR) and whether a gilt was culled for nonreproductive reasons (CFO). Culling codes for CFR and CFO consisted of abort, did not conceive, no heat and vulvar discharge and downer, farrowing productivity, injury, lame, management, rectal prolapse, size, sudden death, unknown reasons, unthrifty and vaginal prolapse, respectively. Culled for reproduction (CFR) was coded in manner that 2 represented being culled for reproductive reason and 1 represented not being culled for a reproductive reason. Culled for nonreproductive reasons (CFO) was coded in a manner that 2 represented being culled for nonreproductive reasons and 1 represented not being culled for nonreproductive reason.

Continuous traits analyzed included a gilts own birth weight recorded at multiplication farms (BWT), age at first service (AFS) and age at first farrowing (AFF). Age at first service was calculated as the difference in days between birthdate and first recorded insemination. Age at first farrowing was calculated as the difference in days between birthdate and the date of first parturition.

Data editing

Of the initial 6,282 gilt records in the dataset, 5,736 were available after editing. Gilts without pedigree information (n=489) were excluded from the analysis. Gilts with an AFS record that was less than 130 d or exceeded 340 d (n=57) were excluded. After data editing AFS and AFF had 5,228 and 4,723 records, respectively. From the edited data set, contemporary groups (n=60) were generated based on the sow farm and entry date of gilts. Gilts in the final data set represented 1,758 different litters.

Statistical analysis

The impacts of early life factors on STAY were first investigated using PROC GLIMMIX (SAS Inst., Cary, NC). Contemporary group, common litter, birth sow parity, birth litter sex ratio, birth litter size, cross-fostering, preweaning average daily gain, adjusted weaning weight and weaning age were considered traits of interest. Common litter was included as a random effect while contemporary group, birth sow parity, birth litter sex ratio, birth litter size, cross-fostering, preweaning average daily gain, adjusted weaning weight and weaning age were analyzed as fixed effects. Due to the structure of the data set PROC GLIMMIX (SAS Inst., Cary, NC) was unable to converge. Therefore, PROC LOGISTIC (SAS Inst., Cary, NC) was used to analyze all early life factors.

Variance components were estimated with an animal model using THRGIBBS1F90 and GIBBS2F90 for binary and continuous traits, respectively. All models included a fixed effect of contemporary group and random effects of common litter environment and animal. Variance components for categorical traits (STAY, CFR and CFO) were estimated using THRGIBBS1F90 (Misztal et al, 2002) as linear models are not ideal for estimating variance components for categorical traits (Gianola and Foulley, 1983). The THRGIBBS1F90 program is part of the BLUPF90 family and uses a Bayesian approach by the Gibbs sampling method (Lee et al, 2002). After 50,000 Gibbs samples were deleted as burn-in, 200,000 iterations (saving every 20th iteration) were used to calculate posterior means, which were used to compile parameter estimates. Variance components for continuous traits (BWT, AFS and AFF) were analyzed using GIBBS2F90 (Misztal et al, 2002). The continuous traits followed the same burn in and thinning rate as categorical traits.

Genetic and phenotypic correlations were estimated between traits using a bivariate analysis. Bivariate analyses containing at least one categorical trait were conducted using THRGIBBS1F90. The bivariate analysis between AFS and AFF was computed using GIBBS2F90. A bivariate analysis was not performed between CFR and CFO because if a gilt was culled for reproductive reasons then she was not culled for other reasons. Gilts that were culled for reproductive or nonreproductive reasons did not farrow a first litter and did not have data for AFF; therefore, a bivariate analysis was not possible between these traits.

Solutions from THRGIBBS1F90 and GIBBS2F90 were further analyzed for convergence and posterior means. Convergence was checked by the use of trace plots. Heritability estimates are represented by the posterior mean distributions and standard errors are the estimation of the posterior standard deviation. Posterior means and posterior standard deviations were calculated using the POSTGIBBSF90 program (Misztal et al., 2002).

Results and Discussion

Gilt culling

Of the 5,736 gilts analyzed for STAY, 4,833 (84.3%) farrowed a litter. Further summary statistics can be found in Table 5. Arango et al. (2005), Knauer et al. (2011) and Lewis and Bunter (2011) reported relatively lower gilt retention rates of 73, 72 and 61%, respectively. Moeller et al. (2004) reported the percent of gilts that farrowed a first litter for six different genetic lines were 75, 77, 77, 77, 78 and 92%. The findings of Moeller et al. (2004) suggest gilt retention is impacted by genetics.

Of the 5,737 gilts analyzed, 433 (7.5%) were culled for reproductive reasons and 470 (8.2%) were culled for nonreproductive reasons. The accuracy of culling codes has been subject to scrutiny by others. Knauer et al. (2007) reported that 23% of sow culling codes were determined to be inaccurate. Yet, several studies have summarized the impact of different culling reasons. In an extensive study of removal reasons, Arango et al. (2005) categorized culling codes into three groups reproductive (RR), nonreproductive (RN) and other (RO). Culling categories of RR, RN, and RO represented 17.5, 4.9, and 4.8% of gilts, respectively. The percent of gilts culled for reproduction in Arango et al. (2005) was considerably higher than the findings of the current study.

Early life factors impacting retention

Contemporary group, preweaning average daily gain and birth litter size influenced ($P < 0.05$) STAY. Yet birth sow parity, birth litter sex ratio, cross-fostering, adjusted weaning weight and weaning age did not impact ($P > 0.05$) STAY. Flowers (2009) reported gilts that were nursed in litters of 7 or less had increased reproductive performance and farrowing rates when compared to gilts raised in litters of 10 or more. The same study showed that gilts raised in smaller litters reached puberty at a younger age when compared to those from large litters. Drickamer et al. (1997) reported that as the proportion of males in a litter increased the probability of a successful first mating for gilts was reduced. However, investigation of sex ratio showed no major effect on gilt retention. Management of preweaning average daily gain and birth litter size should be considered when rearing replacement gilts.

In the current study, the common litter variance for STAY was 0.07 with a posterior standard deviation of 0.03. Similarly, Knauer et al. (2011) reported a common litter variance of STAY to be 0.08. In contrast, Lewis and Bunter (2011) reported the common litter variance for farrowing a first litter was not significant. The differences in results maybe a function of the design of Lewis and Bunter (2011) who initially selected a larger number of gilts. In their study, 32% of gilts were culled before given a chance to mate. Gilts with varying early lifetime performance may have been eliminated at that time. The common litter variance reported in the current study and Knauer et al (2011) implies that models for gilt retention should include a common litter effect.

Heritability estimates

Gilt birth weight was estimated to have a heritability of 0.18. This estimate is relatively higher than the previously reported range of 0.03 to 0.09 (Roehe, 1999; Grandinson et al., 2002; Knol et al., 2002; Arango et al., 2006). Perhaps the higher estimation of heritability in the current study was due to differences in populations. The current study was conducted on F1 crossbred females. Genetic correlations between birth weight with AFS, AFF, STAY, CFR and CFO were low to moderate; however, high posterior standard deviations listed in Table 6 make these correlations unlikely.

In the present study, the heritability estimates for AFS and AFF were 0.24 and 0.20, respectively. Holm et al. (2004) and Holm et al. (2005) reported the heritability of AFS to be higher at 0.31 and 0.38, respectively. Studies have estimated the heritability for AFF from 0.16 to 0.40 (Serenius and Stalder, 2004; Serenius et al., 2008; Knauer et al., 2011). In previous literature, heritability estimates for age at puberty have been in a similar to those of

AFF, ranging from 0.25 to 0.40 (Lamberson et al., 1991; Sterning et al., 1998; Knauer et al., 2010; Knauer et al., 2011).

The heritability estimate for STAY in the current study was 0.11. Knauer et al. (2011) and Lewis and Bunter (2011) reported the heritability of farrowing a first litter to be 0.14 and 0.04, respectively. The additive genetic variance in the current study was 0.135, which is in agreeance with the 0.13 reported by Lewis and Bunter (2011). In contrast, additive genetic variance in Knauer et al. (2011) was 0.183.

