ABSTRACT

WIEGERT, JEFFREY GLENNON. Effects of Practically Increasing Amino Acids and Energy in Late Gestation on Colostrum Intake, Colostrum Composition and Sow Performance (Under the direction of Dr. Mark Knauer).

Genetic selection for increased sow prolificacy without concomitant emphasis on piglet birth weight has reduced piglet survivability and growth, while continued selection for greater carcass leanness in commercial swine has altered body metabolism and increased amino acid requirements. Basal protein and energy requirements are further increased in late gestation to compensate fetal and mammary growth. Four experiments were conducted to titrate the effects of late gestation amino acid and energy intake on colostrum parameters and sow reproductive performance. Differences in nutrient intake were achieved by modifying sow diet, feeding level, or the day in gestation of treatment initiation. In experiment (EXP) 1, 62 sows were assigned at d 104 of gestation in a 2×3 factorial to receive a gestation diet (0.55% SID lysine, 0% added fat, and 2,594 kcal/kg NE; GEST) or lactation diet (0.99% SID lysine, 2.5% added fat, and 2,911 kcal/kg NE; LACT) at 1.5, 3.0 or 4.5 kg/d. In EXP 2, 62 sows were fed 2.05 kg/d LACT beginning at d 93, 100, or 107 or maintained at 2.05 kg/d GEST until farrowing. In EXP 3, 192 sows were fed 1.82 kg/d GEST supplemented daily with 280 g soybean (GEST+SBM), 120 g granulized fat (GEST+FAT) or both SBM and FAT to achieve the lysine and added fat comparable to LACT. In EXP 4, 70 sows were transitioned from GEST to LACT at d 102 of gestation and feeding level increased from 2 to 4 kg/d at d 102, 106, or 110 of gestation or maintained at 2.0 kg/d until farrowing. Farrowings were attended and piglet birthweight (BWT), piglet colostrum intake (CI), pig weaning weight (WWT), and number weaned (NW) were recorded. Sow functional teat number (TEATS) was counted in EXP 2 and 4. Data was analyzed by experiment in SAS with diet, feeding level, and day of feeding initiation and their interactions

as fixed effects where appropriate. A meta-analysis was performed by calculating each sow's total lysine (TLYS), added fat (TFAT), and ME (TME) intake from d 93 of gestation to farrowing. In EXP 1, feeding LACT tended ($P<0.10$) to increase piglet CI and WWT. No treatment differences were observed in EXP 2. In EXP 3, feeding GEST+FAT tended ($P=0.06$) to improve piglet BWT, while sows consuming GEST+SBM tended ($P=0.08$) to produce less colostrum. In EXP 4, piglets born to sows bump fed LACT at d 106 of gestation tended ($P=0.07$) to have greater CI. Meta-analysis estimates indicated that consuming 1 g additional TLYS in late gestation improved ($P<0.02$) CI and WWT by 0.12 g and 1.4 g, respectively, while consuming 1 g TFAT improved ($P=0.01$) CI by 0.03 g. a 1 Mcal increase in TME improved ($P=0.02$) WWT 4.0 g. A one nipple increase in TEATS improved ($P\leq0.05$) CI, NW, and litter WWT by 13.3 g, 0.31 pigs, and 1.85 kg, respectively. Meta-analysis results indicate increasing amino acids and energy in late gestation enhanced average piglet weaning weight.

Effects of Practically Increasing Amino Acids and Energy in Late Gestation on Colostrum Intake, Colostrum Composition and Sow Performance

by
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DEDICATION

This dissertation, and all that it represents, is dedicated to my parents, Elaine and Greg Wiegert.

BIOGRAPHY

Jeff Wiegert is a native of Weldon Spring, Missouri. He is the son of Elaine and Greg Wiegert, who taught him the core values of community, dignity, and common sense, and that every lesson in life worth learning can be learned from baseball. Jeff has two brothers who, in his own opinion, are significantly braver and better men than he.

Jeff's last name is pronounced "WEE-gert."

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: Literature Review

Introduction

The pig is a litter-bearing species. The average litter size of the European wild boar (*Sus scrofa*), the ancestral species of the domestic pig (*Sus scrofa domesticus*), is typically between 3 to 7 piglets per litter, although this may vary greatly between populations according to genetics, geographic location, season of breeding, and nutrient and resource availability (Mauget, 1982; Fernández-Llario and Mateos-Quesada, 1998; Náhlik and Sándor, 2003). The advantage of litter-bearing reproduction in an evolutionary sense is the maximization of a population's reproductive rate to meet the carrying capacity of a given habitat (Cody, 1965; Spencer and Steinhoff, 1968). The disadvantage of litter-bearing reproduction, however, is high preweaning offspring mortality. In one study of free-ranging European wild boar, piglet postnatal mortality was estimated at 55% to 60% of the litter (Náhlik and Sándor, 2003).

According to Smith and Fretwell (1974), two general biological patterns explain the balance between parental energy expenditure and offspring fitness at birth: "1. As the energy expended on individual offspring is increased, the number of offspring that parents can produce is decreased; and, 2. As the energy expended on individual offspring increases, the fitness of individual offspring increases." These patterns imply that as litter size is increased, the maternal resources allocated to each individual fetus is decreased, and the fitness of these offspring is decreased.

Reduced fitness of individual offspring born into large litters is well observed in domestic swine. A one piglet increase in litter size is associated with a 30 to 50 gram decrease in the average individual birthweight of pigs in that litter (Roehe, 1999; Quiniou et al., 2002; Opschoor

et al., 2010). These low birthweight piglets are less viable, at greater risk of pre- and postweaning mortality, show reduced postweaning growth rate and feed efficiency, and are less likely to be full value market hogs at finishing (De Roth and Downie, 1976; Quiniou et al., 2002; Fix et al., 2010b). In recent years, the US swine industry has suffered an increase in piglet preweaning deathloss concurrent with genetic selection for increased litter size (Lund et al., 2002). The average total number of piglets born per litter increased from 11.8 in 2005 to 13.9 per litter in 2017, but at the same time, average piglet preweawning mortality increased from 13.7% to 17.8% (Knauer and Hostetler, 2013; Stalder 2018). The average number of piglets weaned per litter increased from 9.3 in 2005 to 10.2 in 2011, but since that time has only increased to 10.3 pigs in 2017 (Knauer and Hostetler, 2013; Stalder, 2018).

Given the present scenario of reduced maternal resource allocation *in utero* as a consequence of large litter sizes, it follows that greater consideration should be given to the feasibility of increasing postnatal maternal resource allocation through colostrum and milk. The essential role of colostrum in piglet survival and growth cannot be understated. In swine, colostrum serves two fundamental purposes necessary for piglet survival: 1. To provide the piglet with sufficient energy to generate metabolic heat for thermoregulation; and 2. To serve as the vehicle for the passive transfer of maternal antibodies and other immune cells. Without adequate energy or antibodies, the piglet's likelihood of surviving to weaning is jeopardized (Quesnel et al., 2012). In addition, colostrum contains numerous bioactive proteins that are either localized in the intestines or communicated intact across the intestinal barrier to contribute to organogenesis and improved pre and postweaning performance (Pluske, 2016).

This literature review will be divided into four areas related to swine colostrum production and piglet development: 1. Prenatal piglet development; 2. Swine mammogenesis and

lactogenesis; 3. The role of colostrum in postnatal piglet development; and 4. Feeding sows to improve colostrum production and composition.

Section 1. Prenatal piglet development

1.1. Biology of prenatal piglet development

The average litter size in the US swine industry in 2017 was 13.9 total piglets born (Stalder, 2018), yet the actual number of pigs born at farrowing is considerably less than the number of eggs originally ovulated. According to studies reviewed by Foxcroft et al. (2006), the ovulation rate (defined here as the number of corpora lutea present on the ovary after ovulation) of gilts and first-parity sows is 15 to 20 ova, while the ovulation rate of multiparous sows is 20 to 25 ova. A small number of multiparous sows are capable of achieving an ovulation rate over 30. The fertilization rate of these ova is high (95%; Kridli et al., 2016), indicating that embryonic litter size at the beginning of pregnancy may be as much as two-fold that of the ultimate litter size at farrowing.

The majority of embryonic loss occurs at or before approximately 30 days in gestation, and this coincides roughly with the timing of placental development (Wright et al., 2016). The pig placenta is epitheliochorial in structure and utilizes clustered areolae for diffuse exchange of blood and biochemical materials between fetal and uterine tissues (Chen et al., 1975). Accordingly, the capacity for placental oxygen and nutrient throughput from dam to fetus is positively correlated with the extent of placental endometrial surface area occupation (Fenton et al., 1970). In early gestation, space competition between embryos limits placental growth, thereby promoting placental insufficiency and embryonic mortality.

In a landmark study conducted by Knight et al. (1977), unilaterally hysterectomized-ovariectomized gilts (UHOX; n=44) were compared to intact control gilts (n=44) to determine the effects of experimentally-induced intrauterine crowding on placental and fetal development. Owing to compensatory hypertrophy of the remaining contralateral ovary, the ovulation rate between UHOX and control gilts was similar in the experiment, yet the endometrial surface area available for implantation in UHOX gilts was reduced by half. Total hysterectomy and tissue collection of UHOX and control gilts then occurred at 11 regularly-spaced intervals from days 20 to 110 of gestation (n=4 UHOX and 4 control gilts collected at each time point). Placental weight and length were reduced in UHOX compared to controls at the first sampling point at day 20 of gestation, and these differences persisted throughout pregnancy. Placental surface area and the number and distribution of placenta areolae were not recorded until day 35, as placentae before this time were too brittle to withstand dissection from the uterus. However, both placental surface area and the number of areolae at day 35 were greater in control gilts (281.5±18.0 cm^2 and 661.0±59.0 areolae/placenta) than in UHOX gilts (234.1±11.0 cm^2 and 333.2±26.9 areolae/placenta), and these patterns also continued throughout pregnancy. The number of live embryos was similar between groups in early pregnancy, yet between days 30 and 35 of gestation, the number of live embryos dissected from UHOX gilts decreased (11.0±0.4 vs. 8.8±1.3, respectively), but did not change in the control gilts (10.3±1.4 vs. 10.8±2.0, respectively). Finally, a treatment by day of gestation interaction was observed beginning on day 40 of gestation between UHOX and control gilts in both fetal crown-rump length (5.1±0.03 cm vs. 4.8±0.08 cm) and fetal wet weight (9.40±0.14 g vs. 9.10±0.33 g). More pronounced reductions in fetal size were observed in later stages of pregnancy, such that by day 100 of gestation, fetal crown-rump length and fetal wet weight were reduced by 2.1 cm and 170 g,

respectively, in UHOX gilts compared to controls. Collectively, these results suggest that limited uterine capacity stunts placental development by day 20 of pregnancy, causing an increase in embryonic mortality after day 30 of gestation, and a restriction of intrauterine fetal growth beginning at day 40 of gestation. The results of this study, and the underlying theories of uterine capacity limiting fetal growth and litter size through placental insufficiency, have been supported by the more recently conducted studies of Christenson et al. (1987), Biensen et al. (1998), and Freking et al., (2007).

The number of quality pigs produced per sow is the most economically influential trait on the breeding swine farm (De Vries, 1989), and accordingly intense selection pressure has historically been placed on increasing litter size in the commercial industry (Knauer and Hostetler, 2013). Genetic selection for increased litter size results in increased ovulation rate (Gama and Johnson, 1993). Lamberson et al. (1991) identified that a 1 ova increase in ovulation rate increases litter size at farrowing by approximately 0.25 pigs. However, selection for greater litter size has failed to create appreciable changes in uterine dimensions or volume (Gama and Johnson, 1993). It can be said, then, that selection for increased litter size exacerbates uterine crowding and reduces fetal growth.

Separately, researchers at the USDA Meat Animal Research Center in Clay Center, Nebraska, practiced eleven generations of direct selection for either greater ovulation rate or greater uterine capacity. Compared to a randomly selected control line, selection for greater ovulation rate increased ovulation rate and litter size by 3.2 ova and 0.3 piglets, respectively, but decreased uterine capacity and prenatal survival by 0.97 piglets and 10.3%, respectively. On the other hand, selection for greater uterine capacity increased ovulation rate, litter size, uterine capacity, and prenatal survival by 0.13 ova, 0.62 piglets, 2.15 piglets, and 3.5%, respectively

(Leymaster and Christenson, 2000). Following the eleventh generation of the experiment, 593 gilts representing the three selection lines (i.e. selection for greater ovulation rate, selection for greater uterine capacity, and the randomly selected control line) were subjected to UHOX under procedures similar to those utilized in Knight et al. (1977) to establish uterine crowding. Gilts were then bred to boars within line and harvested at days 25, 45, 65, 85, or 105 of gestation (n=24 to 30 gilts sampled per time per line; Freking et al., 2007). As expected, ovulation rate was greatest in the line selected for increased ovulation rate, and no differences in the number of live fetuses were observed between lines at day 25 of gestation. By day 45, however, fetal litter size was greater in gilts selected for greater uterine capacity compared to other lines. Average fetal weight, litter fetal weight, average placental weight, litter placental weight, and uterine length were all greater in gilts selected for greater uterine capacity than in gilts selected for ovulation rate from gestational day 45 onwards.

Results of these genetic selection and hysterectomy-ovariectomy studies conclude that restricted fetal growth and development should be expected following genetic selection for increased litter size. Indeed, surveys of commercial sows suggest that a 1 piglet increase in litter size is associated with a 30 to 50 gram decrease in average piglet birth weight (Roehe, 1999; Quiniou et al., 2002; Opschoor et al., 2010). Increasing litter size is also associated with greater within-litter variation in piglet birth weight (Boulot et al., 2008). Large within-litter variation in piglet birth weight suggests that intrauterine embryonic competition for endometrial surface area and maternal resources also creates divergent patterns in fetal growth. Hence, not only is average piglet birth weight decreased, but the number of exceptionally light birth weight pigs is increased. In one observational study incorporating 12,041 piglets from 965 litters, the proportion of piglets weighing less than 1.0 kg at birth increased from 7% to 23% as litter size

increased from 9 to 17 total number born (calculated in this study as number born alive plus the number stillborn; Quiniou et al., 2002).

Given the considerable economic influence of litter size, continued selection for increasingly hyperprolific sows in the swine industry is to be expected. Selection on the basis of greater litter size at farrowing will increase ovulation rate, thereby expediting uterine crowding issues, decreasing average piglet birth weight, and increasing the number of light birth weight piglets. A greater understanding of the physiological effects of intrauterine growth restriction in swine thus becomes necessary.

1.2 Physiological implications of piglet intrauterine growth restriction

Intrauterine growth restriction (IUGR) in swine results in reduced piglet birth weight and altered fetal physiology that persists throughout adult life. According to Foxcroft et al. (2006), an IUGR piglet is defined as a piglet whose birth weight is an outlier from the mean birth weight of a given litter. On the other hand, small for gestation age (SGA) piglets are defined as those piglets whose birthweights are greater than 2 standard deviations from the mean, but not statistical outliers. For the purposes of comparison, normal birth weight piglets (NBW) are defined as those piglets whose birth weight closely matches the mean litter birth weight. The exact definition of an IUGR or SGA piglet is variable between researchers and reports. Efforts will be made to delineate the definitions of IUGR and SGA piglets used by researchers in the studies included in this section when differing from the definition presented by Foxcroft et al. (2006).

Notable physiological consequences of restricted fetal growth are observed in swine, including impaired skeletal muscle myogenesis and reduced organ size and functionality. These

in turn diminish the pig's production efficiency, as evidenced by increased postnatal morbidity and mortality and decreased lifetime growth rate, feed efficiency, and carcass value (Wu et al., 2006; Fix et al., 2010a; Fix et al., 2010b).

Myogenesis is the formation of primary and secondary skeletal muscle fibers during fetal development (Maltin et al., 2001). Primary muscle fibers are developed prior to day 50 of gestation through the fusion of primary myoblasts. This process is thought to be generally consistent, with little variation between littermates according to the degree of fetal development (Swatland, 1973). Secondary fibers are then established on top of the existing primary fiber architecture, and secondary fiber myogenesis has been demonstrated to be amenable to such factors as placental insufficiency and maternal under- or over-nutrition in mid-gestation (Fig. 1.1; Swatland, 1973; Wigmore and Stickland, 1983; Dwyer et al., 1994; Foxcroft et al., 2006; Zou et al., 2017). Multiple studies have identified reduced secondary muscle fiber number in light weight pigs compared to normal birth weight littermates (Dwyer and Strickland, 1991; Town et al., 2004; Rehfeldt and Kuhn, 2006; McNamara et al., 2006; Alvarenga et al., 2013). It is important to emphasize that no myogenesis occurs postnatally, although hypertrophy of existing fibers does continue after birth, provided adequate nutrition is available (Lefaucheur et al., 2003). Without doubt, disruptions to the developmental biology *in utero* create permanent consequences for the animal. According to studies reviewed by Oksbjerg and Therkildsen (2017), the number of muscle fibers at birth in swine is moderately correlated ($r = 0.42$ to 0.46) with postnatal growth rate, carcass leanness, and feed efficiency.

Diminished intrauterine secondary myofiber formation may be traced to endocrine and transcription factor dysregulation. In particular, the myogenic regulatory factor family (composed of myf-5, myoD, myogenin, and mrf-4) regulate the proliferation and differentiation

of myoblasts into myotubes, and ultimately into myofibers (Oksbjerg and Therkildsen, 2017). Down regulation of *MYOG*, the gene coding for the myogenin transcription factor, has been observed in embryos weighing 85% to 95% of control embryos through mid- and late gestation in both Western crossbreed sows (Tse et al., 2008) and Meishan sows (Zou et al., 2017).

Insulin-like growth factor I (IGF-I) and insulin-like growth factor II (IGF-II) also contribute to prenatal muscle development. The birthweight of IGF-I and IGF-II knockout mice is reduced 30% compared to unaltered controls (Baker et al., 1993). Although both IGF-I and IGF-II contribute to fetal development, IGF-II is thought to have the greater role prenatally, while IGF-I is the more significant mediator of musculoskeletal growth in adulthood (Fowden, 2003; Duan et al., 2010; Kent et al., 2012). These growth factors, although working in concert to initiate fetal development, operate under separate stimuli. As stated by Fowden (2003), IGF-II provides the "constitutive drive for intrauterine growth via its placental effects and direct paracrine actions on fetal tissues," while on the other hand, IGF-I "regulates fetal growth in relation to the nutrient supply." Therefore, IGF-II expression and activity may be thought of as biologically fixed by genotype, while IGF-I activity may be relative to environmental manipulation. Accordingly, Blomberg et al. (2010) reported no statistical differences in IGF-II gene expression at day 50 of gestation between the placentae of IUGR piglets and the placenta of the littermate with the greatest body weight (IUGR defined here as piglets with a body weight at least one standard deviation below the mean body weight and within the lowest 10^{th} percentile of body weights of all fetuses included in the study). Similarly, Chriett et al. (2016) reported greater IGF-I plasma concentrations in NBW compared to IUGR piglets at day 112 of gestation. These patterns persist postnatally, with greater levels of plasma IGF-I identified at slaughter in pigs

weighing greater than 1.75 kg at birth compared to pigs weighing less than 1.10 kg at birth (Gondret et al., 2005).

Stunted organogenesis is also observed in IUGR fetuses. Town et al. (2004) subjected 30 third-parity sows to oviduct ligation to inhibit fertilization of ova from one ovary, thereby experimentally decreasing litter size and creating uncrowded uterine conditions. Fetal growth in the 30 "non-crowded" sows was then compared to fetal growth in 30 sows with normal "crowded" uterine conditions. Half of the crowded and non-crowded sows were sacrificed at day 30 of gestation, and the remainder were sacrificed at day 90 of gestation. At day 30 of gestation, 15.1±0.8 viable embryos were present in the crowded uterus as compared to 9.3±0.8 viable embryos in the non-crowded uterus. The uterine surface area available for placental attachment was not reported, yet given the use of entirely third-parity sows and the low standard deviation in sow body weight at initiation of the study (210±2.01 kg), no differences in uterine dimensions are expected. As expected, placental weight and fetal survival were greater in the non-crowded uterus at day 90 of gestation. Fetuses in the crowded uterus weighed 13.4% less than did fetuses in the oviduct-ligated non-crowded uterus (588±18 g vs. 679±18 g). Weights of the fetal spleen, liver, heart, lungs, and kidneys were 21.4%, 17.1%, 12.0%, 10.5%, and 13.9% less, respectively, in fetuses developed in crowded uterine conditions than the counterpart weights of organs of non-crowded fetuses at day 90 of gestation (Table 1). There was no statistical difference in the weight of the brain of crowded compared to non-crowded fetuses (19.65±0.33 vs. 20.03±0.41 g), likely indicating a sparing mechanism associated with this organ. In point of fact, given the propensity for the body to preserve brain development over other organs, researchers have successfully used subjective scoring of head size at birth to classify IUGR piglets and predict the probability of preweaning survival (Hales et al., 2013).

In a similar study, Wang et al. (2004) compared the organ development of NBW piglets (n=5) with true IUGR littermates (n=5; IUGR defined here as piglets weighing less than 2 standard deviations from the litter mean). Body weight and organ weight at birth of NBW and IUGR piglets are presented in Table 1. From these published data, calculations were made of organ weight as a percent of body weight within birth weight classifications and of organ weight of IUGR piglets as a percent of NBW. Expressing organ weight both as a percentage of body weight, and organ weight of IUGR piglets as a percentage of NBW piglets allows greater identification of developmental patterns. Expressed as a percentage of body weight, the relative organ weights of the liver, stomach, and pancreas of IUGR piglets (2.86%, 0.53%, and 0.13%, respectively) were actually greater than the relative organ weights in NBW piglets (2.61%, 0.49%, and 0.12%, respectively). However, the relative weight of the small and large intestines in IUGR piglets (2.36% and 0.65%, respectively) were less than the relative weight in NBW piglets (2.50% and 0.74%, respectively). Significant growth and maturation of the gastrointestinal tissue is necessary to prepare the piglet for postnatal intestinal nutrient absorption. Indeed, the small intestine is known to increase in relative weight by 70-80% during the last three weeks of gestation (Sangild et al., 2000). This coincides with a period of rapid fetal development in swine (Ji et al., 2017). Other authors have identified similar patterns of gastrointestinal tissue underdevelopment in IGUR piglets at birth (D'Inca et al., 2010; Alvarenga et al., 2013; Hu et al., 2015). Further, when small intestine dimensions are expressed relative to body weight (e.g. cm of small intestine per g of body weight), authors consistently report a longer and thinner intestine in IUGR piglets compared to normal birth weight littermates (D'Inca et al., 2010; Hu et al., 2015). A long and thin intestinal tract may be indicative of shortened villous height, indicating compromised functional capacity of gastrointestinal tissue at birth.