Heritability estimates for CFR and CFO were 0.19 and 0.05, respectively. The low heritability estimate for CFO is not surprising given the nature of the trait. Culling codes within this category are more diverse and are impacted my management. Culled for other includes culling codes that cannot be predicted or are incomplete, for example injury, sudden death and unknown reasons. With the uncertainties associated with culling codes, the practical implementation of CFR within a breeding program may be limited.

Genetic correlations

In the current study AFS and AFF were used as indicator traits for age at puberty, or at what age a gilt becomes reproductive. Capturing data for age at puberty can be labor intensive and may not be recorded within current swine breeding programs. Age at first service is thought to be the best representation of age at puberty in the retrospective analysis of field data (Tummaruk et al, 2001; Holm, 2004). Knauer et al. (2011) estimated the genetic correlation between age at puberty and AFF to be 0.76. The current study estimated the genetic and phenotypic correlation between AFS and AFF are 0.995 and 0.925 respectively.

We propose that when analyzing field data, AFS and AFF can serve as functional replacements for age at puberty.

The genetic correlation between AFS and STAY was -0.78, meaning that gilts with a younger age at first farrowing were more likely to farrow a first litter. This is in agreeance with Knauer et al. (2011), which reported a genetic correlation of -0.27 between age at puberty and STAY. Similar results can be observed from the correlations between AFF and sow longevity traits in published literature (Schukken et al., 1994; Serenius et al., 2008; Knauer et al., 2010; Hoge and Bates, 2011). Increased AFF increased risk of culling in Hoge and Bates (2011) while shortening time spent in the herd in Schukken et al. (1994). Serenius et al. (2008) reported the genetic correlation between AFF and sow longevity to be 0.36, while Knauer et al. (2010) reported AFF accounted for 6% of estimable variation in retention through parity 4. With a genetic correlation of 0.995 for AFS and AFF, AFS should act in the same manner in its impact on sow longevity; however, more work needs to be done in this area.

Selection for gilt retention

We propose the use of indirect selection to improve STAY. Within swine breeding programs AFS is recorded at an earlier age and the results of this study show a greater heritability for AFS than STAY. The possible genetic improvement of gilt retention through direct selection on STAY (R_{STAY}) and indirect selection on AFS (CR_{AFS}) was calculated using the response to selection formulas from Falconer and Mackay (1996). Assuming a selection intensity (i) of 0.75 the following calculations were made.

$$R_X = iacc_X \sigma_{AX}$$

Where acc_X represents the accuracy of selection and σ_{AX} represents the additive genetic variance.

$$CR_Y = iacc_X acc_Y r_A \sigma_{PX} = iacc_Y r_A \sigma_{AX}$$

Where $R_A$represents the genetic correlation, acc_Y represents the accuracy of selection and σ_{PX} represents the phenotypic variance.

$$R_{STAY} = 0.75 * 0.3317 * 0.135 = 0.03358$$

$$CR_{AFS} = 0.75 * 0.4899 * 0.78 * 0.135 = 0.03868$$

$$\frac{CR_{AFS}}{R_{STAY}} =$$

$$= \frac{0.03869}{0.03358} = 1.15$$

Resulting in 15% more genetic improvement in gilt retention through indirect selection on AFS when compared to direct selection for STAY. Under the current ranges of AFS indirect selection can improve retention yet this may change as AFS approaches biological extremes.

Conclusions

The failure of replacement gilts to farrow a first litter represent added costs to commercial swine production and therefore is an economically important trait. The results of this study show that gilt retention is a heritable trait with sufficient genetic variation for selection. Furthermore, the occurrence of reproductive culling was also heritable. The concern with accuracy of culling code data suggests the use of this trait in a breeding program is limited to systems with meticulous record keeping. A trait recorded earlier in life, AFS, had a significantly higher heritability and a strong genetic correlation with STAY. Due to this selection for AFS would result in a correlated response of 15% greater than would occur for selection on STAY. Yet AFS may be challenging to implement if farms within a system do not obtain gilts at a consistent age. Based on the results of this study the author recommends mating gilts at an earlier age while including STAY within the selection index to improve gilt retention rates within the breeding herd.

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Table 4. Descriptive statistics of culling codes.

Culling code	Number of gilts culled	Proportion of total gilts culled (%)	Proportion culled for CFR[1] or CFO[2] (%)
CFR[1] (433)		48	
Abort	52	6	12
Did not conceive	199	22	46
No Heat	177	20	41
Vulvar discharge	5	0.5	1
CFO[2] (470)		52	
Downer	47	5	10
Farrow productivity	9	1	2
Injury	23	3	5
Lame	178	20	38
Management	76	8	16
Rectal Prolapse	7	0.8	1
Size	2	0.2	0.4
Sudden death	52	6	11
Unknown reasons	54	6	11
Unthrifty	17	2	4
Vaginal Prolapse	5	0.6	1
Total	903		

[1]CFR culled as a gilt for reproductive reasons.

[2]CFO culled as a gilt for nonreproductive reasons.

Table 5. Descriptive statistics and estimates[1] of variance components for gilt retention measures. Dataset includes 5,736 Landrace by Large White crossbred gilts.

Trait[2]	No.	Mean	Min	Max	σ_p^2	σ_a^2	σ_l^2	c^2	h^2	SE
STAY	5,736	1.843	1	2	1.21	0.135	0.069	0.057	0.11	0.04
AFS	5,228	261.8	168	340	369.2	88.80	8.16	0.022	0.24	0.04
AFF	4,723	377.5	284	456	388.6	79.12	7.74	0.020	0.20	0.04
CFR	433	1.075	1	2	1.294	0.25	0.038	0.029	0.19	0.06
CFO	470	1.082	1	2	1.098	0.053	0.041	0.037	0.05	0.03
BW	5,736	1.33	0.39	2.69	0.079	0.014	0.023	0.291	0.18	0.06

[1]Estimates are the means of the marginal posterior densities. σ_p^2 phenotypic variance, σ_a^2 additive genetic variance, σ_l^2 common litter variance, C proportion of phenotypic variance due to common litter effect, h^2 heritability, h^2-SE of heritability (posterior SD).

[2]STAY farrowing a first litter, AFS age at first service, AFF age at first farrowing, CFR culled as a gilt for reproduction, CFO culled as a gilt for nonreproductive reasons, BW birth weight.

Table 6. Estimates[1] of phenotypic (r_p) and genetic (r_g) correlations between culling traits[2] with birth weight and age at first service.

	Birth weight		Age at first service	
	r_p	r_g	r_p	r_g
STAY	0.046 (0.020)	0.314 (0.310)	-0.150 (0.025)	-0.777(0.194)
CFO	-0.049 (0.027)	-0.406 (0.453)	0.110 (0.032)	0.771 (0.323)
CFR	-0.027 (0.028)	-0.187 (0.279)	0.154 (0.032)	0.478 (0.181)
AFF	-0.027 (0.017)	0.095 (0.205)	0.925 (0.002)	0.995 (0.005)
AFS	-0.034 (0.016)	0.020 (0.184)	.	.

[1]Estimates are the means (SD) of the marginal posterior densities.

[2]STAY farrowing a first litter, AFS age at first service, AFF age at first farrowing, CFR culled as a gilt for reproduction, CFO culled as a gilt for nonreproductive reasons.