Wang et al. (2005) and Hu et al. (2015) reported decreased microvilli number at birth in the proximal jejunum and ileum, respectively. On the other hand, D'Inca et al. (2010) reported no differences in small intestine villous height between NBR and IUGR piglets (weighing less than 1.5 standard deviation from the mean) at birth (400±18 μm vs. 402±0.15 μm). Yet by two days of age, villous height had increased to a greater extent in the NBW but not the IUGR piglets (687±26 μm vs 508±21 μm). These data may indicate reduced intestinal responsiveness to milk-borne growth factors in IUGR piglets compared to NBW littermates (a more complete discussion of the effects of milk nutrients and growth factors will follow in section three of the literature review). Differences in intestinal attributes in IUGR piglets compared to NBW littermates persist to adulthood (Alvarenga et al., 2013).

Altered intestinal enzyme activity also indicates immature gastrointestinal tissue development in IUGR piglets. In an analysis of 12 pairs of 7 day old NBW and IUGR littermates (weighing less than 1.5 standard deviations of NBW littermates at birth), Hu et al. (2015) reported increased duodenal lactase and decreased alkaline phosphatase activity in IUGR piglets. Lactase is required for milk lactose digestion into the component monosaccharides glucose and galactose, and in the piglet, lactase activity is greatest at birth but decreases with increasing age (Aumaitre and Corring, 1978; Kelly et al., 1991). The increased lactase activity reported by Hu et al. (2015) may therefore indicate protracted reliance on milk lactose in IUGR piglets. Indeed, intestinal absorption of other nutrients, such as amino acids, increases with increasing age in correlation with increasing intestinal mass and length (Le Huërou-Luron and Ferret-Bernard, 2015). Similarly, decreased activity of alkaline phosphatase, a brush-border enzyme that maintains gut health through the detoxification of lipopolysaccharides and prevention of

bacterial infiltration of the gut mucosal barrier, in IUGR piglets likely indicates intestinal immaturity and increased susceptibility to enteric diseases (Chen et al., 1975).

The altered physical development and enzymatic activity observed in SGA and IUGR piglets suggests that these animals are at a reduced biological age, despite being the same chronological age as normal birth weight littermates. The muscular, metabolic, and digestive issues discussed create production challenges for the growing pig.

1.3 Production consequences of piglet intrauterine growth restriction

The combined effects of reduced muscular development and underdeveloped and ineffectual gastrointestinal tissue create lifetime production consequences for the light birthweight pig. Chief among these is the well-documented increased likelihood of pre- and post-weaning mortality. In particular, maternal overlay, or crushing by the sow, within the first 72 hours of farrowing is often cited by scientists and producers as the major cause of postnatal pig death (Edwards and Baxter, 2015). Maternal overlay, however, rarely occurs through random chance. Instead, multiple and complex maternal, environmental, and piglet-specific factors all contribute to postnatal piglet mortality, including, but not limited to: chilling, poor colostrum intake, low viability, inability to compete with littermates at the udder, and deficient immune status (Fig. 1.2). The effects of these factors are exacerbated in low birth weight pigs. Using a dataset of 12,727 piglets born from 1,338 litters over a 5 year period, Roehe and Kalm (2000) reported a curvilinear association between individual piglet birthweight and the probability of preweaning mortality. In their results, the mortality of piglets born weighing less than 1.0 kg, weighing between 1.0 and 1.2 kg, and weighing greater than 1.6 kg was 40%, 15%, and 7%, respectively.

Assuming that the pig survives to weaning, the detrimental consequences of low birth weight persist through life. In an observational study of commercial swine, Fix et al. (2010b) reported a positive linear relationship between pig birth weight and survival in the nursery but not finishing phases of production. Further, Fix et al. (2010a) identified that piglet birth weight is positively associated with average daily gain in both the nursery and finishing phases, and with increasing loin muscle area and back fat thickness at marketing. These results are supported by similar studies correlating the relationships between low muscle fiber number in low birth weight piglets with poor growth rate in the nursery (Dwyer et al., 1993) and finishing phases (Rehfeldt and Kuhn, 2006). Low birth weight pigs are also less likely to be full value at market (full value defined in this instance as pigs that survived to harvest, weighed greater than 100 kg at marketing, and were free of injuries, health issues, and physical deformities; Fix et al., 2010b), and yield carcasses with lower lean meat percentage, high intramuscular fat percentage, and greater carcass drip loss, indicating poor water holding capacity and, thus, poor meat quality (Rehfeldt and Kuhn, 2006).

Section 2. Swine mammogenesis and lactogenesis

2.1 The sow udder

The porcine udder consists of a variable number of mammary glands arranged in two parallel rows along the ventral body wall. Each gland contains a complete lobuloalveolar system that is functionally and anatomically independent from the neighboring and adjacent glands and terminates in a teat with two separate teat canals. Mammary glands are named sequentially according to position on the body, beginning with the most anterior pair: thoracic glands (first

and second pairs), abdominal glands (third, fourth, and fifth pairs), and inguinal glands (sixth and greater, if existing; Farmer and Hurley, 2015). Mammary glands may also be defined simply as anterior or posterior according to their position relative to the navel (McKay and Rahnefeld, 1990; Kim et al., 2000; Wu et al., 2010; Šamanc et al., 2013). The location of the mammary gland on the body is relevant because differences exist between glands in tissue composition, blood supply, and the nutrient profile of the produced milk.

The actual number of mammary glands is variable between individual pigs. In a survey of 987 Meidam (Meishan x Large White) sows, Balzani et al. (2016b) reported a range of 12 to 19 teats per sow, with a mean of 15.6 ± 1.1 total teats. In a separate survey of 118,267 purebred Yorkshire pigs, Felleki and Lundeheim (2015) reported 14.53 ± 0.92 teats, with a range of 9 to 21 teats. These data suggest variation by breed or within populations in the number of mammary glands per female. The number of mammary glands is a moderately to highly heritable trait. Estimates for heritability of total teat number range from 0.20 on the low end (Clayton et al., 1981) to 0.42 on the upper end (McKay and Rahnefeld, 1990). Analyses of the Swedish Yorkshire herd yields consistent trait heritability between 0.30 and 0.35 (Chalkias et al., 2013; Lundeheim et al., 2013; Felleki and Lundeheim, 2015). Lundeheim et al. (2013) also reported heritability for functional teats (0.31) and non-functional teats (0.09). The heritability of inverted teats has been estimated to be 0.20 (Clayton et al., 1981).

Non-genetic factors may influence the total teat number of female swine. In particular, mammary gland number in female pigs is reduced when the litter sex ratio is skewed towards a greater number of male fetuses (Drickamer et al., 1999). Normal litter sex ratio is 1:1 in wild boar and domestic swine (Clutton-Brock and Iason, 1986; Fernandez-Llario et al., 1999). It is hypothesized that testosterone exposure in early-gestation inhibits mammary development in

females (Kratochwil, 1971) and this may occur in litter bearing species when female embryos are positioned between two male embryos (vom Saal and Bronson, 1978) or when the sex ratio is skewed at least 2:1 towards male fetuses (Drickamer et al., 1997). The number of males born in a litter and the intrauterine positioning of female swine fetuses between male littermate fetuses has also been shown to modestly reduce age at puberty (Lamberson et al., 1988; Parfet et al., 1990), alter the dynamics of the gilt's preovulatory LH surge (Seyfang et al., 2018), and decrease conception rates (Drickamer et al., 1997). These experiments collectively indicate intrauterine androgen exposure as consequence of higher male:female sex ratio reduces female reproductive potential later in the life. Skewed male:female sex ratios may result from uterine crowding (Tse et al., 2008), and restricted sow feeding in lactation to elicit a severe negative energy balance at weaning (Vinsky et al., 2006; Oliver et al., 2011). On the other hand, however, prenatal methods to improve mammary number and development have not yet been identified.

Congenital defects and physical injuries to the udder during life may reduce the number of functional teats. Teat functionality is defined as the ability for that teat to excrete milk during lactation. Congenital teat defects include inverted teats (i.e. the mammary gland terminates in a teat that is inverted upwards into the body cavity), blind teats (i.e. no teat exists at the termination of the gland), and pin nipples (i.e. small bud-like projections on the udder unassociated with a fully functioning mammary gland; may be located intermediate between two regularly spaced fully-functioning teats). Of these, inverted teats occur at the greatest frequency, and tend to cluster in the thoracic and abdominal regions (Clayton et al., 1981). In a sample population of 2,160 German Landrace and German Large White breed pigs, Jonas et al. (2008) identified inverted teats on 11.3% of pigs at 180 days of age.

Physical injuries to the teats and udder may further compromise the number of functional teats available for piglet nursing. Udder injuries may stem from improperly maintained farrowing crates, the sow stepping on her own udder, or from aggressive piglet nursing. Injuries are most common on the abdominal and inguinal glands (Persson, 2010). Affected teats are also more susceptible to mastitis (Persson, 2010), which may decrease milking ability in the current or subsequent lactation. Udder injuries are not always included in farm management software culling codes, so data on the prevalence of udder injuries is limited. In an observational report of culling criteria of 21 Swedish sow farms (n=14,234 sows culled over a three-year period), udder problems accounted for 18.1% of sow removal (Engblom et al., 2006). In this report, udder problems included "low or no milk production, mastitis, and/or udder abscess" and was most commonly observed in 4^{th} to 6^{th} parity sows. Removal rate due to udder problems was on par with the removal rate due to "old age" (18.7%), but less than "reproductive disorders" (26.9%) and greater than "lameness and/or foot lesions" (8.6%) and "traumatic injuries" (7.1%).

2.2 Mammogenesis and mammary gland tissue composition

The lobuloalveolar system is the functional unit of the mammary gland. Alveoli are ovular structures consisting of a single layer of cuboidal / columnar epithelial cells surrounding an open lumen. Milk components are absorbed from the blood stream and synthesized within or translocated across the epithelial cells and then secreted into the alveolar lumen. Fluid secretion occurs in response to contraction of the myoepithelial cells surrounding the epithelium. Alveoli are clustered in highly branched terminal ductal lobule units and connected by branching ducts. All ducts terminate in a gland cistern (Horigan et al., 2009). The majority of milk is stored within the alveolar unit, yet a small proportion of fluid is collected in the gland cistern prior to letdown.

In the sow, two complete lobuloalveolar units each terminating in a distinct gland cistern exist within each mammary gland (Nickerson and Akers, 2011). Accordingly, milk accumulating in each gland cistern exits the gland through a separate teat cistern.

The mammary gland alveolar, ductal, and glandular tissue is collectively referred to as parenchymal tissue. Logically, the gland's connective and adipose tissue involved in structural support is titled extraparenchymal tissue (Farmer and Hurley, 2015). Milk production in mammals is positively associated with the number of mammary secretory epithelial cells, amount of parenchymal tissue, and the ratio of parenchymal to extraparenchymal tissue in the mammary gland (Knight et al., 1984; Knight and Peaker, 1984; Kim et al., 2000; Nielsen et al., 2001). Quantification of mammary DNA, protein content, and total tissue content may be used to estimate the number of secretory cells and the amount of parenchymal tissue in the gland, and these measures are often used as indicators of mammary development (Tucker, 1987). In one study, Kim et al. (2000) reported moderate to high correlations between piglet preweaning growth rate and the protein content (r=0.67) and DNA amount (r=0.54) of the mammary gland suckled during lactation. Thus, mammary development as defined by greater secretory epithelial cell number is positively correlated with the milking ability of the gland.

During embryonic development, evidence of primordial mammary tissue first appears between 22 and 28 days of gestation (Evans and Sack, 1973). Progressive tissue development and differentiation occurs within the mammary throughout gestation, such that, at birth, each gland consists of two small (3-4 mm) canals that in time will organize into the gland cistern and alveolar ducts (Rowson et al., 2012). Still, the pig mammary gland at birth largely consists of extraparenchymal connective tissue (Hughes and Varley, 1980).

Mammary development in gilts is slow through the first 90 days of age. According to Sørensen, et al. (2002), who conducted serial sampling of non-pregnant gilt mammary tissue at 10 day intervals beginning at birth, prepubertal mammary development from birth (0.3 mg DNA per gland) to 90 days of age (7 mg DNA per gland; Fig. 1.3; Fig. 1.4) is negligible and largely isometric with body weight gain. From 90 days of age to puberty, however, the accumulation rate of mammary DNA and mammary tissue was 3.9 and 5.6-fold greater, respectively, compared to accumulation rates before 90 days of age.

The increase in the rate of mammary development beginning at 90 days of age coincides with the timing of ovarian development, including the appearance of steroid-producing antral follicles and the initial establishment of the hypothalamic-pituitary-gonadal axis (Dyck and Swierstra, 1983; Camous et al., 1985; Pressing et al., 1992). Multiple authors have reported intrinsic roles for estrogen and prolactin in prepubertal mammary gland development in swine and other mammals (Purup et al., 1993; Bocchinfuso et al., 2000; Farmer and Palin, 2005; Horigan et al., 2009). Estrogen is involved in lobuloalveolar formation and prolactin is required for mammary epithelial cell differentiation (Barrington et al., 1999; Akers, 2017). Attempts to increase mammogenesis during this time through dietary means have been largely unsuccessful (Farmer et al., 2004; Sørenson et al., 2006; Farmer et al., 2007; Farmer et al., 2012).

Puberty attainment, and with it, increased circulating concentrations of estrogen and prolactin, is associated with pronounced increases in mammary DNA, RNA, and tissue content (Sørenson et al., 2002; Farmer et al., 2004; Sørenson et al., 2006). In one study, parenchymal tissue mass of gilts that had attained puberty was 51% greater compared to non-pubertal gilts of the same age (Farmer et al., 2004).

Following puberty, little mammary development is observed until the last trimester of pregnancy. Ji et al. (2006) reported a three-fold increase in mammary growth rate beginning after day 75 of gestation. Similarly, between days 75 and 112 of gestation, Sørenson et al. (2002) reported massive accumulation of mammary DNA (40 vs. 838 mg, respectively) and mammary tissue (80 g vs. 373 d, respectively). The increased tissue accretion in these data reflects accelerated growth rates, while the large accumulation of mammary DNA suggests tissue specialization into functional lobuloalveolar components. Indeed, the percent crude protein of the gland increases from 11.4% to 38.3% in late gestation, while the percent adipose decreases from 87.6% to 58.8% (Ji et al., 2006). Histological measurements of the gland indicate progressive growth of the terminal ductal lobular unit from day 75 to term (Ji et al., 2006).

The anatomical location of the mammary gland influences the size but not the tissue composition of the gland. In general, the abdominal glands (third, fourth, and fifth pairs) are the largest, while inguinal glands (sixth, seventh, and greater pairs) are the smallest, and the size of thoracic glands (first and second pairs) are intermediate. Ji et al. (2006) reported differences in the dry weight of thoracic, abdominal, and inguinal glands at day 112 of gestation (118.0, 135.3, 93.5 g per gland, respectively, SD=40.1 g) but no differences between glands in crude protein, crude ash, or ether extract when expressed as a percent of dry matter. Kim et al. (2000) reported similar patterns in sow mammary glands sampled within 12 hours after farrowing. Hence, the anatomical location of a gland impacts the overall size and total protein, fat, and ash content, but not relative composition of the mammary gland. Multiple arteries supply blood to the sow udder, and a sensible explanation for anatomical differences in mammary gland growth rate and size may be due to differences in blood flow rate at different areas of the udder (Farmer and Hurley, 2015). However, this hypothesis has not yet been tested in the existing scientific literature.

Similar to mammary development early-in-life, mammary growth during pregnancy is largely under endocrine control. Circulating estrogen levels in the pregnant female remain low until approximately 60 days in gestation, after which time increase precipitously until parturition. DeHoff et al. (1986) reported 967.6 pg/ml estrogen at day 60 of gestation and 21,439 pg/ml at day 112. Knight et al. (1973) identified that the elevated estrogen found in the sow's systemic circulation in late gestation is of fetal origin. Interestingly, though, no linear relationship between litter size and mammary development has been observed (Kensinger et al., 1986b). In contrast to estrogen, prolactin's period of influence on mammogenesis does not begin until later in pregnancy. Farmer and Petticlerc (2003) observed a 46% decrease in parenchymal tissue mass when bromocriptine, a dopamine agonist that inhibits prolactin secretion, was fed to gilts from 90 to 109 days of gestation, but no effects on mammary development when bromocriptine was fed from 50 to 69 or 70 to 89 days of gestation. Likewise, feeding domperidone, a dopamine antagonist that stimulates prolactin secretion, from day 90 to 110 of pregnancy increased alveolar lumen diameter and sow milk yield throughout lactation (VanKlompenberg et al., 2013).

Given the considerable mammary growth, as well as the previously discussed concurrent fetal and placental tissue growth in late gestation, it is logical that the sow's nutrient requirements in the third trimester are greater than the first and second. A meta-analysis conducted by Kim et al. (2005) demonstrated the daily lysine requirements of a hypothetical second-parity sow with 14 fetuses and 16 mammary glands in early and late gestation. Daily lysine requirements to support conceptus and mammary growth before day 70 of gestation are 0.27 g/d and 0.17 g/d, respectively, but increase in late gestation to 4.0 g/d and 4.1 g/d, respectively. A more complete description of the impacts of mammary and conceptus growth on

sow nutrient requirements throughout gestation will be provided in Section 4 of the literature review.

After farrowing, piglet nursing becomes responsible for maintaining lactation and promoting continued mammary development. With no nursing pressure, unsuckled glands quickly begin regressing (Kim et al., 2001), and by 72 hours become incapable of maintaining milk production (Theil et al., 2005). In contrast, intense nursing pressure (e.g. frequent nursing interval or large piglets nursing the sow) is associated with increased prolactin secretion (Spinka et al., 1999), which in turn drives further mammary development (Kim et al., 1999).

2.3 Udder and mammary gland vascularization and blood flow

The sow udder is perfused through a complicated vasculature of multiple arteries and veins. The complete circulatory anatomy of the sow udder is presented in Fig. 1.5. The thoracic and anterior abdominal glands are supplied oxygenated blood through the cranial epigastric artery arising from the internal thoracic artery. On the other hand, the posterior pair of abdominal glands and the inguinal glands are supplied by the lateral cranial, middle cranial, and medial cranial branches of the external pudendal artery (Farmer et al., 2015). Venous drainage of the udder is accomplished through bidirectional flow of the same abdominal mammary vein. Blood leaving the anterior half of the udder enters the mammary vein and flows in a cranial direction to the internal thoracic vein, and ultimately reaches the heart at the cranial vena cava. Conversely, blood leaving the posterior half of the udder flows into the mammary vein in a caudal direction to the external pudic vein, and ultimately reaches the heart through the caudal vena cava (Farmer et al., 2015).

Blood flow to a mammary gland is commonly estimated using diffusion principles. Briefly, at a sufficient concentration in arterial blood, the rate at which the concentration of a biological marker, such as a nutrient, gas, or growth factor, in venous blood approaches that of arterial blood increases relative to the rate of blood flow to the organ, assuming that gland uptake of the marker is either negligible or accountable (Kety and Schmidt, 1945). This principle was first utilized to estimate mammary blood flow in lactating swine by Linzell et al. (1969) who catheterized the carotid, internal saphenous, or external pudic arteries and the mammary vein on either side of a functioning mammary gland and infused tritriated water (^3H_2O) into the jugular vein at a constant rate. Synchronized repeated sampling of arterial and venous blood allowed researchers to quantify the concentrations of radiolabeled water through the gland, and hence, estimate blood flow to the mammary. Results of this experiment, and of the more recent studies of Trottier et al. (1997), Guan et al., (2002; 2004a; 2004b), Nielsen et al. (2002a; 2002b), and Renaudeau et al. (2002), utilized these same principles to estimate mammary blood flow and the corresponding plasma:milk (volume:volume) ratio. In these studies, mammary blood flow ranged from 1.9 liters to 5.5 liters of blood flow per minute and 441 liters to 1,050 of blood plasma per liter of milk produced (Farmer et al., 2015). Renaudeau et al. (2002) calculated the coefficient of variation of blood flow through the right pudic artery of a sow in a given day to be 19%.

The primary regulator of blood flow in the lactating sow is piglet nursing pressure. Nielsen et al. (2002b) fostered piglets between sows to achieve litter sizes ranging from 3 to 14 piglets and reported a linear increase in mammary blood flow with increasing litter size. These observations are supported by numerous observational and experimental studies indicating that sow milk yield increases with increasing litter size in a manner reciprocal to piglet demand

(Algers and Jensen, 1991; Toner et al., 1996; King et al., 1997; Auldist et al., 1998). No studies to date have measured or elucidated the regulators of late gestation mammary blood flow.

2.4 Lactogenesis and lactation

The lactation fluids produced by the sow are defined as colostrum or milk according to nutrient composition and timing of production relative to farrowing. Colostrum is synthesized in the mammary gland in late gestation and is available to the piglets immediately after farrowing (Quesnel et al., 2015). Colostrum is characterized by a higher percent protein content compared to milk (Hurley, 2015). Commonly, colostrum is defined as the fluids produced for the first 24 hours of lactation. The nutrient profile of colostrum begins to change almost immediately after farrowing. After 24 hrs, the fluid protein content has decreased to an extent to resemble mature milk more than colostrum (Devillers et al., 2007). Subtle changes in nutrient composition continue until approximately 10 days into lactation, after which time the nutrient profile of the milk is quite stable (Fig. 1.6; Hurley, 2015). Compared to milk, the colostrum produced within the first 6 hours after farrowing is more energy dense (4.9 kJ/g vs. 6.4 kJ/g) and contains greater total solids (20.0% vs. 26.2%) and percent protein (5.3% vs. 15.7%), but less lactose (7.4% vs. 2.8%) and fat (7.4% vs. 6.1%). Immunoglobulin G (IgG) is the major protein in colostrum, but IgA and IgM are the major proteins in milk (Hurley, 2015). A meta-analysis comparing sow milk nutrient composition in reports published in the 1980s and 2010s shows that modern sows produce milk with slightly greater levels of fat and lower levels of lactose compared with previous generations (Zhang et al., 2018a). Colostrum ejection is continuous and freely available to the piglets for the 8 to 11 hours after farrowing, after which time letdown occurs approximately 1.5 times per hour in response to piglet udder stimulation (Castrén et al., 1989). In

established lactation, nursing frequency may vary from 17 to 35 events per day, depending on litter age and nursing intensity (Jensen et al., 1991). Peak lactation in sows occurs at 18.7 days in milk (Hansen et al., 2012b).

Colostrogenesis is the process of colostrum synthesis and begins in the mammary gland in late gestation. The physiological markers used to define colostrogenesis include the histological changes in the mammary gland structure and the appearance of mammary-specific markers in sow blood, specifically lactose (Farmer et al., 2006). β-Lactoglobulin is the first mammary-specific protein detectable in the sow's systemic blood, as early as day 80 of gestation (Dodd et al., 1994). Interestingly, other whey proteins, such as α-lactalbumin, are not found in sow systemic blood until the last week of pregnancy (Dodd et al., 1994). The function of β-lactoglobulin is not as well understood as that of other whey proteins (Kontopidis et al., 2004), and accordingly it would be improper to use this correlation to conclude that colostrogenesis begins five weeks prior to farrowing. Indeed, morphological alterations to the structure of the gland place colostrogenesis closer to day 105 to 112 of gestation. Ji et al. (2006) noted slight distension of the alveolar lumen, an indication of epithelial cell secretory functionality, as early as 102 days of gestation, and more pronounced distension by day 112. Kensinger et al. (1982) also found distended alveoli and small lipid droplets in the mammary glands of gilts at day 105 of gestation. Expansion of the epithelial cell endoplasmic reticulum, the site of milk protein and lipid synthesis, is also observed during this time (Kensinger et al., 1986a). Finally, the lactose content of the sow's blood stream can be used as a reliable estimate of milk fluid synthesis in the mammary gland. In pigs, blood lactose remains low until approximately days 107 to 110 of gestation, and then increases progressively to reach maximal levels in the hours immediately after parturition (Martin et al., 1978; Hartmann et al., 1984). Collectively, then, it may perhaps

be said that colostrogenesis as defined the morphological changes to mammary structure necessary to support glucose conversion to milk substrates begins approximately one week prior to farrowing, but colostrogenesis as defined as the accumulation of physical colostrum within the gland does not begin until the days or hours immediately before farrowing.

The developmental changes in the gland that begin in late gestation continue up to and even following farrowing. As previously mentioned, mammary epithelial cell content is positively correlated with milk production (Kim et al., 2000). Hence, the hormones that stimulate mammogenesis also have lactogenic roles. In particular, prepartum sow prolactin is positively correlated with sow blood lactose content (Martin et al., 1978), total colostrum production (Quesnel et al., 2013), and early lactation piglet growth rate and survival (de Passillé et al., 1993). The essential role of prolactin in swine has been demonstrated experimentally by Farmer et al. (1998), who provided oral doses of bromocriptine, a dopamine agonist, to gilts beginning on day 110 of gestation and noted reduced piglet weight gain in early lactation. In rodents, progesterone inhibits prolactin secretion from the anterior pituitary and reduces prolactin receptor expression in the mammary gland (Haug and Gautvik, 1976). Accordingly, a greater prolactin:progesterone ratio prior to farrowing is a valid marker of greater colostrum production (Devillers et al., 2007; Foisnet et al., 2010, 2011).

The fact that progesterone and prolactin are both incorporated in the parturition induction hormone cascade may be relevant. A simplified explanation of this cascade is that parturition is naturally induced via activation of the fetal hypothalamic-pituitary-adrenal axis, the product of which (fetal cortisol) traverses the umbilicus to remove the progesterone block maintaining pregnancy and simultaneously increasing prolactin secretion (Taverne et al., 1982). Because parturition and, thus, the downstream periparturient increase in sow prolactin concentrations, are

induced by the fetus, some have suggested a fetal role in colostrogenesis. For example, Devillers et al. (2007) suggested a modest correlation (r=0.38) between piglet birth weight and sow colostrum production, although the fetal role in colostrogenesis in this study was only circumstantial. Potentially, large birthweight piglets in the study may have simply had greater vitality at birth and were able to strip more colostrum from the sow immediately after birth.

In established lactation, the sow produces milk reciprocal to litter nursing pressure. Milk production increases linearly with increasing litter size, and is also associated with the time and intensity of piglet teat massage (Algers and Jensen, 1991; Toner et al., 1996). Indeed, Auldist et al. (1998) utilized cross-fostering to create staggered litter sizes of 6, 10, and 14 piglets, and observed daily sow milk yields of 9.80, 13.05, and 15.52 kg, respectively. Also using cross-fostering strategies, King et al. (1997) observed a 26% increase in sow milk production when two-week old piglets were fostered onto dams that had farrowed only 2 days prior, and a 22% decrease in milk production when 2 day old piglets were placed on sows in peak lactation.

Oxytocin is the hormone responsible for initiating milk letdown. Oxytocin is produced in the hypothalamus and released from the posterior pituitary in response to neural stimulation. During farrowing, oxytocin stimulates contraction of the myometrial epithelium (Banks and Thornton, 2003). In the mammary gland, oxytocin stimulates contraction of the myoepithelial cells surrounding the alveolar epithelial cells to eject milk (Ellendorf et al., 1992). In swine, the birth of a piglet is followed by increased intramammary pressure approximately 20 seconds later (Gilbert et al., 1994). Sow systemic oxytocin concentrations remain elevated to such an extent to support continuous colostrum ejection for the first 10 to 12 hrs following farrowing (Devillers et al., 2007; Farmer and Quesnel, 2009). After this time, communication between the sow (in the form of distinct grunts) and piglets (in the form of udder massage) are required to elicit the

neural signal to release oxytocin to begin milk letdown (Jensen et al., 1991). In one study of fifteen catheterized lactating sows and their nursing litters, milk letdown occurred at approximately 45 minute intervals following 2.4 minutes of intense piglet udder massage. Increased sow vocalizations (1.9±0.1 grunts per second) began approximately 23 seconds prior to a rapid increase in intramammary pressure, lasting between 8 and 41 seconds (Ellendorf et al., 1982). The actual duration of milk letdown is brief (8 to 15 seconds; Fraser et al., 1980; Pedersen et al., 2011).

2.5 Nutrient and biochemical uptake into the mammary gland

The mammary gland is not a gluconeogenic organ, yet milk production is responsible for 65-70% of a sow's energy demand in peak lactation (Noblet et al., 1990). Of course, then, significant energetic material is regularly transported into the mammary gland. The major milk precursors utilized by the mammary gland are glucose, triglyceride fatty acids, and amino acids, and these compounds collectively account for approximately 95% of the carbon incorporated into the gland (Boyd et al., 1995). Spincer et al. (1969) used blood vessel catheterization and mammary gland arterio-venous differences to estimate the mammary gland uptake of glucose, triglyceride fat, and amino acids necessary to synthesize 1 dL of milk to be 14.1 g, 2.7 g, and 6.2 g, respectively. Other milk precursors transported into the gland at minor concentrations include acetate, non-esterified fatty acids, β-hydroxybutyrate, lactate, and citrate (Linzell et al., 1969; Spincer et al., 1969).

The nutrient composition of milk is determined by the number, activity, and the hormonal stimulation of epithelial cells and the availability of milk nutrient precursors through both dietary sources and as partitioned from extra-mammary tissues such as muscle and adipose (Boyd et al.,

1995). The majority of the research in this field has been conducted in the bovine and murine species, and the few swine studies available typically focus on the mammary gland in peak lactation. Efforts will be made to delineate species and stage of lactation for transporters or mechanisms not highly conserved across *Mammalia*. It should also be stated that, with the exception of Renaudeau et al. (2003), who measured glucose and fat uptake in heat stressed sows, the most recent studies measuring sow mammary gland uptake of energetic precursors were conducted fifty years ago (Linzell et al., 1969; Spincer et al., 1969) in sows in their 5th and 6th week of lactation. Considerable management and genetic changes have occurred on swine farms since these studies were conducted. An updated investigation into mammary energetics in the modern sow is long overdue.

Glucose accounts for approximately 40 to 60% of the total mass of substrates transported into the mammary gland of a lactating sow (Farmer et al., 2008). Indeed, as much as 60% of available arterial glucose in a lactating sow may be utilized by the mammary glands (Spincer et al., 1969). Renaudeau et al. (2003) estimated a 1,300 g/d glucose requirement to support an 11 kg/d milk yield.

Glucose is a polar and hydrophilic molecule which cannot cross a plasma membrane through simple diffusion. Multiple facilitated transport mechanisms have been described in the mammary epithelial cells of bovine and rodent species, including glucose transporter (GLUT) 1, GLUT8, and GLUT12 (Zhao, 2014). Facilitated transporters are bidirectional energy-independent transporters that move glucose according to concentration gradients. Sodium-dependent cotransporters (SGLT) have also been isolated in bovine epithelial cells. Cotransporters utilize the energy produced through counter-current sodium exchange to move glucose against a concentration gradient (Zhao, 2014). Chen et al. (2017) quantified mRNA

abundance of GLUT1, GLUT8, SGLT1, SGLT3, and SGLT5 in the swine mammary gland in late gestation and in lactation. In this report, GLUT1 mRNA was approximately 10-fold more abundant than other transporters, likely indicating greater physiological significance of this particular transporter. Given the large abundance, one may also infer that most GLUT1 is located on the epithelial cell basolateral membrane (nearest maternal bloodstream), as is the case in other species (Zhao, 2014), which would explain how such a considerable amount of glucose enters the cell from the bloodstream. Other likely locations for GLUT and SGLT glucose transporters are at the Golgi apparatus and the cell apical membrane (nearest the alveolar lumen). Future studies utilizing immunohistochemistry of mammary epithelial cells will be necessary to elucidate glucose transporter location and better understand mammary gland function and metabolism in swine.

Given that significant glucose is transported through concentration gradients, the arterial glucose availability may logically affect mammary glucose uptake. Plasma glucose in pregnant sows is approximately 4.5 mmol glucose/mL blood (Pére et al., 2000). This blood glycemia is similar to ruminant species (3-5 mmol/mL) but less than humans (4-8 mmol/mL) and rodents (9-11 mmol/mL; Zhao, 2014). Previously, Dourmad et al. (2000) noted increased mammary glucose uptake in postprandial lactating sows. Along the same lines, reduced mammary glucose uptake of 70-90% have been observed following 10 to 16 hour fasting periods in rodents (Threadgold et al., 1984; Prosser et al., 1988). However, unpublished data from the Trottier lab at Michigan State University presented in Farmer et al. (2008) describes no response in arterio-venous glucose differences following intravenous glucose infusion to sows following an unspecified duration of fasting. These data may suggest that homeorhetic glucose-freeing mechanisms (e.g.

gluconeogenesis, glycogenolysis) maintain arterial glucose availability at sufficient levels in all but cases of severe starvation.

Blood glucose is also affected by stage of pregnancy and litter size. Many species, including swine, experience decreased insulin secretion and tissue responsiveness to insulin in late gestation, and this is thought to be an evolutionary mechanism to shunt greater glucose to the gravid uterus (Zhao, 2014). Indeed, Pére et al. (2000) noted greater blood glucose and decreased insulinemia beginning after 85 days in pregnancy. More recent work conducted by Pére and Etienne (2018) indicates that uterus glucose uptake increases with increasing litter size, but potentially not at levels sufficient to diminish arterial glucose concentrations.

Hence, increased mammary glucose uptake at constant arterial glucose concentrations is achieved by increased glucose transport number. Chen et al. (2017) reported increased GLUT1 and SGLT3 mRNA abundance in sow mammary glands at farrowing compared to day 97 of pregnancy. Feeding lactating rodents the dopamine agonist bromocriptine decreased mammary GLUT1 receptor number, indicating a role of prolactin in mammary glucose transporter expression (Rudolph et al., 2011). In cows, the advancing stages of pregnancy are associated with increased GLUT1, GLUT8, GLUT12, SGLT1, and SGLT2 (Zhao and Keating, 2007), suggesting that all glucose transporters may be upregulated in late gestation to increase mammary glucose flux.

Once incorporated into the mammary epithelial cell, glucose is used primarily for milk lactose synthesis. According to studies reviewed by Zhang et al. (2018a), approximately 59% of the glucose incorporated into the mammary gland is utilized for milk lactose synthesis. Lactose is a disaccharide energy source providing approximately 4 kCal/g of energy (Mellor and

Cockburn, 1986). Lactose is also the primary osmotic agent in the mammary gland and therefore has a large role in determining milk volume (Zhang et al., 2018b).

Lactose synthesis occurs in the Golgi apparatus and the process is highly conserved across domestic species (Huang et al., 2012; Zhang et al., 2018a). Briefly, glucose is first enzymatically converted to the monosaccharide galactose in cytoplasm and then combined with free glucose in the Golgi. The lactose synthase enzyme, consisting of the regulatory subunit α-lactalbumin (LALBA) and the catalytic subunit β-galactosyltransferase (GALT), is required to produce lactose. Milk lactose content is low in colostrum (approximately 2.8%) but increases in mature milk (approximately 5%; Hurley, 2015). Accordingly, GALT and LALBA mRNA abundance and protein expression are relatively low at farrowing, but increase significantly by approximately 3 days in milk (Chen et al., 2017; Zhang et al., 2018b).

The remaining glucose not utilized for milk lactose synthesis is utilized in normal mammary gland metabolism or is converted into glycerol through glycolysis (Zhang et al., 2018a). Glycerol is combined with three fatty acids in the mammary epithelial cell endoplasmic reticulum to produce milk triglycerides. Only 2% of mammalian milk fat is not bound in triglyceride form (Innis, 2011). Glucose may also be converted directly into fatty acids through *de novo* glycolysis and the TCA cycle to produce a citrate intermediary. In non-ruminant species, short and medium chain fatty acids are produced through *de novo* synthesis in the mammary gland, while long chain fatty acids present in milk are from dietary sources (Bauman and Griinari, 2003). Long chain fatty acids constitute the majority of milk fat in swine colostrum and milk (Zhang et al., 2018a).

Long chain fatty acids are thought to be transported into the mammary gland by fatty acid binding proteins. In bovine and caprine species, FABP3 and FABP4 are both associated with

fatty acid uptake into the mammary gland (Bionaz and Loor, 2008; Shi et al., 2015) yet FABP3 only appears to be the major transport protein in swine (Lv et al., 2015). Further, FABP3 mRNA and protein expression increases as the sow transitions from late gestation to lactation and in response to incubating epithelial cells with increasing levels of long chain fatty acids *in vitro* (Lv et al., 2015; Lv et al., 2018).

Mammary gland protein utilization involves uptake of both amino acids and whole proteins. Compared to mature milk, colostrum is characterized by a higher percent protein content and lower percent fat and lactose (Hurley, 2015). Indeed, proteins account for approximately 60% of the total solids in colostrum, and immunoglobulins (Ig) make up approximately 80% of these proteins (Klobasa et al., 1987).

Immunoglobulin (Ig) G is the major protein in swine colostrum. Immunoglobulin refers to any one of five isotypes (Ig A, D, E, G, and M) differing in location and function and produced by humoral B cells in response to specific antigen challenges (Le Bien and Tedder, 2008). In swine, as in all mammals, IgG is the major constituent of blood serum antibodies, and hence provides systemic protection against previously encountered challenges (Butler and Brown, 1994). However, the piglet immune system is immature at birth because no antigen stimulation of the fetal immune system occurs *in utero* and because the epitheliochorial placental barrier prevents mature maternal antibody transfer from dam to fetus (Chucri et al., 2010). Instead, IgG is translocated from sow blood serum into the mammary lumen by the neonatal Fc receptor (FcRn) where it is incorporated into colostrum, consumed by the postnatal piglet, and absorbed intact into the piglet bloodstream through enterocyte pinocytosis (Clarke and Hardy, 1971; Schnulle and Hurley, 2003; Nechvatalova et al., 2011). Unlike IgG, which is translocated from sow blood serum into colostrum and absorbed intact by the permeable neonatal intestine

into systemic circulation, IgA is derived within the mammary gland from B cells that migrate from the maternal gut through the lymphatic system. After colostrum consumption, IgA remains localized in the piglet gastrointestinal tract to provide immune services against enteric-specific pathogens (Rooke and Bland, 2002). Hence the location of antibody synthesis and existence in the sow (blood serum vs. gut) becomes the location of antibody residence in the piglet, and therefore provides location-specific protection against location-dependent challenges.

Immunoglobulin concentrations in sow colostrum change during the first 24 hours after farrowing. According to a review of 12 studies conducted by Hurley (2015), the concentration of IgG in swine colostrum at 0, 12, and 24 hours from farrowing is 64.4, 34.7 and 10.3 mg/mL, respectively. By 72 hours post-farrowing, IgG levels have decreased to such an extent that IgA becomes the dominant antibody in milk (3.1 mg/mL IgG vs. 4.1 mg/mL IgA; Hurley, 2015). Immunoglubulin M is also present in swine colostrum (8.4 mg/mL) and milk (3.1 mg/mL) at physiologically relevant concentrations (Klobasa et al., 1987; Hurley, 2015).

Significant variation exists in IgG concentration in swine colostrum, with little information available to determine the sources of variation. Hurley (2015), reported the average IgG concentration in sow colostrum collected during farrowing was 64.4 mg/mL, yet the range of reported means in the studies extended from 52 to 102 mg/mL. Greater colostrum and milk Ig concentrations have been reported in older compared to younger sows, and this is logical, as older sows are expected to have been exposed to a greater number and variety of antigenic challenges (either natural or through vaccines) over time (Klobasa and Bulter, 1987; Quesnel, 2012). However, other authors have failed to report parity effects on colostrum IgG content (Keilland et al., 2015).

Late gestation mammary structure may impact milk protein composition by altering the efficacy of epithelial cell transport systems. The effects of late gestation prolactin concentrations on mammary epithelial cell development are known (Martin et al., 1978; Farmer et al., 1998; Devillers et al., 2007; Foisnet et al., 2010; 2011). In cattle, late gestation hyperprolactinemia decreases colostrum protein content by decreasing mammary expression of the FcRn receptor involved in transcytosis of IgG molecules from the bloodstream into the alveolar lumen (Barrington et al., 1999). Similarly, sows with experimentally induced hyperprolactinemia produce colostrum with decreased IgG content, and this may be due to decreased relative mammary gland FcRn mRNA in early lactation (VanKlompenberg et al., 2013). Finally, colostrum IgG content may be gland specific, with anterior glands producing colostrum with greater IgG content compared to posterior glands (Wu et al., 2010).

Proteins are also synthesized from amino acids in epithelial cells, particularly those proteins involved in local biochemical reactions (e.g. enzymes, receptors). Amino acid uptake is accomplished through a variety of transporters, and the rate of uptake varies considerably between individual amino acids (Zhang et al., 2018a). In lactating sows at peak lactation, Trottier et al. (1997) reported the essential amino acids with the greatest rate of extraction (defined as the amino acid arteriovenous difference multiplied by the concentration of the amino acid in arterial blood) are lysine, isoleucine, leucine, arginine, and methionine (53.0%, 39.9%, 37.0%, 34.5%, and 31.2%, respectively) and the amino acids with the lowest extraction rates are phenylalanine, valine, threonine, histidine, and tryptophan (26.4%, 23.4%, 20.9%, 15.7%, and 13.5%, respectively). Amino acids with lower extraction rates are more likely to be found in colostrum and milk as free amino acids unbound to proteins (Wu and Knabe, 1994). This further implies that those amino acids with the greatest rate of extraction from arterial blood have a greater

requirement for incorporation into milk protein. Indeed, lysine, leucine, and isoleucine have the greater presence in bovine LALBA than any other essential amino acids (Brew et al., 1970).

2.6 Methods to measure colostrum and milk production in swine

Estimating sow colostrum and milk yield is a useful assessment of sow health, metabolism, and productivity. Objective measures of milk yield, such as mechanical milking machines, do exist (Fraser et al., 1985; Garst et al., 1999), but are rare and impractical. Accordingly, it is more common to utilize piglet weight change as an indirect measure of sow colostrum and milk production. Three measures for estimating sow colostrum and milk production will be discussed in this section, all varying in labor and laboratory costs. Limitations and considerations to maximize the precision and accuracy of each method will be considered.

The simplest and least labor intensive measure of sow milk production is piglet weaning weight. Provided piglets have no access to creep feed, the sow is the only source of nutrients prior to weaning. Thus, sows that wean heavier piglets could be assumed to have produced greater milk throughout lactation. These measures have value for ordinal ranking of sows in genetic selection programs. Regressions of sow milk production could be performed using published ratios of the efficiency of piglet weight gain at various points in lactation (e.g. 3.8 g of milk to 1g of piglet growth at 3 days of age; 4.9 g of milk to 1 g of piglet growth at 17 days of age; Quesnel et al., 2015) but these calculations would be crude at best. Given the known factors influencing sow milk yield and piglet growth (e.g. litter size, birth weight, lactation length, etc.), using piglet weaning weight as a proxy for milk yield requires significant experimental control to minimize litter variation. Even still, Lewis et al. (1978) noted only a moderate correlation

(r=0.58) between sow milk yield and piglet preweaning growth rate in litters standardized to a common size. No estimates of sow colostrum production may be utilized from this method.