Appendix

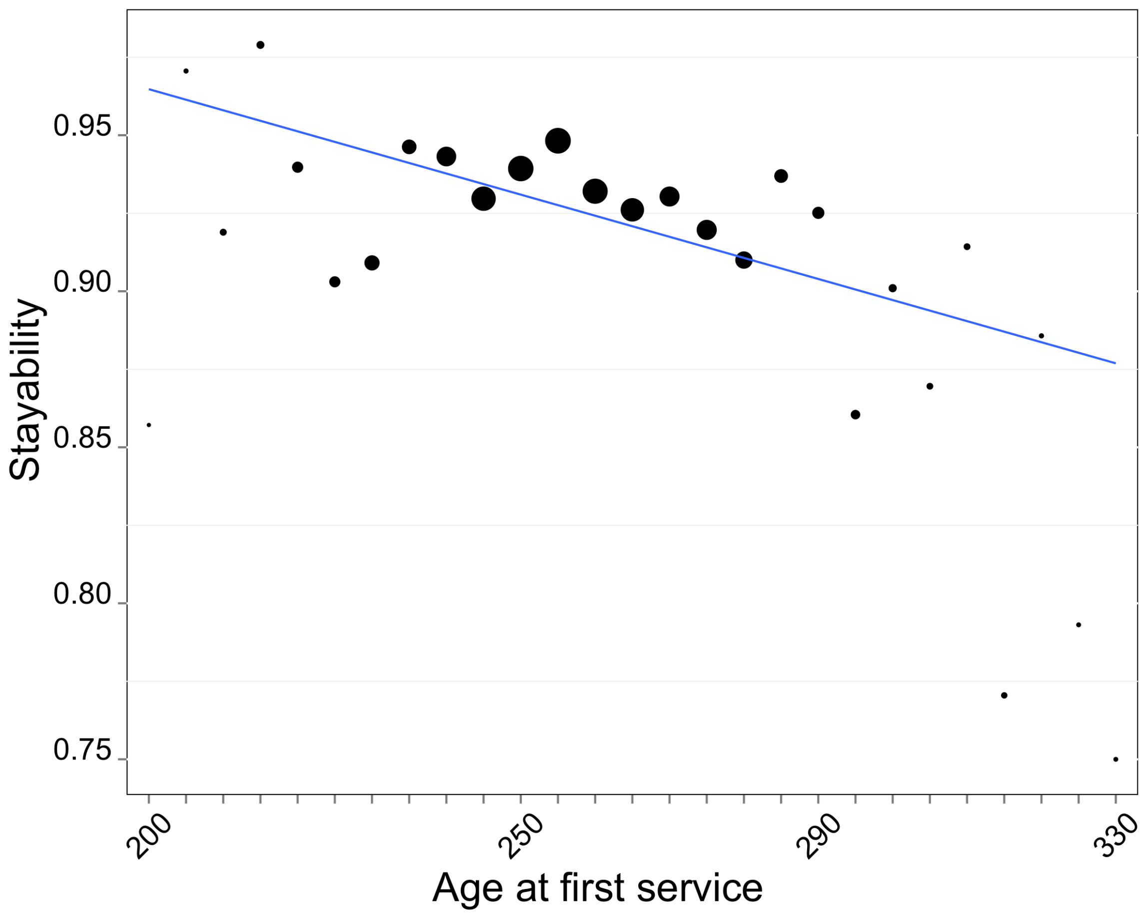

Figure A1. Percentage of gilts that farrow a first litter.

[1]The x-axis represents five-day intervals i.e. 201-205, 206-210.

[2]Data points are weighted to represent number of gilts within each time interval.

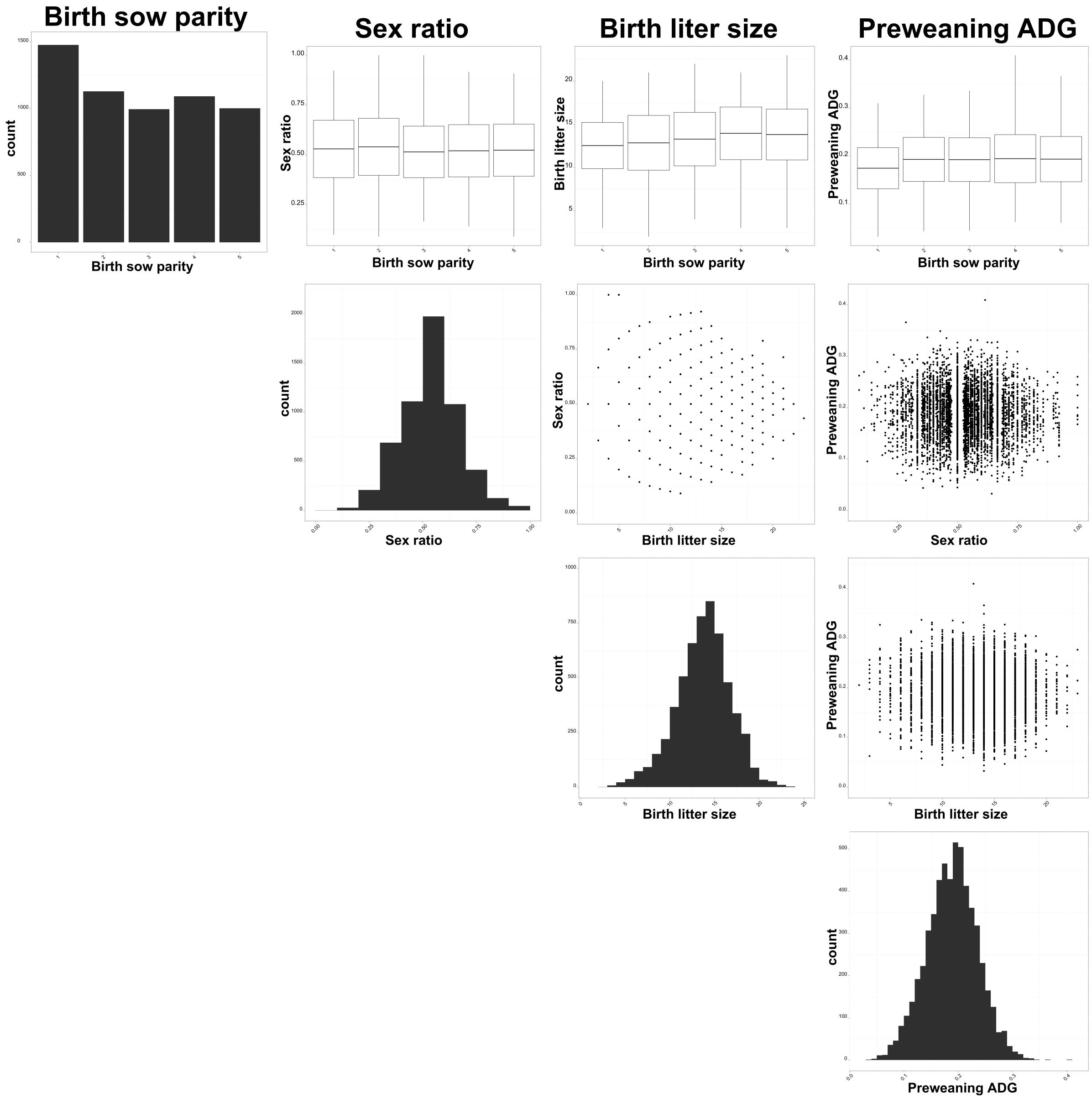

Figure A2. Descriptive plots of early life factors.

[1]Plots on the diagonal are histograms.

[2]Off-diagonal plots represent relationships between early life factors.