In contrast, deuterium oxide dilution is the most accurate measurement of both colostrum and milk production. However, it is also the most costly and requires the greatest inputs of skilled labor and laboratory materials. In this method (as described by Quesnel et al., 2015), sow colostrum and milk samples are first analyzed for water content, and the piglet is fasted for a defined period of time before receiving an injection of deuterated water. After a period of suckling (generally hours or days, depending on whether colostrum or milk production is being measured), a blood sample is collected from the piglet and the dilution of deuterated water is compared against the ingestion of water from milk consumption. Total milk intake may then be calculated based on the water content of the milk sample. This method provides the most objective measurement of milk availability, yet the requirement for costly laboratory materials and skilled laborers to collected serial blood samples from neonatal piglets make this method rare in the scientific literature.

The piglet weigh-suckle-weigh method is the most commonly used method to estimate sow colostrum and milk production in swine lactation studies. In established lactations, the entire litter is weighed before and after each suckling event to measure the amount of milk ejected. This is often repeated multiple times to acclimatize piglets to handling and achieve statistical robustness (Lewis et al., 1978; Spinka et al., 1997). Even still, difficulties controlling piglet urination and defecation between weighings, as well as stress associated with repeated piglet handling, may reduce the accuracy of the weigh-suckle-weigh technique by as much as 20% compared to DO dilution (Quesnel et al., 2015).

Weigh-suckle-weigh methods to measure colostrum production are based on changes in piglet body weight between birth and 24 hours of age. Two regression equations have been proposed to estimate piglet colostrum intake based on 24 hour body weight change. The first was developed by Devillers et al. (2004):

$$\text{Colostrum intake (g)} = -217.4 + 0.217t + 1{,}861{,}019BW24/t + BWB\,(54.80-1{,}861{,}019/t)(0.9985 - 3.7\times10^{-4}T_{FS} + 6.1\times10^{-7}T_{FS}^{2})$$

where t = time (minutes) between first and second weighing; BW24 = body weight (kg) at 24 hours of age; BWB = body weight (kg) at birth; and T_{FS} = the interval (minutes) between birth and first suckle.

A second equation was developed by Theil et al. (2014):

$$\text{Colostrum intake (g)} = -106 + 2.26\Delta WT + 200BWB + 0.111t - 1{,}414\Delta WT/t + 0.0182\Delta WT/BWB$$

where BWB = body weight (kg) at birth; ΔWT = weight change (g) between birth and 24 hours of age; and t = time (minutes) between the first and second weighing.

Both the Devillers et al. (2004) and Theil et al. (2014) equations were developed by comparing the 24 hour growth of piglets nursing a sow to the 24 hour growth of piglets consuming a known amount of colostrum (i.e. a standard). In the case of Devillers et al. (2004), the standard was the colostrum intake of bottle-fed piglets, but in Theil et al. (2014), the standard was the colostrum intake of piglets nursing a sow measured via deuterium oxide dilution. Bottle nursed piglets have different suckling behavior and levels of nursing activity compared to piglets

nursing a sow (e.g. less littermate interaction and no udder competition) and their intake is greater than piglets nursing a sow. In a study comparing the growth rate of piglets nursing a sow to piglets reared on artificial milk of similar nutrient composition, the artificially reared pig average daily gain was 70% greater (395 vs. 232 g/d) and 21 day weaning weight was 53% greater (9.8 vs. 6.4 kg) than piglets nursing a sow (Harrell et al., 1993). Indeed, Theil et al. (2014) also compared actual piglet colostrum intake as defined by deuterium oxide dilution to the estimated value provided by Devillers et al. (2004) and found that the original prediction equation underestimated piglet colostrum intake by 43%. Accordingly, the Theil et al. (2014) regression equation provides a more biologically accurate estimation of true piglet colostrum intake and total sow colostrum production. The choice of which equation to use is particularly impactful if the author's goal is to justify a recommended minimum amount of colostrum intake required to ensure satisfactory piglet performance (Le Dividich et al., 2005; Quesnel et al., 2012)

Section 3. The role of colostrum in postnatal piglet development

3.1 Piglet sucking behavior and teat competition

The piglet stands and begins seeking a teat within minutes of birth. Sampling of multiple teats occurs within the first 8 or so hours of life (de Passillé and Rushen, 1989), concomitant with the period of continuous sow colostrum ejection (Devillers et al., 2007; Farmer and Quesnel, 2009). Piglets that suckle more teats during this period consume more colostrum, as evidenced by greater piglet systemic IgG levels at 12 hours of age (de Passillé et al., 1988). The litter demonstrates cyclic suckling behavior immediately after farrowing, wherein the first-born piglets suckle for the first 2 to 3 hours of life, fall asleep, and then begin suckling again. Pigs

born in the second-half of the litter therefore have unfettered udder access while the first-born piglets sleep (Castrén et al., 1989). Hence, authors have reported that piglet birth order in non-dystocic farrowings may have relatively little effect on the piglet's ability to consume colostrum (Devillers et al., 2011; Le Dividich et al., 2017).

The number of piglets born in the litter has a substantial effect on individual pig colostrum intake. Large litter sizes result in a longer latency between birth and first suckle, increased udder competition, and a greater number of failed nursing attempts (Milligan et al., 2001; Andersen et al., 2011; Balzani et al., 2016b). Indeed, piglet colostrum intake decreases by 11 to 20 g for each additional piglet born (Decaluwé et al., 2014b; Keilland et al., 2015). Investigations into the role of litter dynamics and udder access in modern hyperprolific sows is justified.

Considering the effects of litter size on piglet colostrum intake, placing greater emphasis on udder characteristics and piglet nursing ability would be logical. Few studies to date, however, have considered the effects of functional teat number or teat location in relation to piglet colostrum intake. Vasdal and Andersen (2012) noted that newborn piglets prefer to suckle teats from one row of mammary glands, and Balzani et al. (2016a) reported a tendency for piglets to suckle teats closest to the sow's dorsal midline. These findings are logical because the sow lies on her side during and following farrowing and piglets may not be strong enough to lift the sow's udder or back leg to expose the bottom row or the most posterior teats. These data also indicate that a greater number of functional teats per sow is associated with increased piglet suckling opportunities after farrowing.

Although unconfirmed experimentally, the impact of sow functional teat number on piglet colostrum intake may be implied through associations between preweaning survival and

the number of piglets weaned per litter. Greater functional teat number should logically increase the number of pigs weaned by decreasing udder competition. Previously, authors have reported moderate correlations between teat number and the litter size at 21 days in lactation (r=0.35, Allen et al., 1959; r=0.19, Skjervold, 1963). On the other hand, however, Balzani et al. (2016b) reported a low phenotypic correlation (r=0.03) between sow total teat number and the number of piglets alive at 10 days in lactation, yet this may be due to the sows used in this study having a larger number of teats (15.6±1.1) than number of piglets born alive (11.7±3.1). Non-significant phenotypic correlations between teat number and the number of piglets weaned per litter have also been observed when cross-fostering is used to standardize litters within 24 hours of birth (Pumfrey et al., 1980). Perhaps these results indicate that functional teat number is an important factor for litter performance in large litters or when intensive farrowing room management strategies such as cross-fostering are not used.

Piglet-specific factors have greater impacts on piglet colostrum intake. Indeed, piglet colostrum intake is heavily dependent on the piglet's ability to approach the udder and compete with littermates after birth. Devillers et al. (2007) reported a moderate correlation (r=0.38) between mean litter birth weight and 24 hour sow colostrum yield. Other factors that contribute to decreased piglet vitality at birth, such as a ruptured umbilical cord, splayed legs, and hypoxia, further impair piglet colostrum intake (Devillers et al., 2007).

3.2 The role of colostrum in piglet energetics

Colostrum is an energy-dense and high utilizable food source for baby pigs The energy content of colostrum at farrowing is greater than the energy value of mature milk produced in an established lactation (1.5 Kcal/g vs. 1.2 Kcal/g; Hurley, 2015). As much as 91% of the

metabolizable energy present in the fluid is retained and utilized by the piglet (Le Dividich et al., 1994b). This is vital, as piglets are born with sparse hepatic glycogen stores (approximately 14.4% of liver weight and 0.14% of body weight, respectively) and muscle glycogen stores (approximately 9.0% of muscle weight and 2.6% of body weight, respectively), little white body fat (approximately 1.5% of body weight), no thermogenic brown fat, thin hair coats, and a large surface area relative to body mass (Herpin et al., 2002; Lay et al., 2002; Theil et al., 2011; Edwards and Baxter, 2015). The majority of white body fat at birth is structural and not readily utilizable, leaving glycogen oxidation as the primary energy source in the neonatal pig (Herpin et al., 2002; Theil et al., 2011). Without colostrum intake, glycogen content is fatally depleted within 16 hours of birth (Theil et al., 2011). The energy mobilized from the two neonatal glycogen pools (liver and muscle) have different purposes. According to Theil et al. (2011), hepatic glycogen stores are oxidized to support the biochemical reactions associated with systemic glucose homeostasis (e.g. gluconeogenesis and glycogenolysis), while muscle glycogen stores are consumed within the muscle to support locomotion and shivering thermogenesis.

The energy provided through colostrum is vital to sustain the piglet during early life. Piglet intestinal lactase activity is high at birth and continues to increase through the first week of life to liberate glucose from the disaccharide lactose (Aumaitre and Corring, 1978). Nearly all colostrum fat is incorporated directly into adipose tissue (van Es, 1977; Le Dividich et al., 1994b). Fat deposition in the piglet continues throughout lactation (Elliot and Lodge, 1977; Le Dividich et al., 1994a). Piglet adipose tissue lipoprotein lipase activity to liberate fatty acids from white adipose tissue increases progressively during lactation in response to the increased fat content of mature milk compared to colostrum (Le Dividich et al., 1997; Liu et al., 2001).

Farrowing is associated with a sudden decrease in ambient temperature as the piglet passes from the warm birth canal and into the colder natural world. This drastic (at least 15-25^{o}F) change forces shivering behavior to generate body heat, which stresses the piglet's already stretched energy preserves. Berthorn et al. (1994) reported the piglet's lower critical temperature to be 33.85^{o}C (92.9^{o}F), defined as the ambient temperature at which muscle contractile activity (i.e. shivering) as measured by electromyography commences and increases linearly with decreasing ambient temperature. Shivering is an inefficient means of heat production: approximately 10% of body energy utilized for shivering is converted to heat (Herpin and LeDividich, 1995). Achieving such heat production requires hefty energetic inputs. In the first 48 hours of life, muscle glycogen content decreases as much as 50% in pigs reared in thermoneutral environments and to an even greater extent in cold-stressed pigs (Berthorn et al., 1996; Theil et al., 2011). Piglets born into environments without supplemental insulation (e.g. nesting materials) or heat sources (e.g. heating lamps) will quickly deplete energy reserves, grow slower, and are at greater risk of pre-weaning mortality (Adams et al., 1980; Edwards and Baxter, 2015).

3.3 The role of colostrum in piglet immunity, survival, and growth

That colostrum has an essential role in the piglet as an energy source is clear, yet proteins clearly constitute the major macronutrient class of the fluid (Hurley, 2015). Le Dividich et al. (1994b) estimated the efficiency of piglet utilization of colostrum nitrogen content to be 89%. Similarly, Lin et al. (2009) reported colostrum crude protein and dry matter digestibilities of 97% and 98%, respectively. Such high efficiency is possible because large macro-proteins are absorbed into the piglet's immature enterocytes (incorporating both non-specific and receptor-mediated transport processes) and subsequently transported into the systemic bloodstream intact

(Xu, 1996; Pluske, 2016). Intestinal permeability to large proteins is possible for the first 24-36 hours of life (Lecce et al., 1964). Proteins can also remain unabsorbed to provide local developmental functions and antibacterial/immune protection within the gastrointestinal tract (Pluske, 2016). More than 60 different bioactive proteinaceous immune cells, growth factors and hormones exist in mammalian milk (Grosvenor et al., 1993; Michaelidou and Steijns, 2006).

Immunoglobulin G is transported directly from maternal blood into colostrum, and, in the piglet, is absorbed directly from the intestinal lumen into systemic circulation. Immunoglobulin A, on the other hand, exerts antibacterial actions within the intestine (Rooke and Bland, 2002). Multiple studies have identified an essential role of colostral immunoglobulins in protection against diarrheal and respiratory diseases in neonatal livestock (Elahi et al., 2006; Parreño et al., 2010; Steele et al., 2013). The pig's capacity to synthesize IgG in later lactation and after weaning is positively associated with greater IgG intake through colostrum (Rooke et al., 2003).

Significant variation exists in piglet IgG uptake and persistence in blood. Keilland et al. (2015) conducted a multilevel linear regression analysis of piglet plasma IgG content at 24 hours of age on 644 piglets born to 58 multiparous sows on 4 Norwegian sow farms. The authors of this study reported that the individual piglet effect explained 64% of the variation in piglet plasma IgG content, while the effect of sow and farm explained only 34% and 9%, respectively. The large piglet effect is logical, given the effects of piglet birth weight and vitality on colostrum intake. By providing oral doses of iodine-labelled IgG to neonatal pigs, Curtis and Bourne (1973) reported an approximately one week IgG half-life in blood, yet the range observed in the study was 6.5 to 22.5 days.

Maternal somatic (non-protein) cells with immunoprotective and growth promoting properties also exist in swine colostrum, including leukocytes, lactoferrin, and lysozyme. The

total number of somatic cells in swine colostrum is large, yet the variation between sows is also substantial ($2x10^5$ to $5x10^7$ cells/mL; Evans et al., 1982). Many of these cells are absorbed by the intestine and evident in blood within hours of first suckle (Williams, 1993). Leukocytes (white blood cells) include T and B lymphocytes, neutrophils, macrophages, and eosinophils that contribute to anti-bacterial, anti-inflammatory, and immunostimulatory purposes in piglets (Uruakpa et al., 2002; Hurley, 2015). Similarly, lactoferrin concentrations are greater in colostrum than milk, and have multiple roles in the baby pig intestine, including inhibition of bacterial growth and promotion of intestinal iron uptake (Yang et al., 2000). Lysozyme is a complement enzyme that increases IgA bactericidal activities in piglet intestines by degrading the bacterial cell wall (Hill and Porter, 1974).

Swine colostrum contains bioactive growth factors and hormones that promote postnatal tissue and organ development. Some of these agents are absorbed intact into systemic circulation to exert physiological action on distal tissues (Xu and Wang, 1996; Shen and Xu, 2000), yet most remain localized in the gastrointestinal tract to stimulate intestinal cell proliferation and hypertrophy (Shen and Xu, 1996; Burrin et al., 1997). According to studies reviewed by Odle (1996), the major non-nutritive proteins present in swine colostrum that contribute to piglet development are epidermal growth factor (EGF; 1,500±525 μg/L), insulin (12.3±3.3 μg/L), insulin-like growth factor I (IGF-I; 39 to 357 μg/L), and insulin-like growth factor II (IGF-II; 82.3±57.5 μg/L). Concentrations of each of these proteins are greater in colostrum than in milk.

The piglet gastrointestinal tract experiences significant postnatal allometry. Widdowson and Crabb (1976) first described the relative change in suckling piglet body weight and organ size from birth to 24 hours of age: compared to an 8% increase in body weight, the weights of the stomach, small intestine, and large intestine increase by 28%, 61%, and 42%, respectively, in

the same time. Xu et al. (1992) similarly reported a 70% increase in small intestine weight during the first day of life, but also increases in the small intestine mucosal tissue weight (115%), intestinal length (24%) and diameter (15%), crypt depth (24%), and villus height (33%). On the other hand, piglets that are denied colostrum and offered only water for the first 24 hours of life experience negligent or negative growth in body weight (-1%) and the weights of the stomach (0%), small intestine (-13%) and large intestine (-5%; Widdowson and Crabb, 1976). The essential non-nutritive role of colostrum in piglet development was described experimentally by comparing whole body protein synthesis in neonatal piglets fed colostrum with neonatal piglets fed either mature milk collected from sows in the third week of lactation or fed an artificial formula formulated to mimic sow colostrum macronutrient content (Burrin et al., 1992; Burrin et al., 1995). In these studies, protein synthesis rates in liver, kidney, spleen, pancreas, and the longissimus dorsi and gastrocnemius muscles were greater in piglets fed colostrum compared to milk or formula. Plasma concentrations of IGF-I was also greater in piglets fed colostrum, but no differences in insulin concentrations were detected.

Researchers from Auburn University and Rutgers University have coined the term "lactocrine hypothesis" to explain the process whereby maternal milk-borne growth factors and hormones exert physiological actions in the neonate to promote organogenesis (Bartol et al., 2008). These efforts have concerned the effects of relaxin produced in the maternal reproductive tract and mammary gland and communicated through colostrum to act on relaxin receptors in the neonatal gilt to induce growth of cervical and uterine tissues and increase uterine estrogen receptor expression (Yan et al., 2005; Yan et al., 2006). Greater colostrum intake as measured by piglet blood serum immunoglobulin content at one day of age has been associated with

increased reproductive potential in adulthood, including decreased age at puberty, greater subsequent litter size, and increased milking ability (Vallet et al., 2015).

Collectively, the immune properties, nutrients, and non-nutritive growth promoters make colostrum an essential foodstuff for the piglet. Multiple authors have reported positive associations between colostrum intake and preweaning survival and weaning weight (Devillers et al., 2011; Decaluwé et al., 2014b; Declerck et al., 2016; Moreria et al., 2017). The benefits of colostrum intake are long term. Devillers et al. (2011) reported positive correlations between piglet colostrum intake and the concentrations of immune cells at weaning (r=0.32). Similarly, in a study of 1,455 piglets across ten commercial herds representing five different genetic lines, Declerck et al. (2016) showed that a one gram increase in colostrum intake was associated with a 3.5 g increase in piglet body weight at weaning (21 days of age) and a 17 g increase in pig body weight at finishing (154 days of age). The benefits of colostrum intake on preweaning and postweaning growth in this study were more pronounced in piglets with birth weights greater than one standard deviation below the mean.

Section 4. Feeding sows to improve colostrum production and composition

4.1 Sow nutrient requirements in late gestation

Considerable maternal and fetal growth and development occur in the sow throughout pregnancy. The majority of tissue accumulation, however, occurs in the last trimester (Kim et al., 2005). Logically, then, a sow's daily nutrient requirements also change according to stage of gestation. In particular, dietary protein and energy needs are greatest in late gestation to support the rapidly growing fetal, uterine, and mammary systems (Goodband et al., 2013; Trottier et al.,

2015). Nutrient requirements in all stages of pregnancy are greater in gilts than in sows due to nutrient competition from the growing maternal body. To be sure, the requirements of all nutrients change over the course of a pregnancy (Goodband et al., 2013; Bikker and Blok, 2017), yet attention will be given primarily to protein and energy in this section.

Five protein pools exist in gestating sows that dictate dietary protein requirements: the maternal body, the mammary system, the uterus, the placenta and associated fluids, and the fetal body. Of these, protein usage by the udder and litter increase to the greatest extent in late gestation (Trottier et al., 2015). Indeed, in a meta-analysis of previous publications, Kim et al. (2005) produced regressions showing steep increases in fetal and mammary protein accretion beginning at days 68.5 and 81.6 of gestation, respectively. These authors further calculated that a hypothetical multiparous sow with 14 fetuses and 16 mammary glands would require 0.27 and 4.00 g/d lysine to support fetal growth before and after day 68.5 of gestation, respectively, and 0.17 and 4.09 g/d lysine to support mammary growth before and after day 81.6 of gestation, respectively. Kim et al. (2009) suggested the next limiting amino acid after lysine in sows in early-gestation is threonine (Lys:Thr ratios 1.0:0.79 and 1.0:0.71 before and after day 60 of gestation, respectively), and in late gestation, the next limiting amino acids are arginine (Lys:Arg ratios 1.0:0.89 and 1.0:0.98 before and after day 60 of gestation, respectively) and leucine (Lys:Leu ratios 1.0:0.88 and 1.0:0.95 before and after day 60 of gestation, respectively). Total protein gain throughout pregnancy in the specific protein pools and the total body is presented in Fig. 1.7.

The sow's energy needs also increase with advancing stages of pregnancy, albeit to a lesser extent than protein requirements. Maternal maintenance costs and the energy lost as heat represent the greatest energy expenditures throughout pregnancy, while a minority but still

relevant level of energy expenditure is associated with supporting protein deposition and fetal energy retention (Fig. 1.8; Trottier et al., 2015). Noblet et al. (1985) calculated energy content and modeled energy expenditure of maternal and fetal components throughout gestation by feeding pregnant sows high or low (7,165 vs. 4,777 kcal ME/d) energy meals in heat-sink calorimeters and comparing tissue composition and heat production to similarly fed non-pregnant control sows. In sows fed the high energy diets, the authors reported that the energy content of the gravid uterus and udder increase by 60% and 37% between days 90 and 110 of gestation, respectively. Much of the energy accumulation in the uterus at this time is credited to the feto-placental unit. In sows fed the lower energy diet, the rate of energy accumulation in the gravid uterus was reduced and the energy content of the gravid uterus and mammary glands at 110 days of gestation was decreased by 25% and 73%, respectively.

Sows raised in the US are generally fed according to guidelines published in the National Research Council's *Nutrient Requirements of Swine* (NRC, 2012). NRC recommendations for gestating sow nutrient requirements are modeled from meta-analyses of multiple scientific reports. In reality, significant variation may exist in sow requirements according to many biological and environmental conditions. For example, factors that increase sow protein or energy requirements include: primiparity, large litter size, disease, group housing, exercise, conductive heat loss through housing on concrete flooring, cold stress, genetic selection for greater carcass leanness, and advancing stages of pregnancy. NRC dietary nutrient intake recommendations before and after day 90 of gestation are presented for sows housed in modern production environments with hypothetically defined breeding weights, litter sizes, and daily feed intakes in Table 1.3.

Providing multiple diets in early and late gestation to satiate the nutrient requirements of females of different parities and stages of pregnancy presents significant equipment costs (i.e. a greater number of feed bins and feed lines) and logistical challenges (i.e. constraints on breeding group assembly and reduced freedom to move females within barns). Instead, a typical sow farm generally only has one gestation diet and one lactation diet containing greater SID lysine and ME on site. Hence, producers may utilize multiple strategies to compensate for the greater sow needs, as described in Goodband et al. (2013). Overfeeding the gestation diet during mid-gestation will increase sow body adiposity and create energy reserves for utilization in late gestation, yet the greater feed costs associated with overfeeding costly and unutilized amino acids makes this a poor choice of strategy. Otherwise, producers may simply increase feed intake of the gestation diet beginning in late gestation (termed "bump feeding"), yet the greater energy intake may satiate sow appetite before amino acid requirements are achieved. Similarly, transitioning sows to the lactation diet in late gestation will provide sows with greater protein and energy without having to increase feed intake. In commercial production, sows are commonly transitioned to the lactation diet at move-in to the farrowing room, but the timing of this transition is more likely to be defined by the convenience of farrowing crate availability rather than sow nutrient requirements.

4.2 Effects of bump feeding on sow reproduction and lactation

The NRC recommends an 18% increase in gestation feed intake after day 90 of gestation to satisfy increased nutrient requirements. According to these recommended intake values, a multiparous sow eating 2.10 kg/d and 2.48 kg/d before and after day 90 of gestation, respectively, would consume 10.0 g/d SID lysine and 6,930 kcal/d ME in early and mid-

gestation and 16.6 g/d SID lysine and 8,184 kcal/d ME in late gestation. These values are in line with those estimated by Goodband et al. (2013) for what is provided on a typical US sow farm.

Studies evaluating the effectiveness of bump feeding protocols have typically targeted changes to piglet birthweight as their indication of success or failure. A recent review by Gonçalves et al. (2016a) summarized five bump feeding trials and reported that feeding sows an additional 3.1 g SID lysine and 3.5 Mcal ME per day from d 90 of gestation to farrowing improved average piglet birth weight by 28 g. However, significant variation exists within this small sample set of studies and in others regarding the effectiveness of bump feeding as an effective tool to improve performance.

For starters, bump feeding consistently yields more positive results in gilt pregnancies than in multiparous sows (Shelton et al., 2009; Soto et al., 2011; Gonçalves et al., 2016b). The reason for this is simply that, unlike the sow body, the gilt body is still growing and is competing with fetal, uterine, and mammary tissues for nutrients (Kim et al., 2005). The exception to this trend is the study of Cromwell et al. (1989), who reported a greater improvement in piglet birthweight in bump fed sows than in gilts. However, data in this study were compiled over two consecutive parities, and females provided one treatment (bump fed vs. not bump fed) as gilts were then provided the same treatment as sows. Dams maintained in appropriate body conditions during late gestation and lactation have improved reproductive potential in the subsequent breeding (Zak et al., 1997; Beyga and Rekiel, 2010). Therefore, bump fed gilts may have been in better body condition after their first lactation, and this likely accounted for the differences observed between treatments in sows. On the other hand, Mallman et al. (2018) failed to observe a difference in piglet birthweights in either gilts or sows fed 1.8 vs. 2.2 kg/d from day 90 to 112 day of gestation. The feed levels provided in this study translated to an additional 2.6 g lysine

and 1,300 Kcal ME per day, and the average total number born was 14.7. Hence, the additional 0.18 g lysine and 88.4 Kcal ME provided per fetus per day in the study may have been insufficient to elicit a detectable response in piglet birthweight.

Fewer studies have considered the effects of late gestation nutrient intake and sow metabolism on colostrogenesis. To be sure, efforts to supplement individual ingredients, such as carnitine or polyunsaturated long chain fatty acids into isocaloric or isonitrogenous diets to increase colostrum energy value or immune cell content has been studied to varying degrees of success (Eder, 2009; Bontempo and Jiang, 2015), yet these are beyond the scope of this review.

There is variation in the results of studies conducted to date that have considered sow physical and metabolic characteristics in relation in colostrum production. Decaluwé et al. (2013) first noted a positive correlation between late gestation backfat thickness and colostrum yield, whereby sows that gained backfat in the last 8 d of gestation produced more colostrum. Yet the multiparous sows enrolled in this study were fed 1.9 kg/d during this time and potentially experiencing nutrient deficiency. Indeed, the consensus of other studies appears to favor the reverse, whereby greater backfat thickness one week prior to farrowing, as well as greater backfat tissue mobilization during the last week of gestation, is associated with greater colostrum yield and milk yield in established lactation (Hansen et al., 2012a; Decaluwé et al., 2014a). Indeed, in a meta-analysis of five previously conducted fiber feeding studies encompassing 121 sows at Aarhus University, Vadmand et al. (2015) reported a positive correlation between colostrum yield and sow backfat thickness 8 d prior to farrowing ($r=0.19$) and a negative correlation between colostrum yield and backfat mobilization ($r=-0.26$), indicating that sows with greater backfat tissue loss produced more colostrum.

Similarly, biomarkers indicating a catabolic metabolism are generally associated with increased colostrum yield. Positive correlations have been detected between colostrum yield and late gestation concentrations of urea and other indicators of protein degradation (Decaluwé et al., 2013; Loisel et al., 2014). These data presents strong evidence for a substantial amino acid requirement to support colostrogenesis. In regards to energy, Hansen et al. (2012a) reported positive correlations between litter weight gain within the first 24 hrs of life and various energetic substrates in sow blood plasma, including propionate and butyrate on d 112 of gestation and glucose and acetate on the day of farrowing. On the other hand, Loisel et al. (2014) failed to observe any significant correlations between colostrum yield and energetic indicators in gilts, including concentrations of glucose, lactate, and non-esterified fatty acids. Sows enrolled in the studies of Hansen et al. (2012a) and Loisel et al. (2014) were of similar parity and body condition, yet differences in the time of day of blood sample collection in relation to the time of feeding could have influenced these results. Regardless, the definitive trend in the literature is that greater colostrum yield is associated with greater body tissue mobilization during late pregnancy.

Given that nutrients are in such high demand that sows must sacrifice body condition to withstand late term fetal development, mammogenesis, and colostrogenesis, one would assume that increasing nutrient intake during late gestation may improve colostrum yield. Decaluwé et al. (2014a) first considered the effects of maternal feeding level on colostrum yield by feeding multiparous sows 1.5 or 4.5 feed allowance per day of a transition diet from d 108 of gestation until farrowing. The transition diet used in the study contained 13.0% crude protein, but the amino acid and energy values of the diet were not reported. No differences in piglet birthweight were observed, yet the sows fed 4.5 kg/d produced more colostrum than did sows fed 1.5 kg/d

(4.0 kg vs. 3.5 kg). These sows also produced colostrum with greater lactose content (2.5% vs. 2.2%) and less protein (14.7% vs. 15.3%). No differences in preweaning growth were detected. The results of this initial study were encouraging that colostrum yield may be mediated through feed intake, however, because diet formulations were unavailable, sow nutrient intake in relation to requirements was unclear. Given the large difference in feed intake (4.5 vs. 1.5 kg/d), one may assume that sows in this experiment were fed either above or below requirements without an adequate control group (i.e. sows fed at requirements). Hence, it is indistinguishable whether colostrum yield was improved as result of increased feed intake or reduced due to nutrient restriction. Correlations posed by Vadmand et al. (2015) suggest positive associations between sow colostrum yield and average daily feed intake (r=0.24) and daily ME intake (r=0.17) in the last week prior to farrowing.

More recently, Mallman et al. (2019) proposed a negative relationship between late gestation feed intake and colostrum yield in gilts. In their experiment, gilts were fed 1.8, 2.3, 2.8 or 3.3 kg/d of a diet containing 0.64% SID lysine and 3,288 Kcal/kg from d 90 of gestation through farrowing. Gilt colostrum yield decreased linearly with increased feed intake (3.6, 3.5, 3.3, and 3.2 kg, respectively). It appears, however, that colostrum measurements were incorrectly performed in this study, as cross fostering was utilized to standardize litter size within the first 24 hours of birth. This flaw in the experimental method presents opportunity for artifact to influence the results. The authors also elected to utilize the colostrum intake prediction equation presented by Devillers et al. (2004), which has since been shown to have a 30-40% error rate in estimating piglet colostrum intake compared to the equation formulated by Theil et al. (2014).

Conclusions

Genetic selection for increased litter size in swine has resulted in reduced fetal prenatal development. Pigs that are lightweight at birth exhibit reduced growth and feed efficiency throughout life, and are at greater risk of deathloss or becoming reduced value hogs at marketing. Impaired prenatal development occurs during situations of large litter size because the sow's uterine capacity restricts placental ability to transfer nutrients and oxygen to the fetus. The effects of intrauterine growth restriction on the developing fetuses are observable in mid-gestation, yet most fetal growth actually occurs in late gestation. Hence, the sow's nutrient requirements increase substantially during late gestation to compensate for increased fetal growth. Little success has been found in efforts to improve piglet birthweight through dietary means. Yet significant growth also occurs in the mammary glands during late gestation. Studies considering the effects of late gestation nutrient supplementation on sow performance may be viewing only half of the picture by considering just piglet birthweight. A sparse number of studies have been conducted to date on the impacts of increased sow amino acid and energy intake during late gestation on colostrum production, piglet survival, and preweaning growth. Therefore, the experiments and results described in Chapter 2 of this dissertation were designed to answer the question of whether or not late gestation sow nutrition impacts piglet colostrum intake, colostrum nutrient composition, and litter throughput.

Table 1.1 Gastrointestinal organ weights and dimensions in intrauterine growth restricted piglets and normal birthweight littermates at birth. Adapted from Wang et al. (2005).

	IUGR piglets (n=5)	Normal birthweight piglets (n=5)	IUGR as percent of normal, %
Birth weight (BW), kg	0.60±0.03**	1.02±0.03	58.8
Organ Weights			
Liver, g (% of BW)	17.16±1.2** (2.86%)	26.62±0.90 (2.61)	64.5
Stomach, g (% of BW)	3.18±0.20** (0.53)	4.98±0.29 (0.49)	63.9
Pancreas, g (% of BW)	0.75±0.05* (0.13)	1.26±0.08 (0.12)	59.5
Small intestine, g (% of BW)	14.18±0.66** (2.36)	25.55±1.01 (2.50)	55.5
Large intestine, g (% of BW)	3.91±0.19* (0.65)	7.51±0.40 (0.74)	52.1
Intestinal Dimensions			
Duodenum, cm	7.42±0.59*	9.32±0.26	79.6
Proximal jejunum, cm	41.54±1.15*	58.68±6.12	70.8
Small intestine, cm	173.58±4.75*	244.04±24.31	71.1
Large intestine, cm	50.87±2.93*	69.84±3.55	72.8

*Results within line differ at P<0.05 level; **Results within line differ at P<0.01 level.

Table 1.2 Recommended dietary levels of lysine and metabolizable energy in gestating sows before and after day 90 of gestation[1].

Parity	1		2		3	
Body weight at breeding, kg	140		165		185	
Anticipated litter size	12.5		13.5		13.5	
Anticipated gestation weight gain, kg	65		60		52.5	
Days in gestation	< 90	> 90	< 90	> 90	< 90	> 90
Estimated feed intake, kg/d[2]	2.13	2.53	2.21	2.61	2.21	2.61
Metabolizable energy (kcal/kg)	3,300	3,300	3,300	3,300	3,300	3,300
SID lysine, % of diet	0.57	0.76	0.48	0.67	0.41	0.58

[1] Data presented in this table are derived from NRC (2012) recommendations with 10% added to lysine to compensate for inaccuracies in feed preparation and variation in sow performance as presented in Trottier et al. (2015).

[2] Estimated feed intake includes an additional 5% to account for feed wastage.

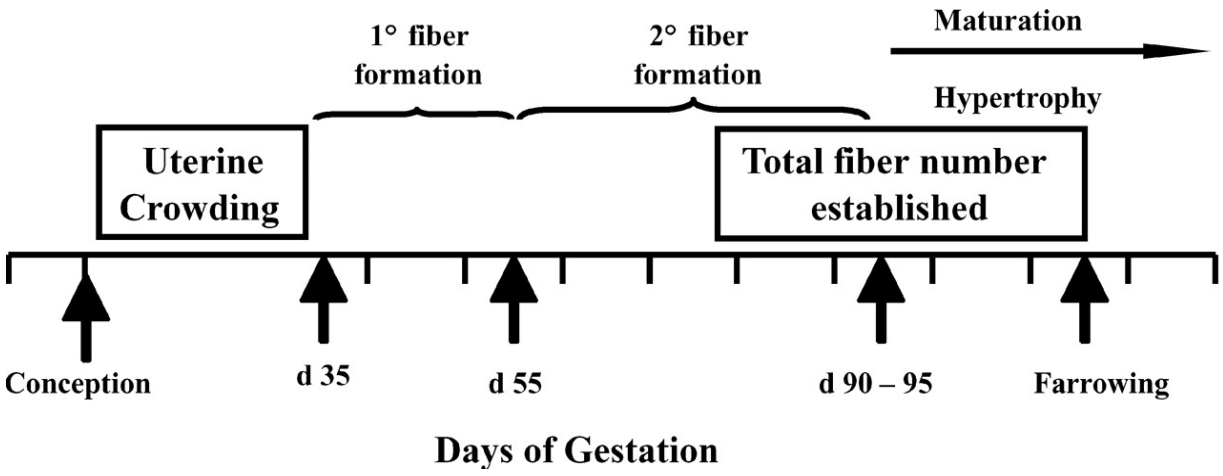


Figure 1.1 Timing of fetal primary and secondary fiber myogenesis relative to the period of uterine crowding in gestation. Originally published in Foxcroft et al. (2006).

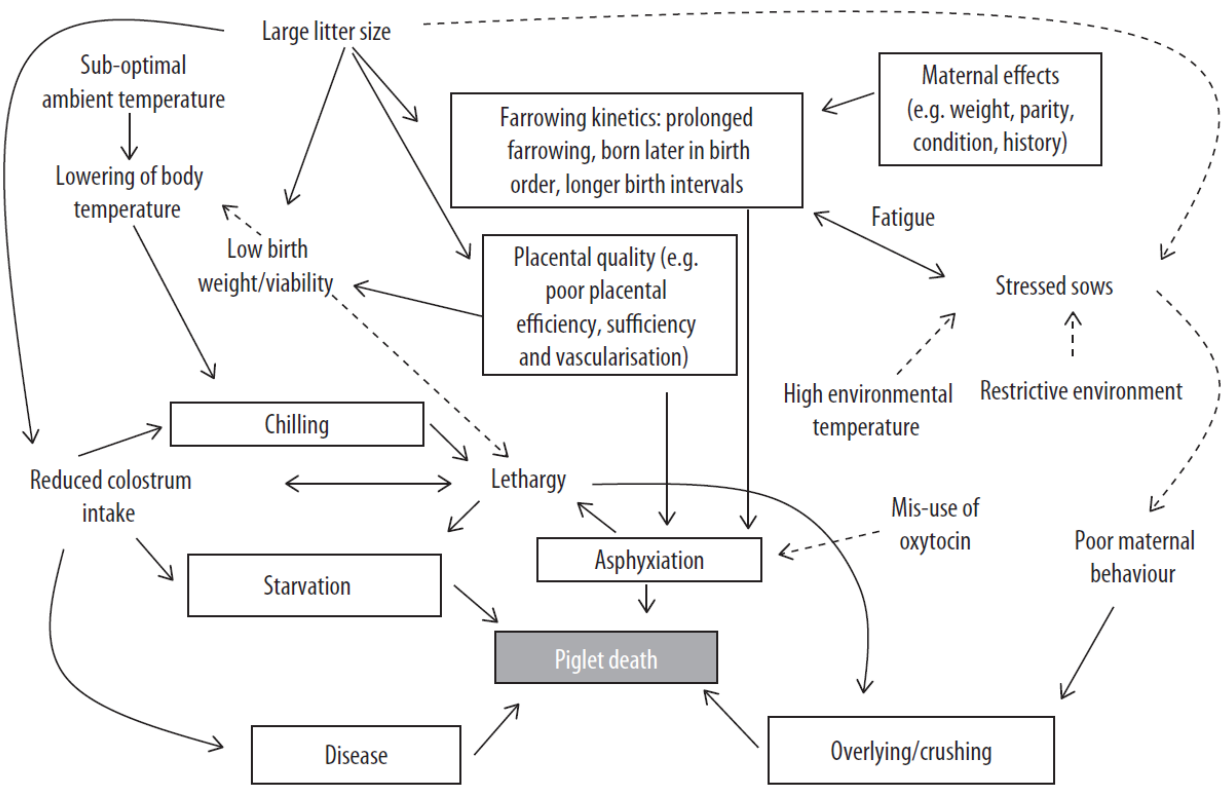


Figure 1.2 Maternal, environmental, and piglet-specific factors contributing to piglet deathloss during and after farrowing. Originally published in Edwards and Baxter (2015).

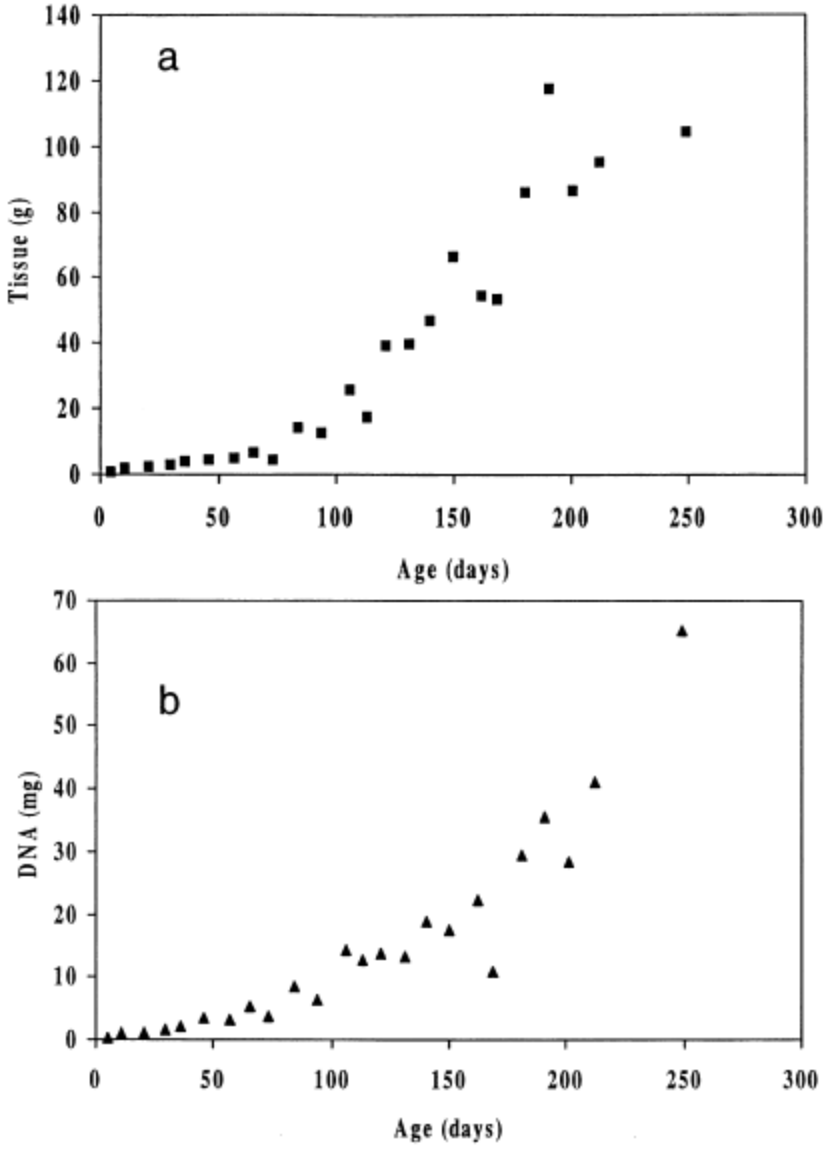


Figure 1.3 The accumulation of mammary tissue (squares) and DNA (triangles) in serially sacrificed gilts from birth to 300 days of age. Originally published in Sørenson et al. (2002).