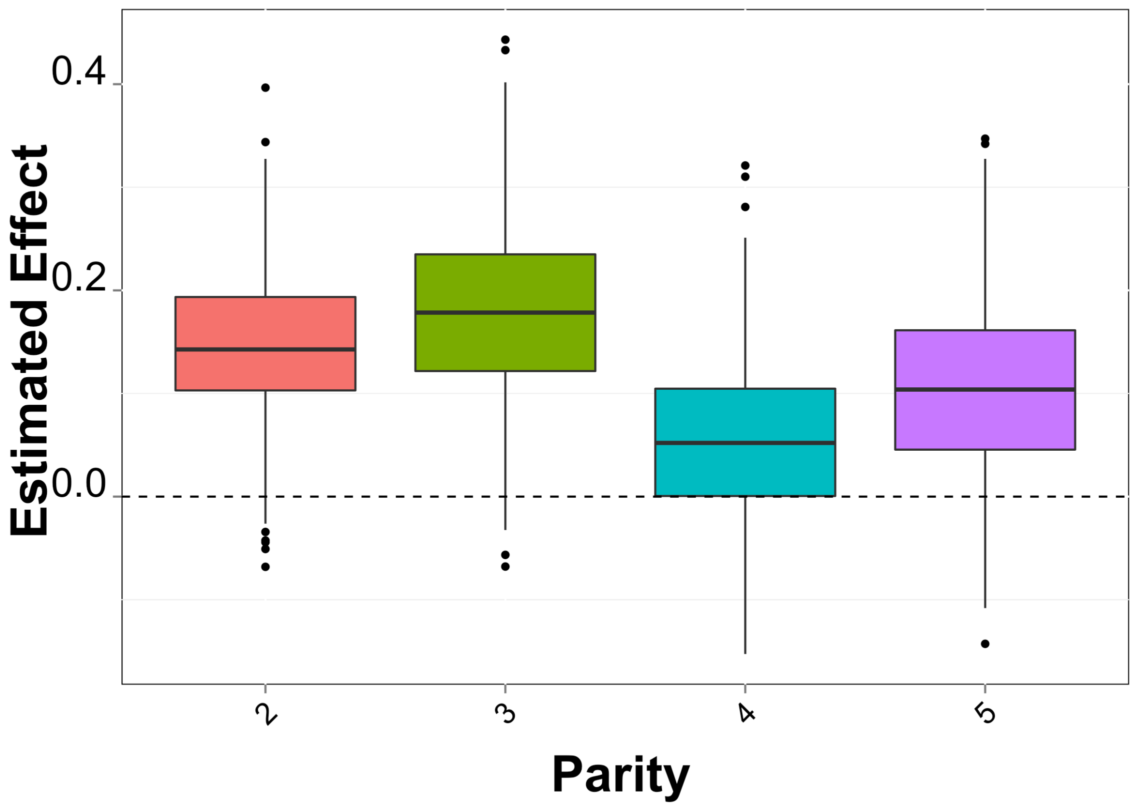

Figure A3. Estimated effect of BSP on STAY.

[1]BSP 1 used as reference parity.

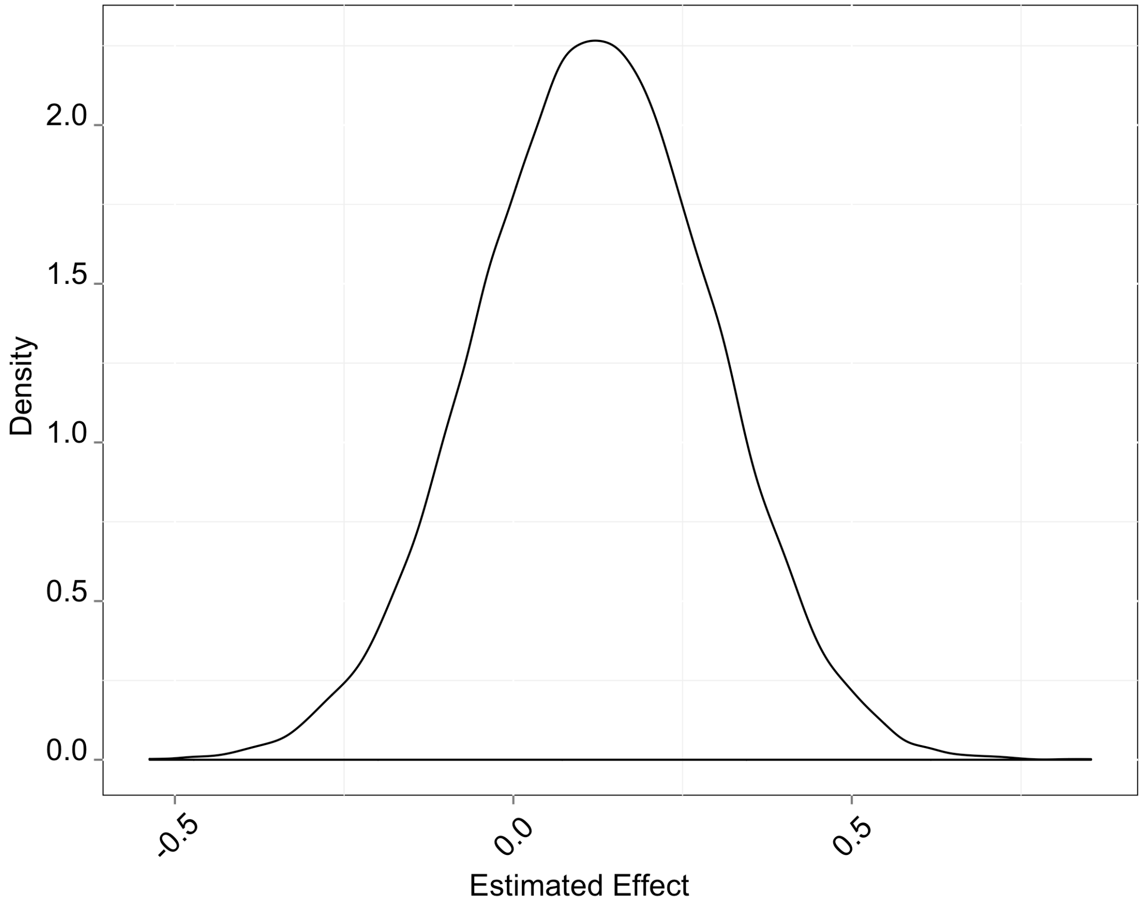

Figure A4. Estimated effect of sex ratio on stayability[1].

[1]Whether or not a gilt farrows a first litter.

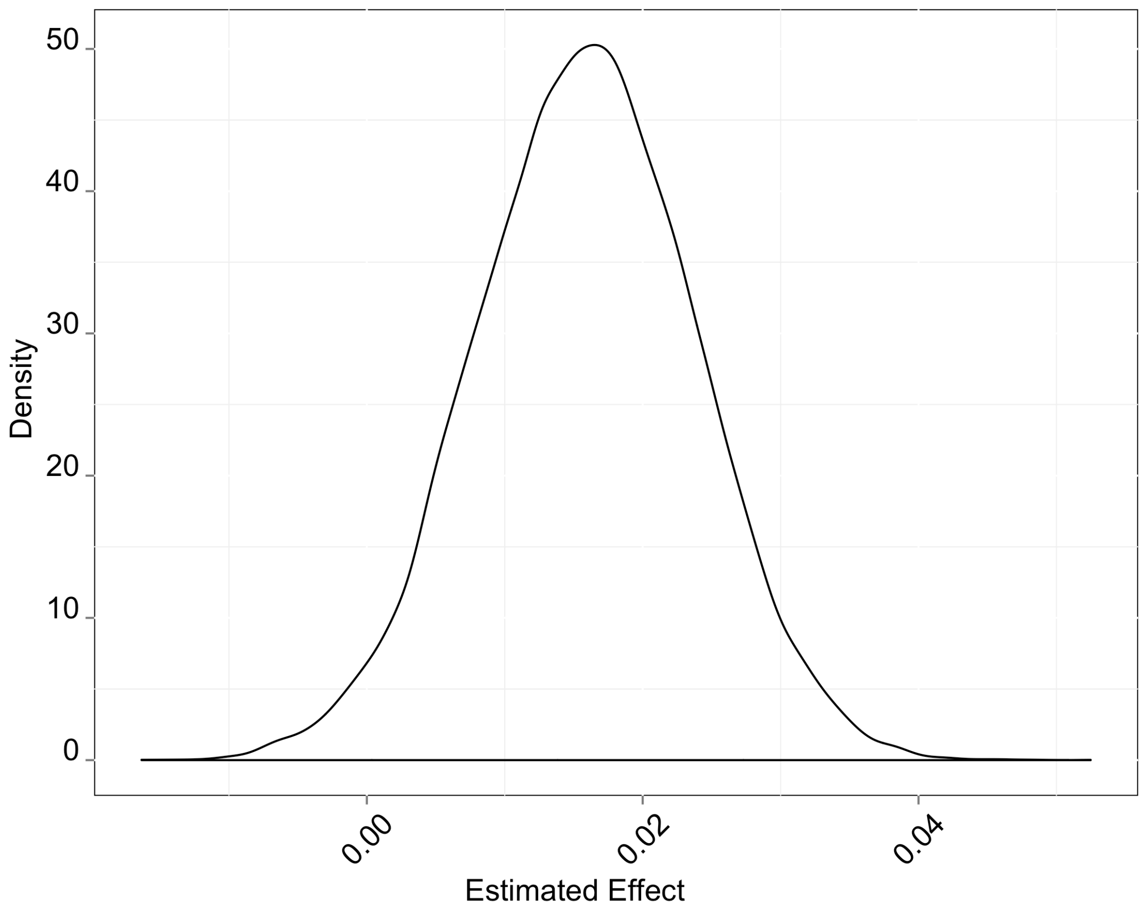

Figure A5. Estimated effect of birth litter size on stayability[1].

[1]Whether or not a gilt farrows litter.

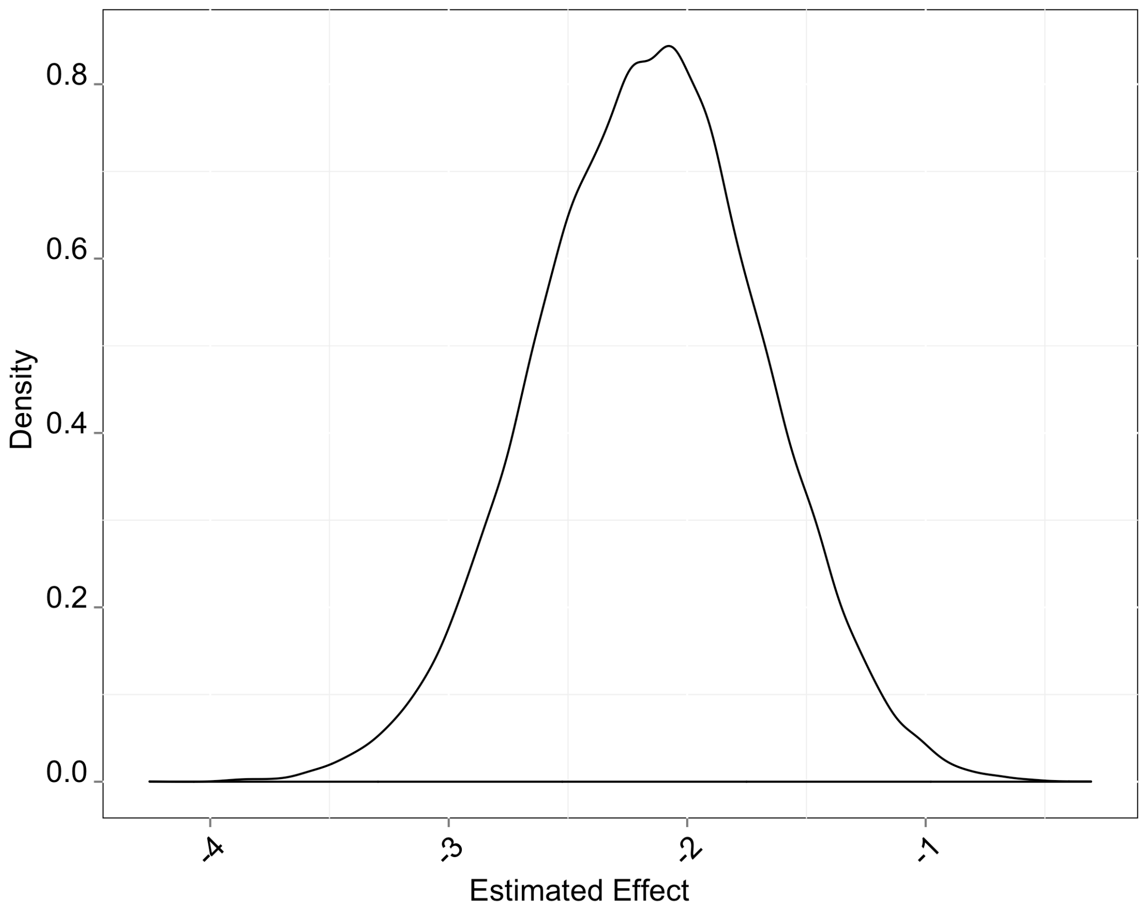

Figure A6. Estimated effect of preweaning average daily gain on stayability[1].

[1]Whether or not a gilt farrows litter.

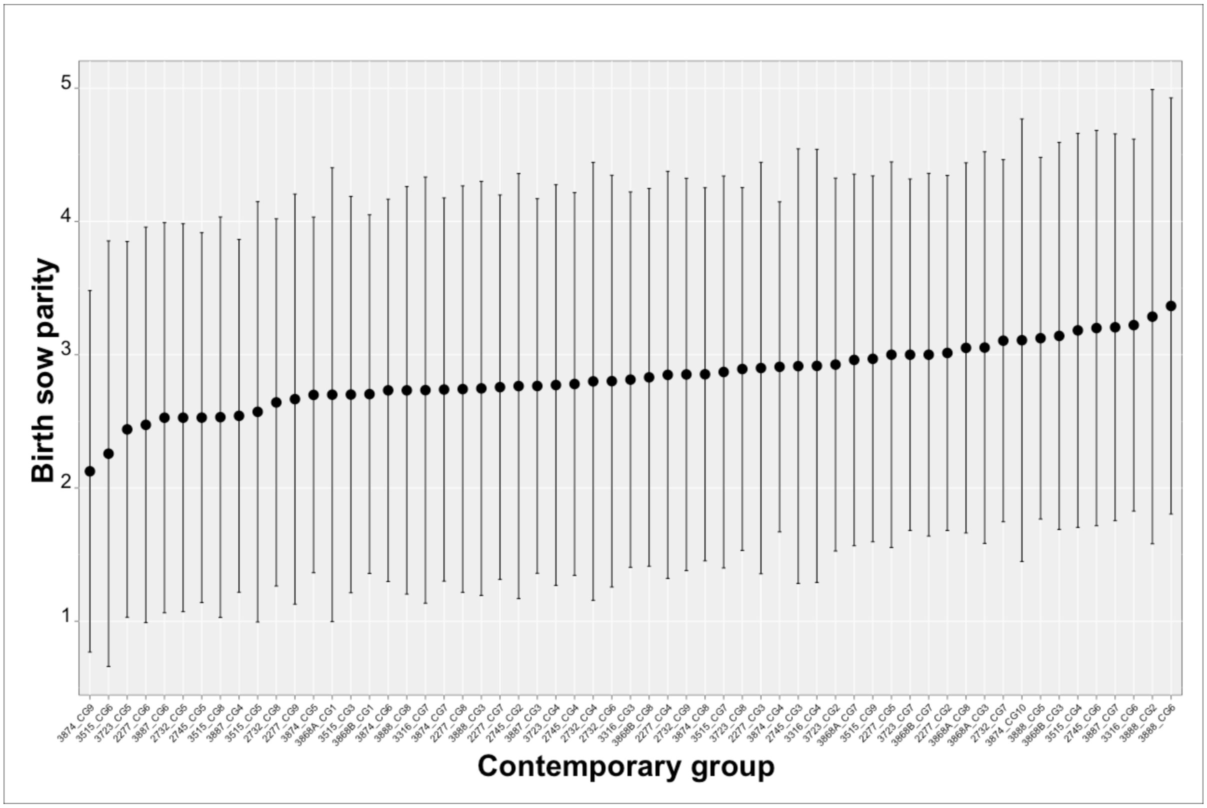

Figure A7. Mean birth sow parity for each contemporary group.