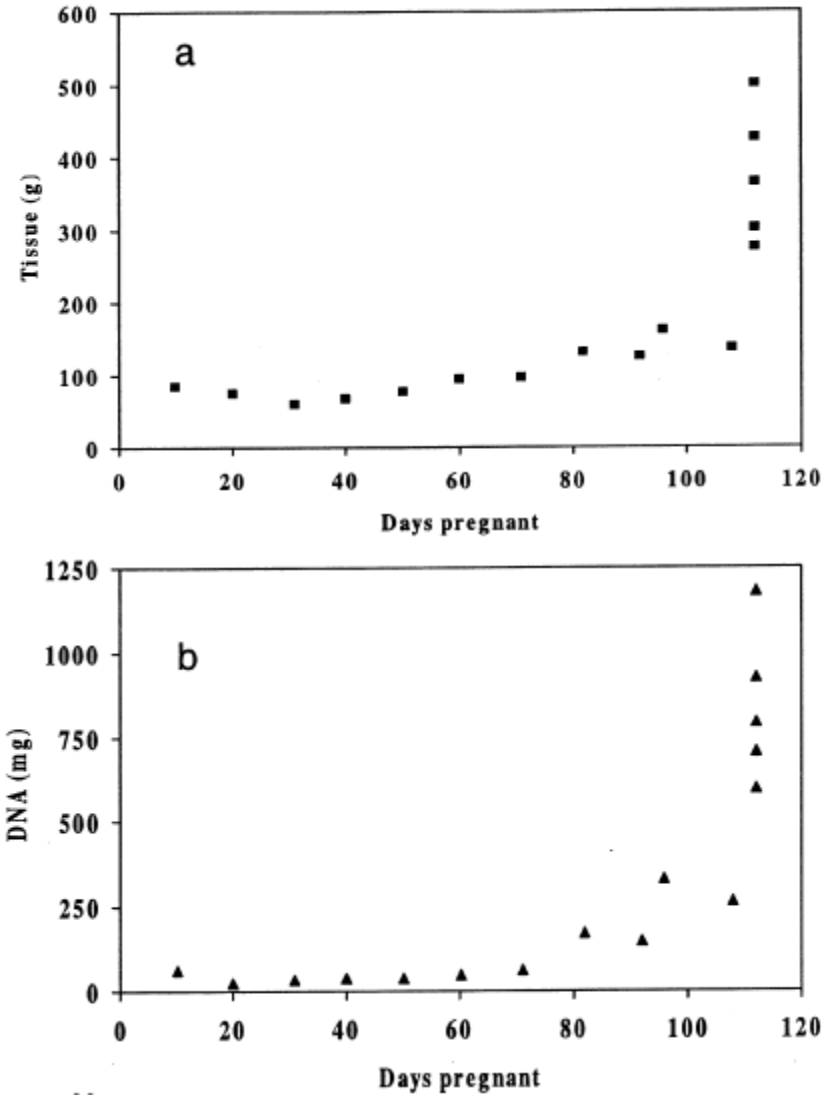


Figure 1.4 The accumulation of mammary tissue (squares) and DNA (triangles) in pregnant gilts from breeding (day 0) to farrowing. Originally published in Sørenson et al. (2002).

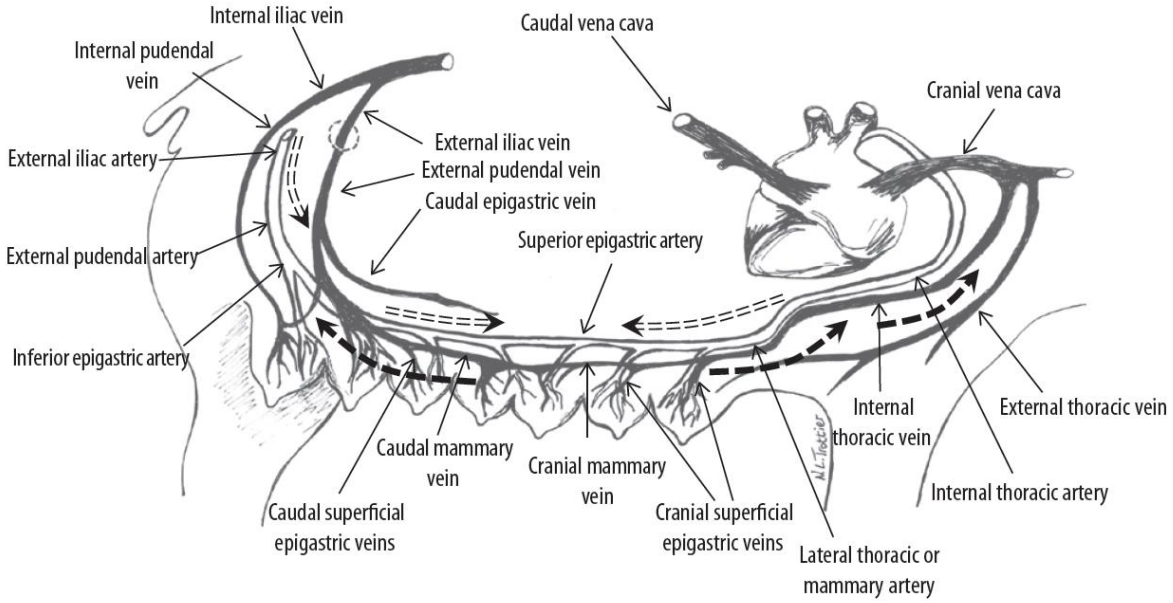
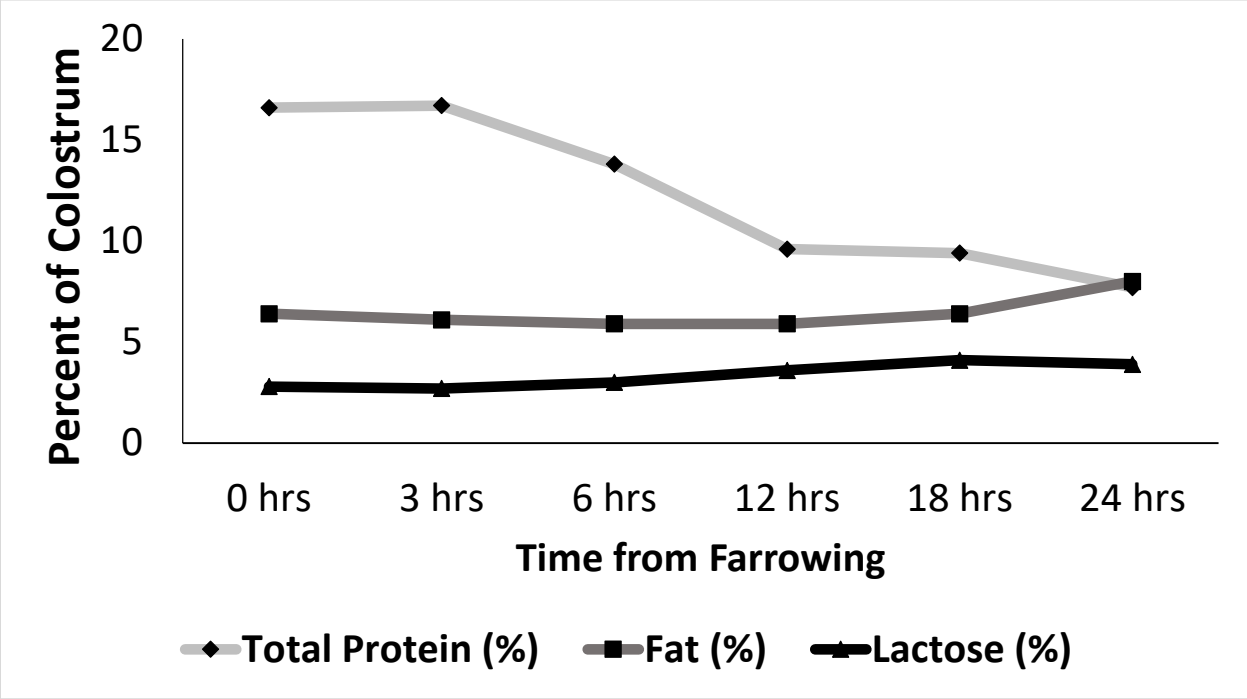


Figure 1.5. Cardiovascular anatomy of the sow udder. Originally published in Farmer et al. (2015). In this illustration, double-dashed arrows represent the direction of arterial blood flow, and single-dashed arrows represent the direction of venous blood flow.

A)



B)

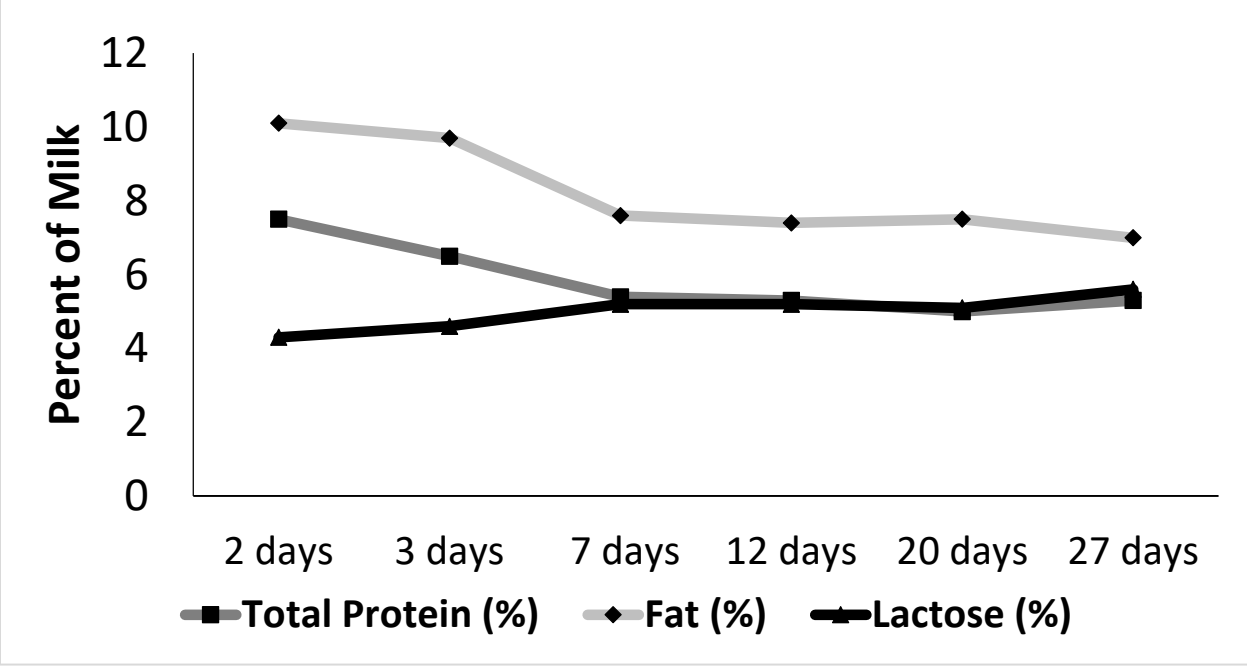


Figure 1.6 The percent protein, lactose, and fat in A) colostrum produced in the first 24 hours of lactation, and B) milk produced from 1 to 27 days of lactation. Adapted from Hurley (2015).

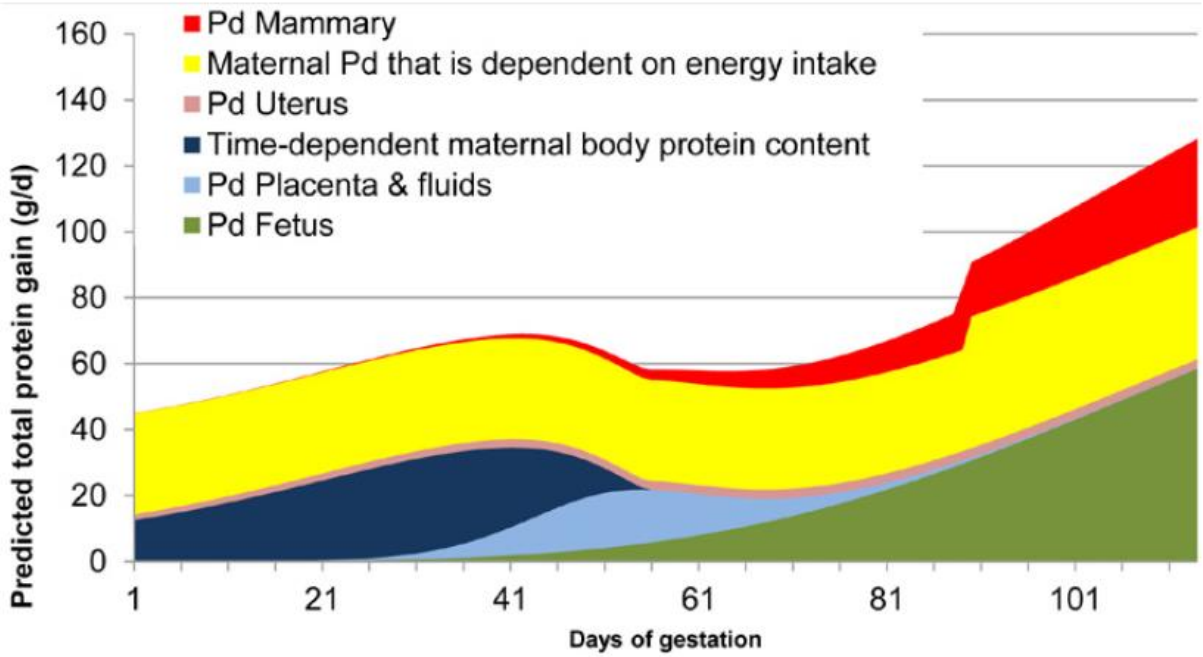


Figure 1.7 Total protein gain of maternal protein pools in a hypothetical second-parity sow over the course of gestation. Originally published by Goodband et al. (2013) using NRC (2012) data.

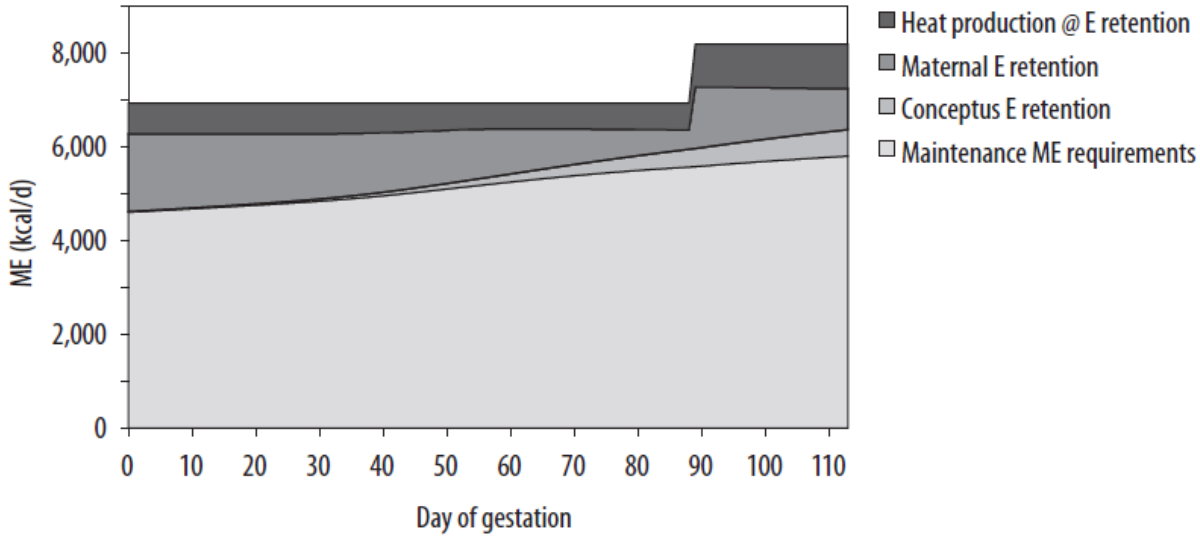


Figure 1.8 Dietary energy partitioning to maternal maintenance, maternal growth, conceptus growth, and heat production and adipose tissue throughout pregnancy. Originally published in Trottier et al. (2015) using NRC (2012) data.

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Chapter 2. Effects of practically increasing amino acids and energy in late gestation on colostrum intake, colostrum composition and sow performance.

Abstract

Four experiments were conducted to titrate the effects of late gestation amino acid and energy intake on colostrum parameters and sow reproductive performance. Differences in nutrient intake were achieved by modifying sow diet, feeding level, or the day in gestation of treatment initiation. In experiment (EXP) 1, 62 sows were assigned at d 104 of gestation in a 2×3 factorial to receive a gestation diet (0.55% SID lysine, 0% added fat, and 2,594 kcal/kg NE; GEST) or lactation diet (0.99% SID lysine, 2.5% added fat, and 2,911 kcal/kg NE; LACT) at 1.5, 3.0 or 4.5 kg/d. In EXP 2, 62 sows were fed 2.05 kg/d LACT beginning at d 93, 100, or 107 or maintained at 2.05 kg/d GEST until farrowing. In EXP 3, 192 sows were fed 1.82 kg/d GEST supplemented daily with 280 g soybean (GEST+SBM), 120 g granulized fat (GEST+FAT) or both SBM and FAT to achieve the lysine and added fat comparable to LACT. In EXP 4, 70 sows were transitioned from GEST to LACT at d 102 of gestation and feeding level increased from 2 to 4 kg/d at d 102, 106, or 110 of gestation or maintained at 2.0 kg/d until farrowing. Farrowings were attended and piglet birthweight (BWT), piglet colostrum intake (CI), pig weaning weight (WWT), and litter size at weaning (LSW) were recorded. Sow functional teat number (TEATS) was counted in EXP 2 and 4. Data were analyzed by experiment in SAS with diet, feeding level, and day of feeding initiation and their interactions as fixed effects where appropriate. A meta-analysis was performed by calculating each sow's total lysine (TLYS), added fat (TFAT), and NE (TNE) intake from d 93 of gestation to farrowing. In EXP 1, feeding high levels of LACT improved (P=0.03) CI. No treatment differences were observed in EXP 2. In EXP 3, feeding

GEST+FAT tended (P=0.06) to improve piglet BWT, while sows consuming GEST+SBM tended (P=0.08) to produce less colostrum. In EXP 4, piglets born to sows bump fed LACT at d 106 of gestation tended (P=0.07) to have greater CI. Meta-analysis estimates indicated that consuming 1 g additional TLYS in late gestation improved (P=0.03) WWT by 1.4 g and tended (P≤0.10) to improve CI and litter WWT by 0.1 and 15.9 g, respectively, while consuming 1 g TFAT improved (P=0.02) CI by 0.03 g. No effects (P>0.10) of TNE were observed. A one nipple increase in TEATS improved (P≤0.05) CI, NW, and litter WWT by 13.3 g, 0.31 pigs, and 1.85 kg, respectively. Meta-analysis results indicate increasing amino acids in late gestation enhanced piglet CI and WWT.

Introduction

Genetic selection for increased sow prolificacy without concomitant emphasis on piglet birth weight has reduced piglet survivability and growth (Roehe, 1999; Lund et al., 2002). Continued selection for greater carcass leanness in commercial swine has also altered body metabolism and increased amino acid requirements (Kim et al., 2005). Basal protein and energy requirements are further increased in late gestation to compensate for fetal and mammary growth (Kim et al., 2009; Goodband et al., 2013; Feyera and Theil, 2017).

Attention has been devoted in recent years to feeding strategies that increase intake in late gestation to satiate sow nutrient requirements and enhance litter performance (Gonçalves et al., 2016a). Previous studies increasing feed allowance in late gestation have primarily investigated effects on piglet birth weight (Cromwell et al., 1989; Miller et al., 2000; Gonçalves et al., 2016b; Mallman et al., 2018). Comparatively fewer studies have considered the effects of late gestation feed intake on colostrum production (Decaluwé et al., 2014a; Mallman et al., 2019). Colostrum

is produced in late gestation, is available to the piglets immediately after parturition, and provides the piglet with sufficient energy to generate metabolic heat as well as serves as the vehicle for passive transfer of maternal antibodies (Quesnel et al., 2015). Hence, piglet colostrum intake is positively correlated with piglet growth and survival (Decaluwé et al., 2014b; Declerck et al., 2016). Decaluwé et al. (2014a) reported greater colostrum yield in sows fed above nutritional requirements (4.5 kg/d) compared to sows fed below requirements (1.5 kg/d). The lack of an adequate control group (i.e. sows fed at requirements), however, makes the practical interpretation of these results difficult. Hence, it was hypothesized that increasing nutrient availability in late gestation may improve piglet colostrum intake and litter performance.

Materials and Methods

All experimental methods and animal handling procedures were approved by the North Carolina State University Institutional Animal Care and Use Committee. Experiments (EXP) 1, 2, and 4 were conducted at the North Carolina Department of Agriculture Tidewater Research Station (NCDA) near Plymouth, NC. Sows enrolled in EXP 1, 2, and 4 were second-parity Landrace x Large White composite females originating from PIC (Pig Improvement Company, Hendersonville, TN) stock. Experiment 3 was conducted on a 2,400 sow North Carolina commercial sow farm with multiparous commercial genetics (Smithfield Premium Genetics, Rose Hill, NC).

All four trials were conducted during summer months. The average daytime (0800 to 2000) temperatures in EXP 1 through 4 were 28.4^{o}C, 28.5^{o}C, 29.5^{o}C, and 29.1^{o}C, respectively, and the average nighttime temperatures were 23.0^{o}C, 22.0^{o}C, 23.8^{o}C, and 23.9^{o}C, respectively. Sows in all experiments were individually housed throughout pregnancy on concrete slats with

ad libitum water access. The NCDA gestation barn was naturally ventilated with stir fans and the commercially owned gestation barn in EXP 3 was tunnel ventilated. Farrowing facilities at both farms were mechanically ventilated, yet only the commercial farrowing barn provided supplemental cooling via evaporative cool cell pads. Sows on NCDA facilities farrowed in batch over a one week period; while the commercial farm used continuous farrowing groups. One 125 watt heat lamp was installed per farrowing crate in NCDA farrowing facilities while 30×90 cm floor heating pads were used as the piglet's supplemental heat source in EXP 3.

Experiment Design and Treatment Feeding

Four experiments were designed to evaluate the effects of late gestation lysine, fat, and net energy (NE) intake on sow reproduction and lactation performance. Common gestation (GEST; 0.69% lysine, 2,594 kcal/kg NE, and 0% added fat) and lactation (LACT; 1.1% lysine, 2,911 kcal/kg NE, and 2.5% added fat; Table 2.1) diets were used as base diets. In EXP 1, 2, and 4, differences in nutrient intake were achieved by modifying sow diet (GEST or LACT), feeding level, or feeding duration. In EXP 3, sows were fed GEST top-dressed with additional soybean meal or fat to achieve the same lysine or added fat content of LACT. Prior to initiation of treatment feeding, sows were limit-fed GEST based on body condition (1.5 to 2.3 kg/d range). During treatment feeding, sows were hand-fed by research staff and any feed remaining from the previous day was removed and weighed. Sows were fed treatment diets up to the day of farrowing. After farrowing, all sows were fed LACT to appetite daily.