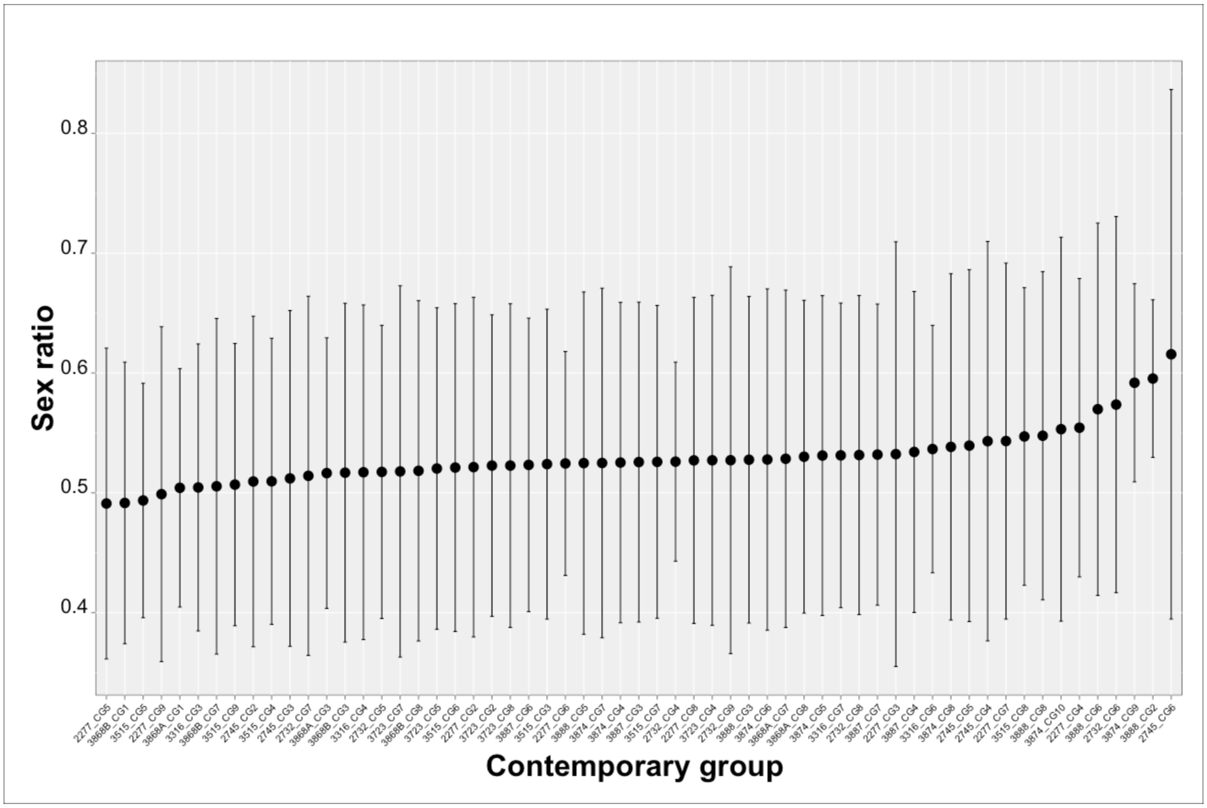

Figure A8. Mean sex ratio for each contemporary group.

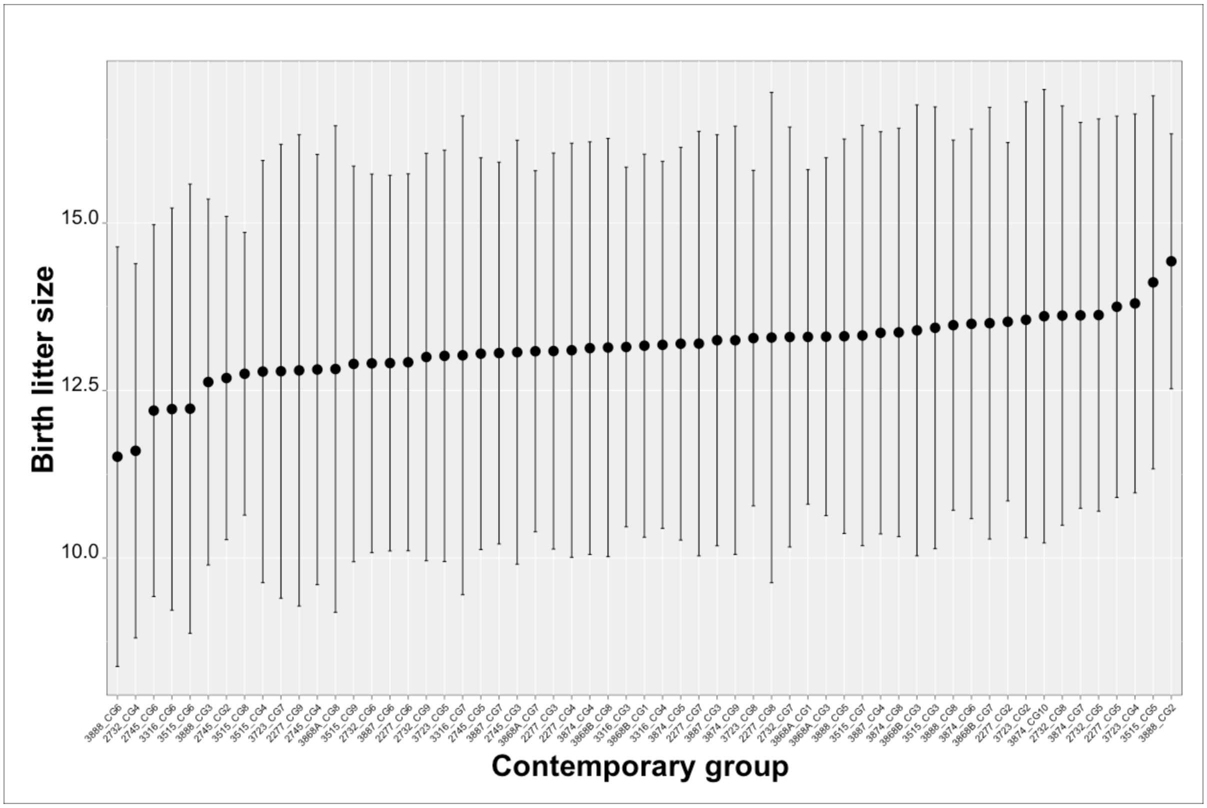

Figure A9. Mean birth liter size for each contemporary group.