Sows were allocated to treatments based on body condition in all EXP and parity in EXP 3 only. Sow body condition score (BCS) was measured at the last rib with a sow body condition caliper (Knauer and Baitinger, 2015). The sow caliper quantifies the angularity of the sow's

back. The scoring system for the sow caliper (thin < 12; ideal 12 to 15; over conditioned >15) is based on reproductive potential (Bryan, 2014).

In EXP 1, a total of 62 second-parity sows were randomly allocated based on BCS in a 2×3 factorial design. Beginning at d 104 of gestation, sows received either GEST or LACT at one of three feeding levels (1.5, 3.0, or 4.5 kg/d) until farrowing.

In EXP 2, a total of 62 second-parity sows were transitioned from GEST to LACT at one of four time points in late gestation: d 93, d 100, d 107, or not until farrowing. The feeding level of all sows from d 93 of gestation to farrowing was 2.05 kg/d.

In EXP 3, a total of 192 multiparous sows (average parity 2.3±1.6) over two consecutive weekly groups in a continuous farrowing system were assigned to receive one of four treatments beginning at d 107 of gestation in a 2×2 factorial. Treatment diets consisted of GEST, GEST supplemented with 280 g soybean meal to provide an additional 6.2 g lysine (GEST+SBM), GEST supplemented with 120 g granulized fat to increase to increase added fat level to 6% (GEST+FAT), or both soybean meal and fat (GEST+BOTH) to achieve a lysine and added fat level comparable to LACT. Farrowings were strategically attended to maximize labor inputs during peak expected farrowing times. Per farm protocol, all sows were given a 1.0 mL intramuscular oxytocin injection after farrowing to facilitate placenta expulsion.

In EXP 4, a total of 70 second-parity sows were transitioned from GEST to LACT beginning at d 102 of gestation and feeding level increased from 2 kg/d feed intake to 4 kg/d feed intake at d 102, d 106, or d 110, or feed intake was maintained at 2 kg/d until farrowing.

Reproductive and Colostrum Measurements

Procedures to measure sow reproductive and colostrum performance were identical across EXP. Continuous farrowing room supervision began when the sow with the earliest due date in the farrowing group reached 112 days of gestation. At parturition, all piglets were dried, warmed, birth weight was recorded, and each piglet was given an identifying individual notch on the left ear before being returned to the sow. Piglets were individually weighed again 24 hrs after birth and individual piglet colostrum intake was estimated using a mechanistic equation proposed by Theil et al. (2014). The equation incorporates the variables birth weight, weight change within 24 hrs, and the duration in minutes of allowed suckling. Sow colostrum yield was calculated as the sum of litter colostrum intake.

A 50 mL colostrum sample was collected from each sow approximately 75 minutes following the birth of the first pigs from a representative sample of teats into a single collection cup. Samples were thoroughly mixed within the collection cup before transfer into vials containing a single milk preservative (D&F Control Systems, Inc. Norwood, MA). Colostrum samples were refrigerated for less than one wk prior to infrared spectrophotometry analysis at the United Dairy Herd Improvement Association Lab (Radford, VA) for percent fat, protein, lactose, and total solids. Colostrum energy content was calculated from the macronutrient composition according to Klaver et al. (1981). Laboratory error prevented nutrient analysis of EXP 1 colostrum samples. In EXP 2 and 4, the number of functional teats per sow was recorded. A teat was considered functional if colostrum could be stripped from the gland by hand during farrowing.

Litter characteristics recorded included the number of piglets born alive and number of stillborn piglets. Total number born was the sum of the number born alive and the number

stillborn. Farrowing duration was defined as the interval between the birth of the first and last piglets in the litter. Piglet fostering was performed only under extreme circumstances, such as sow removal from the experiment (involving 4.9% of litters). Hence, litter size at weaning and piglet weaning weight were recorded at 20.6±2.8 days in lactation as traits of the biological dam. Piglet survival was calculated as the litter size at weaning divided by total number born. Sow gestation length was also recorded.

Statistical Analysis

Data were analyzed by experiment and as a meta-analysis of all experiments using the GLM procedure of SAS (SAS Institute, Inc., Cary, NC) with sow as the experimental unit. The categorical effect variables used in the statistical models of EXP 1 through 4 are shown in Table 2.2. In EXP 1, 10 of the 20 sows receiving 4.5 kg/d failed to consume the entire meal. The average daily feed intake of these sows was calculated and this trait was included as a linear term in place of feeding level in EXP 1 analysis. Total number and gestation length was included as a covariate in all experiments for analyses of birthweight, piglet colostrum intake, sow colostrum yield, litter size at weaning, weaning weight, and preweaning survival. Lactation length was included as a covariate for litter size at weaning, weaning weight, and preweaning survival analyses. In EXP 3, sow parity category (≤ 2 parities = YOUNG; ≥ 3 = MATURE) was included as a fixed effect to account for the multiparous population. Colostrum composition models included gestation length and BCS as covariates. The time of colostrum collection relative to the birth of the first piglet was tested in colostrum composition models but excluded due to non-significance.

A meta-analysis of all four experiments (n=376 sows) was conducted by calculating the total lysine (TLYS), total added fat (TFAT), and total net energy (TNE) intake of each sow from day 93 of gestation to farrowing. Net energy was calculated according to digestible nutrient contents of the diets (NRC, 2012). Total intake of each nutrient for the period was calculated with the following equation:

$$Total\ Intake = (I - 93) * (GFL * GNC) + (GL - I) * (TFL * TNC)$$

where:

I is the day in gestation of initiation of treatment feeding,

GFL is the gestation diet feeding level the sow received prior to treatment feeding,

GNC is the gestation diet nutrient content the sow received prior to treatment feeding,

GL is the sow's gestation length in days,

TFL is the treatment feeding level of the experiment, and

TNC is the treatment nutrient content of the experiment.

Hence, the total intake of a given nutrient from day 93 of gestation to farrowing was included in the meta-analysis, regardless of when in gestation treatment feeding was initiated. Day 93 was chosen because this was the earliest day in gestation that a feeding treatment diet was initiated. Piglet birth weight and colostrum intake were recorded for 290 sows. Statistical models for total nutrient intake models included EXP and parity category as categorical effects and total number born, gestation length, and the day in gestation of initiation of treatment feeding as covariates.

Relevant trait associations and analyses were also made within the meta-analysis dataset. Parameter estimates of the effects of piglet sow functional teat number (n=122 sows) and colostrum macronutrient composition (n=225 sows) on pig performance were analyzed independently as response variables in GLM in SAS with model effects EXP, total number born,

gestation length, and lactation length where appropriate. The effects of sow and litter traits on piglet colostrum intake, sow colostrum yield, and colostrum macronutrient composition and yield were analyzed independently in GLM as dependent variables with EXP and parity category as categorical traits and total number born, gestation length, and lactation length as covariates. Finally, the effect of colostrum traits on litter size at weaning, weaning weight, and litter preweaning survival were analyzed with the colostrum trait as an independent variable in PROC GLM with EXP and parity category as categorical effects and total number born, gestation length, and lactation length (linear and quadratic terms) as covariates.

Results

Summary Statistics

Average sow BCS was greater in EXP 3 (17.1±2.2) than in EXP 1, 2, and 4 (15.6±1.9, 15.5±1.9, and 15.3±2.1, respectively). The average gestation length in EXP 1 through 4 were similar (115.2±1.5 d, 115.7±1.7 d, 114.8±1.2 d, and 115.3±1.1 d, respectively).

Experiment 1

The main effects of sow diet and feeding level on reproductive performance are presented in Table 2.3. Feeding LACT in place of GEST tended to improve (P=0.09) litter weaning weight, yet no other main effects relating to diet were observed. A tendency (P=0.06) for a linear effect of feeding level on piglet colostrum intake was observed, whereby a 1 kg increase in sow daily feed intake improved colostrum intake by 11.6 g. Significant diet by feeding level interactions were observed for piglet colostrum intake (P=0.03; Figure 1) and litter weaning weight (P=0.02; Figure 2).

Experiment 2

Sow reproductive and lactation performance traits are presented in Table 2.4. No differences (P>0.10) in piglet or litter birth weight or growth were observed as result of feeding LACT in place of GEST at a similar feeding level. No differences (P>0.10) were observed in piglet colostrum intake or sow colostrum yield. Colostrum protein content was greatest (P<0.01) when sows were fed GEST for the entirety of gestation, but sow diet did not impact (P>0.10) any other colostrum composition traits.

Experiment 3

The third experiment was conducted on a cooperating commercial sow farm in eastern North Carolina. Sow reproductive and colostrum results are presented by diet in Table 2.5. Feeding GEST+SBM tended (P=0.08) to reduce sow colostrum yield by 9.8 to 12.4% compared to other treatments (Fig. 2.1), while supplementing FAT tended (P=0.06) to improve piglet birth weight compared to sows consuming GEST+SBM or LACT (Fig. 2.2). No treatment differences were observed (P>0.10) in litter size at weaning, preweaning survival, or weaning weight.

Differences (P≤0.05) in reproductive performance were observed between young and old females. Compared to YOUNG, MATURE sows farrowed a greater total number born (12.9±0.3 vs. 14.7±0.4), number born alive (12.3±0.3 vs 13.3±0.4), and number stillborn (0.6±0.1 vs. 1.4±0.1). However, preweaning survival (81.7±1.3 % vs. 75.6±1.4 %) and litter size at weaning (11.0±0.2 vs. 10.1±0.2) were reduced in MATURE. No differences (P>0.10) between YOUNG and MATURE females were observed in piglet colostrum intake (475.1 g vs. 488.7 g) or sow colostrum yield (5.9 kg vs. 5.7 kg). Colostrum produced by MATURE sows contained less

(P=0.02) percent fat (5.8±0.2 % vs. 5.2±0.2 %), but no differences were observed (P>0.10) in colostrum protein (16.1±0.2 % vs. 16.2±0.3 %) or lactose content (3.5±0.05 % vs. 3.4±0.05 %).

Experiment 4

Sow reproductive and lactation results are presented in Table 2.6. Increasing feeding level of LACT at d 110 of gestation was associated with increased (P=0.03) number stillborn. A tendency (P=0.06) for greater piglet colostrum intake was observed in piglets born to sows bump fed LACT at d 106 of gestation compared to piglets born to sows bump fed at d 102 or 110. Control sows fed LACT at 2 kg/d produced colostrum with greater protein content and less lactose (P≤0.05). No other differences (P>0.10) in colostrum composition were observed.

Meta-Analysis

Mean nutrient intake from d 93 of gestation to farrowing were 324.9 g TLYS (179.6 to 694.0 g range), 624.3 g TFAT (0 to 1,950 g range), and 126.0 Mcal TNE (86.4 to 247.9 Mcal range). Pearson correlations between TLYS and NE were higher (r=0.90) than between TLYS and TFAT (r=0.60) or TFAT and TNE (r=0.52).

Average total number born, piglet colostrum intake, sow colostrum yield, litter size at weaning, and piglet weaning weight in the meta-analysis were 13.4±3.5 pigs, 468±112.8 g, 5.5±1.2 kg, 10.5±2.5 pigs, and 5.6±1.2 kg, respectively. Associations between nutrient intake and sow reproductive performance are presented in Table 2.10. Nutrient intake did not impact (P>0.10) piglet birthweight, preweaning survival, or litter size at weaning. A 1 g increase in TFAT improve (P=0.03) piglet colostrum intake by 0.03 g (Figure 2.3) and tended to improve (P=0.06) to improve sow colostrum yield by 0.3 g. A 1 g increase in TLYS tended to enhance

(P=0.10) piglet colostrum intake by 0.1 g but improved (P=0.03) piglet weaning weight by 1.4 g and tended to improve litter weaning weight (P=0.09) by 15.9 g. No associations (P>0.10) between TNE and reproductive performance were observed. Colostrum macronutrient composition and yield were not impacted (P>0.10) by sow nutrient intake.

Sow teat availability impacted piglet colostrum intake. A one unit increase in TEATS improved (P≤0.02) piglet colostrum intake, sow colostrum yield, and litter size at weaning by 13.3 g (Fig. 2.6), 287 g, and 0.31 pigs, respectively. Functional teats was not associated (P=0.19) with average piglet weaning weight, but improved (P=0.05) total litter weaning weight by 1.85 kg per teat.

Parameter estimates of colostrum production and nutrient content traits with sow, litter, and weaning traits are presented in Table 2.11. Farrowing duration was not associated (P>0.05) with colostrum production or colostrum composition traits. A one day increase in gestation length improved (P=0.04) piglet colostrum intake by 7.1 g, yet no associations between gestation length and sow colostrum yield were observed (P=0.78). Piglet colostrum intake was increased (P<0.01) with increasing piglet birth weight and litter birth weight, but decreased (P<0.01) as litter size increased.

Colostrum macronutrient content was associated with sow and litter traits, as well as the presence of other nutrients. No associations between gestation length and farrowing duration with colostrum composition was observed (P>0.10), but a 1 unit increase in BCS was associated with a 0.16% reduction (P=0.03) in colostrum protein concentration and a 0.02% increase (P=0.04) in colostrum lactose. A one pig increase in total number born was associated with increased (P<0.01) colostrum fat (0.07%) and protein (0.1%), but a 0.03% decrease (P<0.01) in lactose. Piglet and total litter birth weight were not associated (P>0.10) with any composition

traits. A 0.1% increase in colostrum lactose was associated with decreased (P<0.01) protein and fat by 0.5% and 0.05%, respectively. A 0.1% increase in colostrum lactose was also associated with increased (P=0.01) piglet colostrum intake by 3.8 g and a tendency for increased (P=0.07) sow colostrum yield by 37.8 g. A 1% increase in colostrum protein was associated with decreased (P=0.01) intake by 5.7 g and a tendency for decreased (P=0.06) total yield by 60.6 g. No associations between colostrum fat and colostrum yield or intake were observed (P>0.10)

Weaning traits were impacted by colostrum production and nutrient content. A 1 kg increase in sow colostrum production improved (P<0.05) litter preweaning survival, litter size at weaning, and piglet weaning weight by 5%, 0.8 pigs, and 0.1 kg, respectively, while a 1 g increase in piglet colostrum intake improved (P<0.05) preweaning survival and weaning weight by 0.02% and 3.3 g, respectively, and tended (P=0.08) to improve the litter size at weaning by 0.002 pigs. Colostrum composition did not influence weaning traits, except that a 0.1 % increase in colostrum lactose content reduced (P=0.04) WWT by 34.7 g.

Discussion

The present experiments were designed to improve piglet colostrum intake and piglet quality by increasing sow amino acid, fat, and NE intake in late pregnancy. Genetic selection for greater litter sizes have resulted in reduced piglet birthweight, decreased litter uniformity, increased preweaning mortality, impaired muscle development, and reduced lifetime growth rate, G:F, and likelihood of achieving full value at market (Roehe, 1999; Quiniou et al., 2002; Town et al., 2004; Fix et al., 2010) due to sow uterine capacity limitations on feto-placental growth and development (Knight et al., 1977). Given that prenatal maternal resources per individual piglet are reduced, a viable option is to consider the role of postnatal maternal resources. The necessity

of adequate colostrum intake for piglet growth and survival is clear (Decaluwé et al., 2014; Declerck et al., 2016). Without colostrum, piglet energy reserves are depleted within 16 hours of birth (Theil et al., 2011). Experiments 1, 2, and 4 were designed to test the level and duration of increasing feeding level of a common lactation diet in late gestation on sow reproductive and lactation performance. In contrast, EXP 3 was designed to test the effects of the component dietary amino acid and fat levels on sow and pig performance. The calculated average sow daily nutrient intake during late gestation (the period extending from d 93 of gestation to farrowing) across studies was 14.6 g lysine and 5.7 Mcal NE, comparable to late gestation sow requirements estimated empirically by Kim et al. (2009) and in a factorial approach by Feyera and Theil (2017).

No differences in piglet BWT were observed in EXP 1, 2, or 4. This was anticipated, as the majority of sows were second-parity. Increasing feeding level in late gestation has shown to generally increase piglet birth weight in gilts but not sows (Gonçalves et al., 2016a). However, in EXP 3 a tendency for increased piglet BWT was observed in sows fed GEST+FAT compared to sows fed GEST+SBM or LACT. Piglet BWT in the GEST+FAT was not statistically different from GEST. The LACT diet was achieved by top-dressing GEST with both 120 g of granulized fat and 280 g soybean meal. Hence, the elevated BWT in EXP 3 may be the result of a positive effect of fat addition or a negative effect of soybean meal addition. Previous studies have reported no effects of late gestation fat supplementation on piglet BWT (Bishop et al., 1985; Coffey et al., 1987; Azain, 1993; van der Peet-Schwering et al., 2004), yet Mahan (1998) observed reduced piglet BWT in sows fed diets with 19.4% soybean meal compared to sows fed 12.0% soybean meal throughout gestation. Reduced sow colostrum yield was also observed in GEST+SBM fed sows compared to others. Soybeans contain several anti-nutritional factors such

as trypsin inhibitors and phytic acids (van der Poel, 1990) as well as isoflavone phytoestrogens such as genistein and daidzein (Wang et al., 1990). The soybean meal used in EXP 3 was not tested for anti-nutritional factor or phytogestrogen content, yet we hypothesize that these agents may be responsible for the reduced birth weight and colostrum yield.). In particular, isoflavones are thought have an estrogenic role in low-estrogen environments, but an antagonistic role when circulating estrogen levels are high (i.e. receptor competition; Sun Hwang et al., 2006). The late gestation sow is clearly a high-estrogen environment. Data from DeHoff et al. (1986) indicate that sow estrogen levels are 22-fold greater at day 112 than at day 60 of gestation. Yet previous studies administering isoflavones daily through feed or intramuscular injection during the last trimester (day 85-90 of gestation to farrowing) have reported no changes in body weight yet increased body fat of piglets at birth (Rehfeldt et al., 2007; Hu et al., 2015; Farmer et al., 2016). Piglet preweaning growth rate has either been increased (Hu et al., 2015) or slightly decreased (Farmer et al., 2016) following late gestation isoflavone administration, perhaps indicating either promoted or suppressed sow milk production in through lactation. The mechanism through which daily soybean meal supplementation depressed piglet birth weight and colostrum production in EXP 3 cannot be determined, yet the potential application of isoflavones in the late gestation sow perhaps deserves greater consideration.

In EXP 1, piglet colostrum intake was linearly increased with increasing sow late gestation feed intake, yet litter weaning weight was improved when sows consumed LACT in place of GEST from d 104 of gestation to farrowing. Diet by feeding interactions indicated that piglet colostrum intake and litter weaning weight were greatest when sows consumed high levels of LACT instead of GEST. Hence, EXP 2 and 4 were designed to verify the relationship between late gestation diets and bump feeding levels on sow performance. In EXP 2, no differences in

sow and litter performance were observed when sows were fed GEST and LACT at a feeding level similar to what sows are commonly offered on commercial farms in the last trimester (2.05 kg/d). The ineffectiveness of a diet change alone to elicit performance results is perhaps explained by the low feeding level. Lysine intake of a sow receiving 2.05 kg/d LACT in EXP 2 was 20.3 g/d, while lysine intake of a sow receiving 4.5 kg/d LACT in EXP 1 or 4.0 kg/d LACT in EXP 4 were 44.6 and 39.6 g/d respectively. Feyera and Theil (2017) estimated that sow lysine requirements increase from 13.9 to 34.6 g/d from d 104 to 115 of gestation. Hence, transitioning sows from GEST to LACT at a continuous level of feed allowance in EXP 2 may have provided nutrients at a level insufficient to satiate nutrient demand and improve sow performance. Piglet colostrum intake in EXP 4 tended to be greatest when sows were fed LACT and feeding level was increased from 2 to 4 kg/d beginning at d 106 of gestation. Together, the results of EXP 1 and 4 indicate that feeding 4 to 4.5 kg/d LACT beginning between 104 and 106 d of gestation through farrowing may increase piglet colostrum intake. Decaluwé et al. (2014a) similarly observed increased sow colostrum yield in sows fed 4.5 kg/d compared to 1.5 kg/d beginning at d 108 of gestation.

Since there was no effect of nutrient intake on piglet birthweight in the meta-analysis, perhaps the uterus was not the destination of the additional nutrients. Considerable mammary gland development occurs between d 102 and 106 of gestation, including increased epithelial cell functional differentiation, cellular organelle accumulation, alveoli distension, and upregulation of immunoglobulin g (IgG) receptors and glucose transporters (Kensinger et al., 1982; Kensinger et al., 1986; Ji et al., 2006; Nechvatalova et al., 2011; Chen et al., 2017). Immunoglobulin G is a humoral antibody and accounts for the majority of the protein in colostrum (Klobasa et al., 1987). Actual, albeit minute, colostrum synthesis begins around d 107 of gestation, as evidenced

by the appearance of low levels of α-lactalbumin and lactose in sow blood plasma at this time (Hartmann et al., 1984; Dodd et al., 1994). However, the rate of colostrum synthesis during the last week of gestation is curvilinear, whereby accumulation rate is slow but accelerates with approaching parturition (Feyera et al., 2019). Colostrum fat and lactose synthesis are also greatest nearer to parturition, but IgG translocation from sow blood plasma to the mammary lumen begins as early as 10 d prior to farrowing (Kensinger et al., 1982; Feyera et al., 2019). Hence, optimizing sow nutrition at the onset of mammary colostrogenic activity may present a valid means of improving piglet colostrum intake and litter performance.

Linear estimate results of the meta-analysis indicate that a 1 g increase in TFAT from d 93 of gestation to farrowing improved piglet colostrum intake by 0.03 g (Fig. 5) and tended to improve sow colostrum yield by 0.3 g. A 1 g increase in TLYS also tended to improve colostrum intake (Fig. 6), but no effects of TNE were observed (Fig. 7). Yet neither TFAT nor TNE enhanced litter weaning traits. Increasing TLYS improved sow milking ability, as evidenced by a 1 g increase in TLYS increasing piglet weaning weight by 1.4 g and litter weaning weight by 15.9 g. These data are supported by previous reports noting improved pig weaning weights following late gestation protein supplementation (Revell et al., 1998; Kusina et al., 1999). Gonçalves et al. (2016b) also noted reduced preweaning mortality in sows fed diets high in soybean meal from d 90 to 111 of gestation, yet no effect of TLYS on preweaning survival was apparent in this meta-analysis.