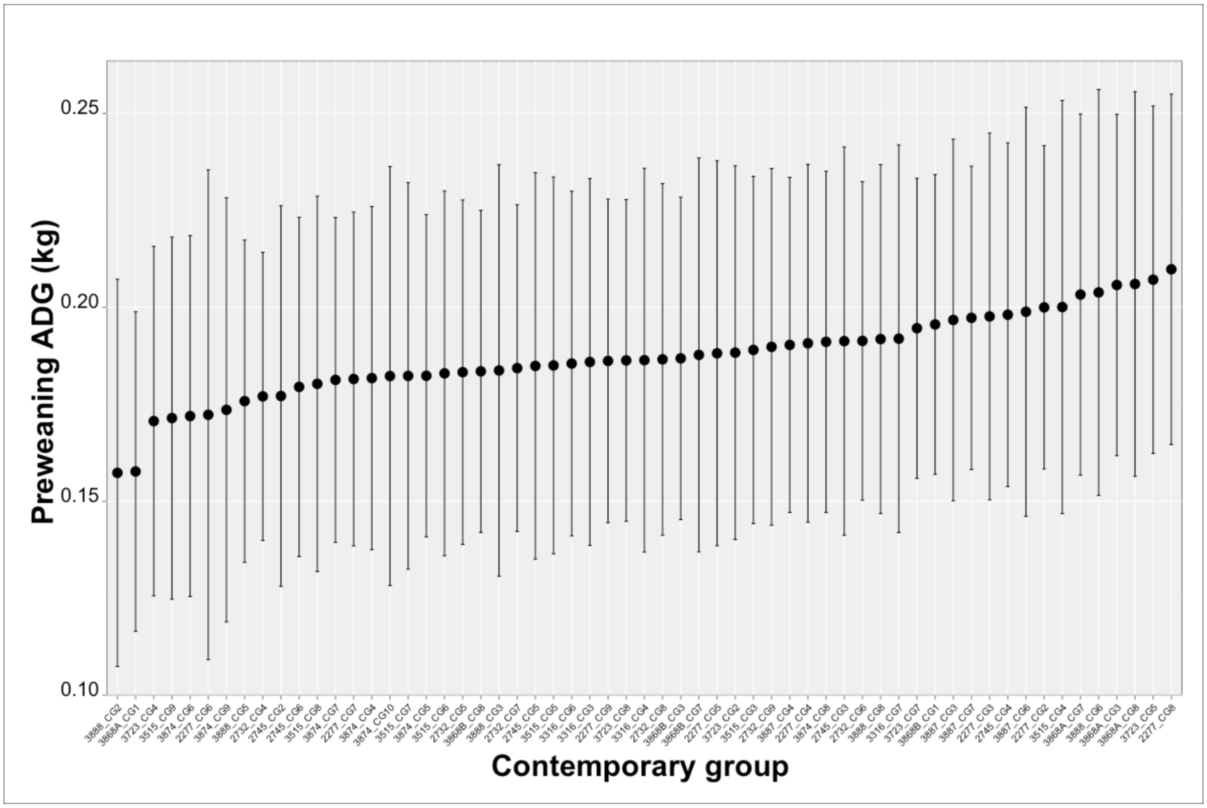

Figure A10. Mean preweaning average daily gain for each contemporary group.

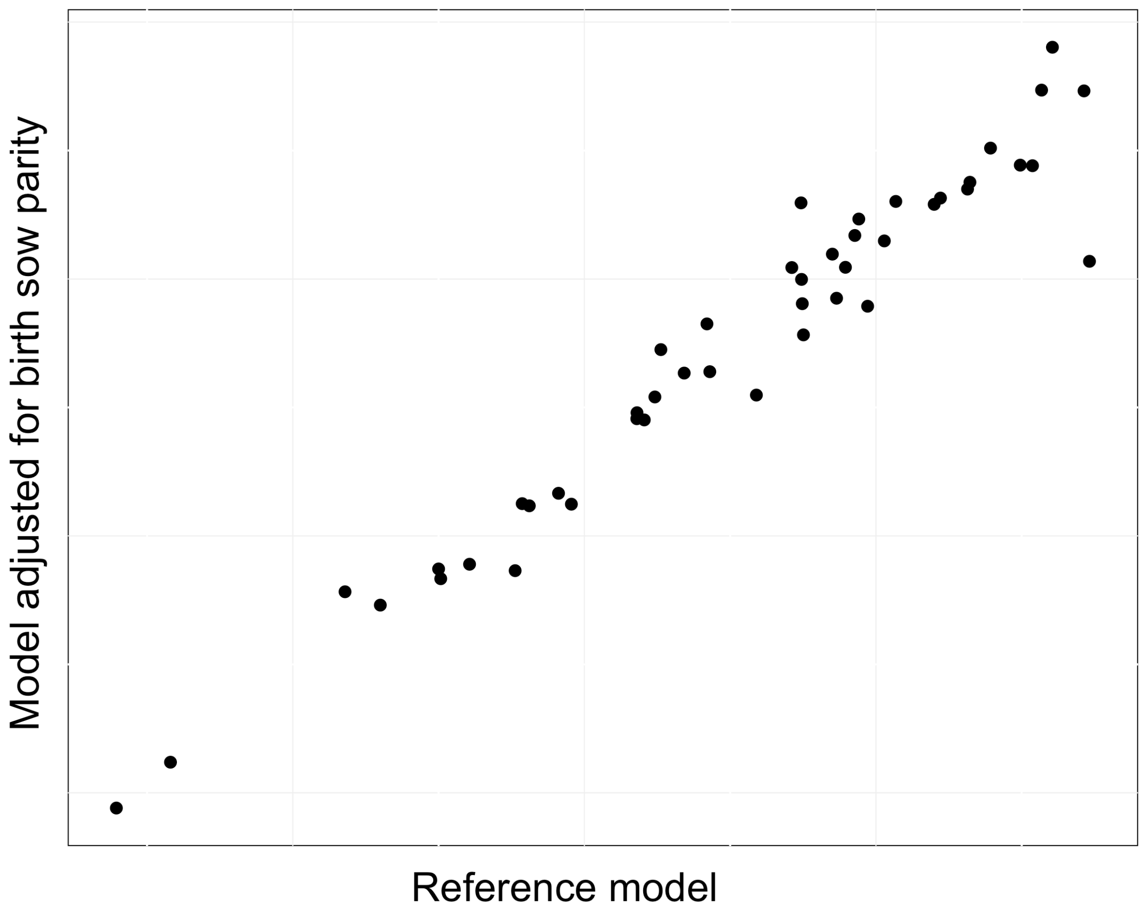

Figure A11. Re-ranking of sires based on breeding values for stayability[1].

[1]Whether or not a gilt farrows litter.

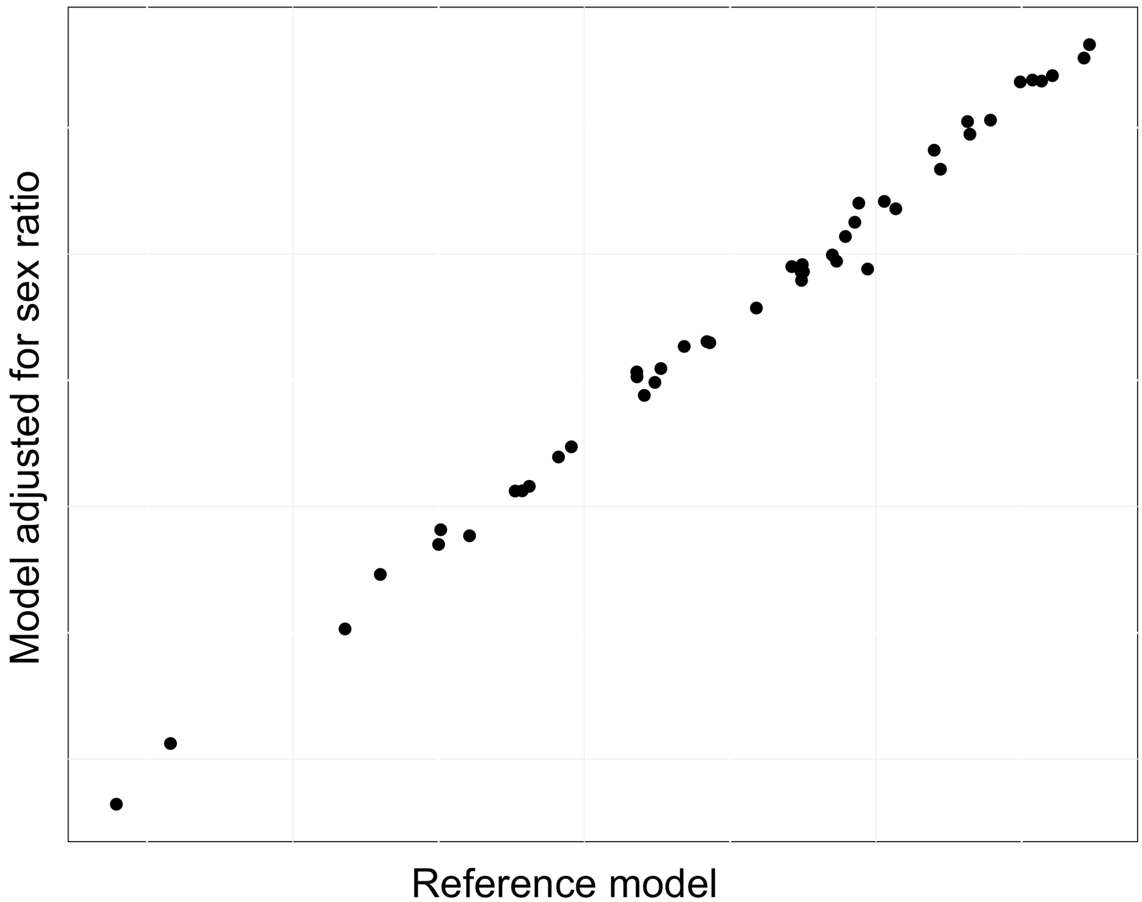

Figure A12. Re-ranking of sires based on breeding values for stayability[1].

[1]Whether or not a gilt farrows litter.

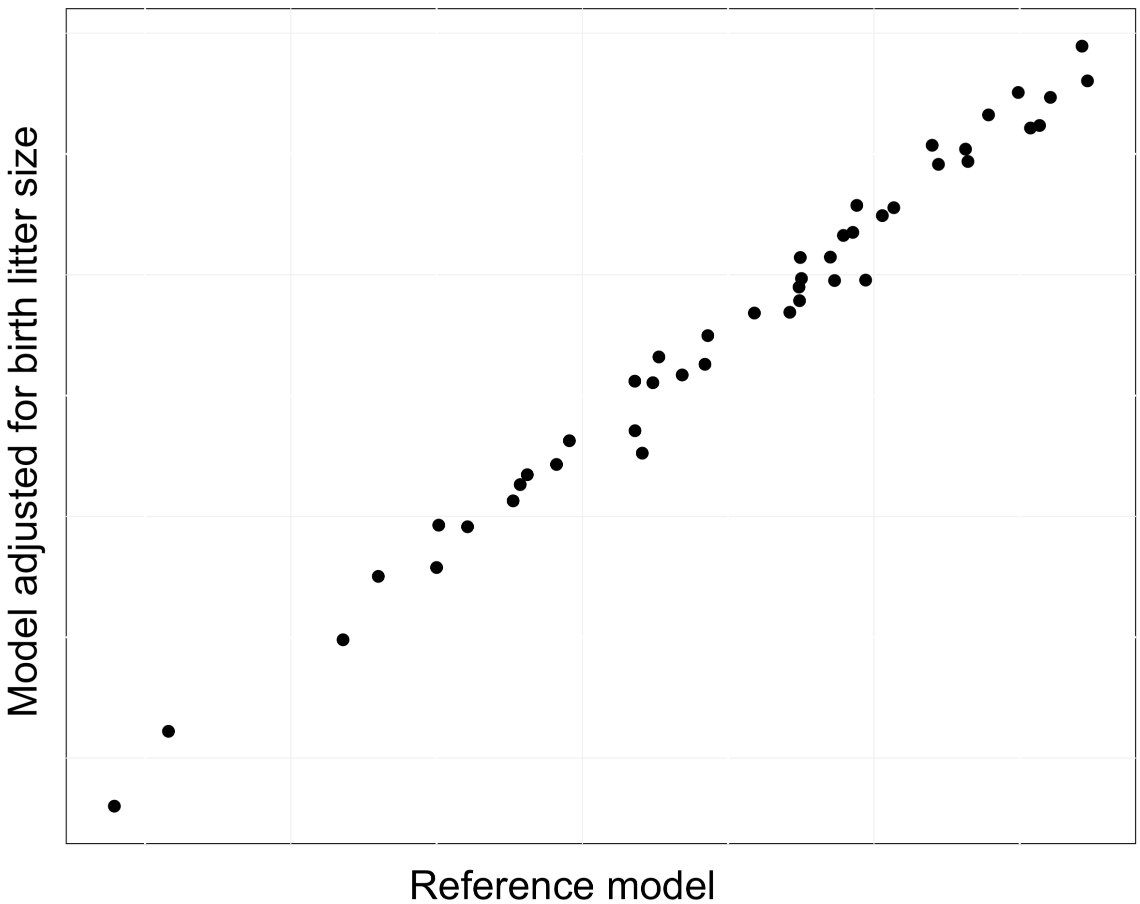

Figure A13. Re-ranking of sires based on breeding values for stayability[1].

[1]Whether or not a gilt farrows litter.

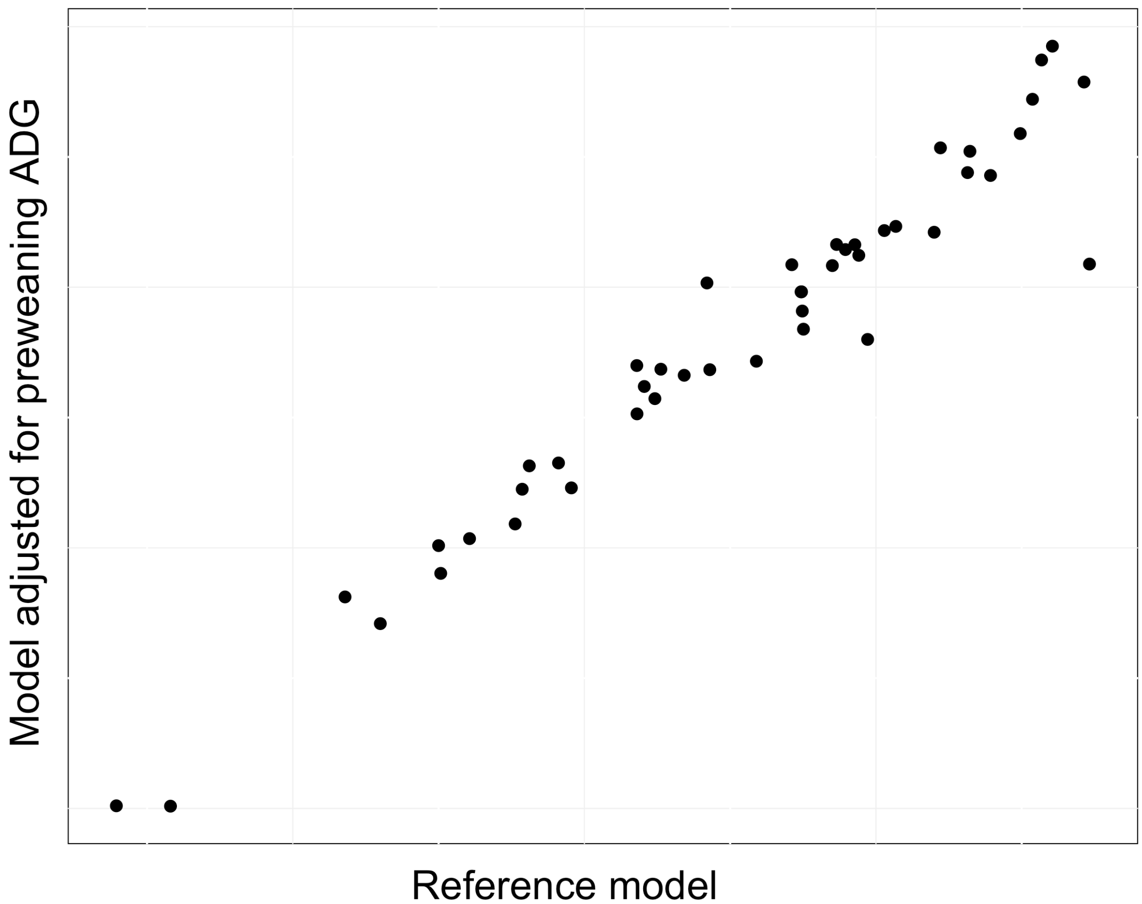

Figure A14. Re-ranking of sires based on breeding values for stayability[1].

[1]Whether or not a gilt farrows litter.

Table A1. Spearman correlations between models adjusted for early life factors and the reference model

Effect[2]	Spearman correlation[1]
BSP	0.96
SR	0.99
BLS	0.99
PADG	0.96

[1]Spearmen correlations were calculated between each model and the base model for sire breeding values.

[2]BSP birth sow parity, SR sex ratio, BLS birth litter size, PADG preweaning average daily gain.