Parameter estimates between colostrum production and sow, litter, and colostrum composition traits were made in the meta-analysis. In agreement with Quesnel (2011), the duration of farrowing had no effect on any colostrum variables. Sow BCS also did not impact colostrum yield or intake. In a similarly conducted meta-analysis of five sow diet studies

incorporating 121 sows, Vadmand et al. (2015) reported a positive correlation between sow colostrum yield and backfat thickness eight days prior to farrowing (r=0.19). The backfat thickness range in Vadmand et al. (2015) was 9.6 mm to 41.0 mm, whereas the caliper scores of sows in the present study were more uniform (16.2±2.2, range 9 to 22). Perhaps the greater variation in body condition in Vadmand et al. (2015) permitted these researchers to plot a stronger regression.

A one day increase in gestation length improved CI by 7.1 g, but no effects on sow colostrum yield were observed. Colostrogenesis is accelerated as farrowing approaches (Feyera et al., 2019), yet the role of the feto-placental unit to dictate colostrum production is poorly understood. Hence, it is unclear whether a longer gestation length would be associated with greater colostrum production due to hormonal effects of the fetus, or due to greater litter vitality at birth and greater piglet ability to strip more colostrum from the udder. A positive genetic correlation exists between gestation length and average piglet birthweight (Rydhmer et al., 2008), and piglet birthweight is similarly positively correlated with piglet colostrum intake (Devillers et al., 2007). Indeed, relative to sow traits, litter size and piglet birth traits have a larger influence on variation in colostrum production. A 1 pig increase in total number born improved sow yield by 160.5 g (Fig. 8), but decreased piglet intake by 23.7 g, while a 1 kg increase in litter birthweight improved sow yield and average piglet intake by 166.0 g and 9.4 g, respectively. The decreased average piglet colostrum intake resulting from a 1 pig increased in TNB is similar to the 20 g decrease estimated by Decaluwé et al. (2014) but greater than the 11 g decrease observed by Keilland et al. (2015). Vadmand et al. (2015) also reported positive correlations between sow colostrum yield with litter size (r=0.36) and litter birth weight (r=0.61). High correlations between these traits are logical, as piglet birth weight is incorporated into the

colostrum intake estimation equation posed by Theil et al. (2014) used to quantify colostrum traits in both Vadmand et al. (2015) and the present study.

Colostrum macronutrient composition is associated with litter traits and with the volume of colostrum produced, yet the extent to which these relationships are causative is unclear. Greater sow BCS was associated with increased colostrum lactose but decreased colostrum protein. A one pig increase in total number born increased colostrum lactose by 0.03% by increased colostrum protein by 0.14% and fat by 0.07%. Uterine glucose uptake increases with increasing litter size (Pére and Etienne, 2018), and it may be that glucose shunting towards the late-term fetuses decreased arterial availability for lactose synthesis in the late gestation mammary gland. Lactose is the primary osmolyte in the lactating mammary gland and accordingly is highly associated with milk water volume (Zhang et al., 2018). In the present study, a 0.1% increase in colostrum lactose content was associated with 37.9 g increase in sow colostrum yield. In piglets, lactose is a disaccharide providing approximately 4 Kcal/g (Mellor and Cockburn, 1986). However, colostrum lactose was negatively correlated (r=-0.82) with protein. A simple explanation for the phenomenon may be that IgG accumulation into the mammary gland is largely complete by the time farrowing is initiated (Barrington et al., 2001) whereas the majority of lactose and fat synthesis occurs during and even following farrowing (Feyera et al., 2019). Perhaps proteins become diluted in colostrum with high lactose and therefore high water content. The extent to which these interactions impact pig performance appear negligible, however, as the concentration of no individual macronutrient class was significantly associated with litter survival or preweaning growth. No quantification of individual proteins, oligosaccharides, or fatty acids were made in the present study. Yet the sum appears to be greater than the whole. Parameter estimates conclude that pig colostrum intake more greatly

influenced litter throughput than did any individual nutrient. A 1 kg increase in sow colostrum yield improved preweaning survival and weaning weight by 5% and 0.8 pigs, respectively, and a 1 g increase in pig colostrum intake improved pig weaning weight by 3.3 g. Declerck et al. (2016) similarly reported that a 1 g increase in colostrum intake was associated with an additional 3.5 g of pig body weight at 21 d of age and 17 g of body weight at 154 d of age.

Piglets stand and begin sampling multiple teats within minutes of birth, and piglets that sample more teats consume more colostrum (de Passillé et al., 1988). Littermate competition at the udder is inherent from birth and results in a greater number of failed nursing attempts (Milligan et al., 2001; Andersen et al., 2011). The sow is postured in lateral recumbency during and following farrowing, and neonatal piglets are not strong enough to lift her udder or hind legs to reveal the bottom row and most posterior teats. Hence, anterior teats on the top row are suckled more than others during the first 24 hours of life (Vasdal and Andersen, 2012; Balzani, 2016a). A greater number of functional teats per sow would then logically be associated with increased piglet suckling opportunities. In the present study, a one nipple increase in functional teat number increased pig colostrum intake, sow colostrum yield, the number of pigs weaned per litter, and the litter weaning weight by 9.9 g (Fig. 9), 287 g, 0.31 pigs, and 1.85 kg, respectively. No effects of functional teat number on average pig weaning weight were observed, and this is likely explained by the fact that piglets establish preferences for certain nipples early in life (Špink and Illman, 2015) and that an individual mammary gland' milk production is reciprocal to nursing pressure (King et al., 1997). Hence, having a larger number of functional teats improves litter performance by increasing the number of pigs that can consume an adequate volume of colostrum but does not appear to increase lactation milk yield. Previously, authors have reported modest correlations between teat number and litter size at 21 days in lactation (r=0.35, Allen et

al., 1959; r=0.19, Skjervold, 1963) when cross fostering is not utilized, but lower phenotypic correlations (r=-0.04, Pumfrey et al., 1980; r=0.03, Balzani et al., 2016b) when piglet cross fostering is utilized to standardize litter sizes during the first day of lactation. Cross fostering was minimized in the present study. Ensuring an adequate number of functional teats per sow is important on all farms, but will be particularly impactful in situations where cross fostering strategies are not employed or are avoided to minimize disease issues. The number of mammary glands and the number of functional teats per sow are moderately heritable traits (0.39 and 0.31, respectively; Lundeheim et al., 2013). That a one nipple increase in sow functional teat number translated to a 0.3 pig increase in number weaned provides an economic incentive for greater attention to these traits at replacement gilt selection and for greater incorporation into selected indices.

Conclusions

Four experiments were designed and a meta-analysis of the experiments was conducted to test the effectiveness of providing additional amino acids, fat, and NE to sows in late gestation to improve litter characteristics, piglet colostrum intake, sow colostrum yield, and piglet preweaning survival and growth. Increasing the lysine and added fat content of sow diets in late gestation increased piglet colostrum intake, yet only increased lysine enhanced sow productivity as evidenced by increased average piglet weaning weight. Preweaning survival was not impacted by sow late gestation diet. The effects of sow functional teat number on piglet colostrum intake and litter performance were pronounced. Litter quality may be improved in commercial pig production systems by incorporating sow functional teat number into genetic selection indices and by more accurately evaluating underline quality during replacement gilt selection.

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Table 2.1 Ingredient composition, calculated nutrient content, and nutrient analysis of the gestation (GEST) and lactation (LACT) diets utilized in the experiments.

	Diet	
	GEST	**LACT**
Ingredient Composition, %		
Corn	72.2	70.025
Soybean Meal	8.8	22.65
Soy Hulls	15	0
Sow Vitamin / Mineral Mix	4	4
GroMax 7.5XE#	0	0.325
Laxative	0	0.5
Soy Oil	0	2.5
Calculated Nutrients		
Net energy, Kcal/kg	2,594	2,911
Lysine, %	0.68	1.1
SID Lysine, %	0.58	0.99
Nutrient Analysis		
Crude protein, %	12.14	17.81
Fat, %	3.03	5.04
Neutral detergent fiber, %	15.06	8.15
Acid detergent fiber, %	9.00	3.59
Non-fiber carbohydrate,%	63.98	63.30
Ash, %	5.79	5.69
Calcium, %	0.76	0.69
Phosphorous, %	0.58	0.65
Sulfur, %	0.26	0.36
Magnesium, %	0.25	0.26
Sodium, %	0.18	0.18
Potassium, %	0.72	0.92
Copper, ppm	26	36
Iron, ppm	421	378
Zinc, ppm	125	114

Table 2.2 Variables[1] classified as categorical effects in the statistical models of experiments 1 through 4.

	D	L	I	P	D*L	L*I	D*P
Experiment 1[2]	X	X			X		
Experiment 2			X				
Experiment 3	X			X			X
Experiment 4						X	

[1]Variable abbreviations: D = diet; L = feeding level; I = day of gestation of initiation of treatment feeding; P = sow parity category (≤2 vs. ≥3). The * superscript indicates statistical analysis of interactions between terms.

[2]Sow average daily feed intake was calculated and included as a linear rather than categorical variable in EXP 1 due to 50% of the sows assigned to receive 4.5 kg/d failing to consume the entire meal.

Table 2.3 The main effects of late-gestation (day 104 to farrowing) sow diet (LSMEANS) and feeding level (estimates) on sow reproductive performance in EXP 1.

	Diet				Feeding Level		
Trait	GEST	LACT	SE	P value	Estimate	SE	P value
Total number born	13.4	13.0	0.5	0.34	0.2	0.2	0.97
Number born alive	13.1	12.5	0.5	0.27	-0.2	0.2	0.92
Number stillborn	0.3	0.5	0.1	0.69	0.02	0.05	0.83
Piglet birth weight, g	1,178	1,140	24	0.33	2	10	0.73
Litter birth weight, g	15.3	14.4	0.4	0.15	0.1	0.2	0.95
Birth weight CV, %	20.2	16.9	1.1	0.41	-0.5	0.4	0.84
Piglet colostrum intake, g	407.7	439.5	10.1	0.22	11.6	4.2	0.06
Sow colostrum yield, kg	4.9	5.2	0.2	0.17	116.7	616	0.34
Litter size at weaning	10.9	11.1	0.3	0.37	0.05	0.1	0.63
Preweaning survival, %	84.2	86.4	2.0	0.40	0.3	0.8	0.54
Weaning weight, kg	5.5	5.7	0.1	0.76	0.07	0.04	0.31
Litter weaning weight, kg	59.6	62.5	1.5	0.09	1.2	0.6	0.66
Weaning weight CV, %	17.8	14.9	0.9	0.75	-0.3	0.4	0.91

Table 2.4 Sow reproduction and lactation performance in EXP 2 following transition from a gestation to a lactation diet at a continuous feeding level (2.05 kg/d) at day 93, 100, or 107 of gestation or not until the day of farrowing.

	Day of Gestation					
Trait	**93**	**100**	**107**	**Farrowing**	**SE**	**P value**
Total number born	14.0	13.1	13.3	14.4	0.8	0.70
Number born alive	13.3	12.6	12.7	13.9	0.8	0.63
Number still born	0.7	0.5	0.6	0.5	0.2	0.81
Piglet birth weight, g	1,328	1,293	1,390	1,245	51	0.25
Litter birth weight, kg	18.3	17.5	18.3	17.3	0.7	0.63
Birth weight CV, %	23.9	19.6	17.6	19.8	1.9	0.15
Litter size at weaning	10.6	10.5	10.5	11.3	0.4	0.34
Preweaning survival, %	79.6	78.1	78.3	84.8	2.6	0.20
Piglet weaning weight, kg	5.7	5.7	5.8	5.6	0.2	0.85
Litter weaning weight, kg	60.0	61.0	60.0	61.1	2.7	0.99
Weaning weight CV, %	18.5	16.6	15.6	16.9	1.6	0.67
Piglet colostrum intake, g	455.4	438.3	484.8	457.5	18.8	0.40
Sow colostrum yield, kg	5.5	5.5	5.8	5.7	0.3	0.78
Colostrum fat, %	6.6	6.1	5.8	5.6	0.5	0.57
Colostrum protein, %	16.2^{A}	17.0^{A}	16.9^{A}	19.4^{B}	0.6	<0.01
Colostrum lactose, %	3.7	3.7	3.7	3.5	0.1	0.37
Colostrum solids, %	28.8	28.6	28.2	30.1	0.7	0.27
Colostrum energy, Kcal/g	1.80	1.74	1.72	1.83	0.06	0.52

$^{A, B}$ Values within row without common superscript are different (P<0.05).

Table 2.5 Sow reproduction and lactation results in EXP 3 following daily supplementation of a gestation diet (GEST) with 120 g of fat (GEST+FAT) or 280 g of soybean meal (GEST+SBM) or with both fat and soybean meal to create lysine and added fat values comparable to a lactation (LACT) diet beginning at day 107 of gestation.

Trait	Diet				SE	P-value
	GEST	GEST+FAT	GEST+SBM	LACT		
Total number born	14.0	13.7	13.7	13.8	0.5	0.97
Number born alive	13.1	12.6	12.7	12.8	0.5	0.89
Number still born	0.9	1.1	1.0	1.0	0.2	0.80
Piglet birth weight, g	1,482^{A,B}	1,559^{A}	1,430^{B}	1,433^{B}	37	0.07
Litter birth weight, kg	20.3	20.9	19.4	19.9	0.5	0.24
Birth weight CV, %	21.6	21.7	21.9	22.0	1.7	0.99
Litter size at weaning	10.3	10.7	10.6	10.5	0.3	0.79
Preweaning survival, %	77.1	79.0	79.8	78.0	1.9	0.77
Piglet weaning weight, kg	5.3	5.0	5.2	5.3	0.1	0.31
Litter weaning weight, kg	54.6	52.7	55.0	54.7	1.9	0.81
Weaning weight CV, %	19.7	20.5	21.2	20.1	1.2	0.88
Piglet colostrum intake, g	498.1^{A}	502.1^{A}	439.8^{B}	487.7^{A}	17.2	0.06
Sow colostrum yield, kg	5.9^{A}	5.9^{A}	5.3^{B}	6.1^{A}	0.2	0.06
Colostrum fat, %	5.7	5.3	5.5	5.5	0.3	0.69
Colostrum protein, %	16.0	15.8	16.5	16.0	0.3	0.48
Colostrum lactose, %	3.5	3.4	3.5	3.4	0.1	0.76
Colostrum solids, %	28.6	28.1	28.7	28.6	0.5	0.91
Colostrum energy, Kcal/g	1.74	1.70	1.74	1.73	0.04	0.90

^{A,B} Means within row without common superscript tend to be different (P=0.07).

Table 2.6 Reproduction and lactation performance of sows in EXP 4 transitioned from a gestation to the lactation diet at day 102 of gestation and feeding level increased from 2 to 4 kg/d at days 102, 106, or 110 of gestation or not until farrowing.

Trait	Day of Gestation				SE	P value
	102	106	110	Farrowing		
Total number born alive	11.6	12.4	12.0	13.3	0.9	0.25
Number born alive	11.3	11.8	10.8	10.1	0.9	0.47
Number still born	0.3[A]	0.5[A]	1.2[B]	0.2[A]	0.3	0.03
Piglet birth weight, g	1,552	1,692	1,539	1,575	60	0.16
Litter birth weight, kg	17.3	19.3	18.3	18.0	0.7	0.15
Birth weight CV, %	15.2	17.3	17.2	14.3	1.6	0.30
Litter size at weaning	9.7	10.2	9.2	10.0	0.6	0.45
Preweaning survival, %	83.4	86.4	78.3	87.1	4.6	0.40
Piglet weaning weight, kg	7.5	7.5	7.2	7.4	0.2	0.49
Litter weaning weight, kg	70.6	74.5	64.7	71.7	4.1	0.29
Weaning weight CV, %	10.3	13.6	12.0	10.6	1.3	0.16
Piglet colostrum intake, g	493.3[C]	546.8[D]	470.7[C]	512.9[C,D]	23.4	0.07
Sow colostrum yield, kg	5.2	5.7	4.9	5.8	0.4	0.25
Colostrum fat, %	5.6	5.3	5.7	6.0	0.4	0.42
Colostrum protein, %	16.7	17.2	15.9	17.2	0.8	0.53
Colostrum lactose, %	3.6	3.7	3.8	3.5	0.1	0.49
Colostrum solids, %	28.1	28.2	27.4	28.7	0.8	0.56
Colostrum energy, Kcal/g	1.72	1.71	1.67	1.77	0.06	0.56

[A, B] Values within rows without common superscripts are different (P<0.05).

[C, D] Values within rows without common superscripts tend to be different (P=0.07)

Table 2.7 Parameters estimates and probability values corresponding to the main effects of sow total lysine (TLYS), total added fat (TFAT) and total net energy (TME) intake from day 93 of gestation to farrowing on sow reproduction and lactation traits. Values are presented as the parameter estimates resulting from a 1 g addition in TLYS or TFAT or a 1 Mcal addition in TNE.

	TLYS		TFAT		TNE	
Trait[1]	**Estimate**	**P-value**	**Estimate**	**P-value**	**Estimate**	**P-value**
Birth weight, g	-0.02	0.89	0.01	0.65	0.2	0.70
Litter birth weight, g	-0.5	0.80	0.07	0.84	2.5	0.68
Birth weight CV, %	-0.009	0.13	-0.002	0.12	-0.01	0.59
Litter size at weaning	0.0006	0.67	0.0002	0.23	-0.0002	0.97
Preweaning survival, %	0.004	0.70	0.001	0.34	-0.01	0.72
Weaning weight, g	1.4	0.03	-0.1	0.30	1.9	0.36
Litter weaning weight, g	15.9	0.09	-0.02	0.99	17.2	0.57
Weaning weight CV, %	-0.001	0.81	-0.0008	0.30	0.008	0.64
Piglet colostrum intake , g	0.1	0.10	0.03	0.02	0.3	0.19
Sow colostrum yield, g	0.75	0.35	0.3	0.06	2.4	0.36
Colostrum fat content, %	-0.0006	0.76	-0.0002	0.45	-0.005	0.48
Colostrum fat yield, g	-0.02	0.88	0.01	0.58	-0.02	0.96
Colostrum protein content, %	0.003	0.27	0.00001	0.98	0.01	0.25
Colostrum protein yield, g	0.1	0.70	0.05	0.18	0.9	0.37
Colostrum lactose content, %	-0.0003	0.50	-0.00007	0.31	-0.002	0.31
Colostrum lactose yield, g	-0.02	0.80	0.009	0.33	0.03	0.89
Colostrum solids content, %	0.0008	0.80	-0.0003	0.57	0.0004	0.97
Colostrum solids yield, g	0.01	0.97	0.08	0.21	0.7	0.64
Colostrum energy content, Kcal/g	-0.00005	0.96	-0.00009	0.56	-0.001	0.77
Colostrum energy yield, Kcal	-0.86	0.94	1.8	0.25	12.1	0.76

Table 2.8 Parameter estimates of colostrum production and colostrum nutrient composition with sow, litter, and weaning traits. Estimates are presented as the result of a 1 unit addition of the independent variable.[1]

Traits[2]	Colostrum Production, g				Colostrum Nutrient Composition%					
	CY		**CI**		**COLFAT**		**COLPRO**		**COLLAC**	
	Estimate	**SE**	**Estimate**	**SE**	**Estimate**	**SE**	**Estimate**	**SE**	**Estimate**	**SE**
Sow Traits										
GL, d	13.1	47.3	7.1*	3.4	0.004	0.07	-0.08	0.12	-0.002	0.02
FD, minutes	-0.14	0.54	-0.03	0.04	0.0004	0.0008	-0.0008	0.001	0.00008	0.0002
BCS, units	28.6	29.9	1.7	2.2	0.04	0.05	-0.16*	0.08	0.02*	0.01
Litter Traits										
TNB	160.5**	17.4	-23.7**	1.2	0.07**	0.03	0.14**	0.04	-0.03**	0.006
BWT, g	1.7**	0.3	0.15**	0.02	0.0005	0.0005	-0.0003	0.0008	-0.0001	0.0001
Litter BWT, kg	166.0**	23.7	9.4**	1.8	0.01	0.04	0.03	0.06	-0.009	0.009
Weaning Traits										
SURV, %	0.005**	0.0006	0.02*	0.009	0.14	0.6	0.5	0.4	-0.2	2.3
LSW	0.0008**	0.00009	0.003†	0.01	0.02	0.09	0.06	0.05	-0.05	0.3
WWT, g	0.11*	0.05	3.0**	0.6	11.3	40.5	22.6	24.1	-257	155.4
Colostrum Composition Traits										
COLFAT, %	-76.2	53.9	-5.7	3.9	--	--	0.05	0.1	-0.04*	0.02
COLPRO, %	-60.6†	32.1	-5.7*	2.3	0.02	0.04	--	--	-0.12**	0.006
COLLAC, %	378.8†	208.2	38.4*	14.9	-0.5*	0.3	-5.2**	0.3	--	--

[1] Sow trait, litter trait, and colostrum composition trait parameter estimates were analyzed with colostrum production and colostrum nutrient content traits as dependent variables. Weaning traits were computed with colostrum production and nutrient content traits as independent variables.

[2]Trait Abbreviation: CY = sow colostrum yield; CI = mean piglet colostrum intake; COLFAT = percent colostrum fat; COLPRO = percent colostrum protein; COLLAC = percent colostrum lactose; GL = gestation length; FD = farrowing duration; BCS = sow body condition caliper score; TNB = total number born; BWT = mean piglet birthweight; SURV = percent preweaning survival; LSW = litter size at weaning; WWT = mean piglet weaning weight.

† $P \leq 0.10$; * $P \leq 0.05$; ** $P \leq 0.01$

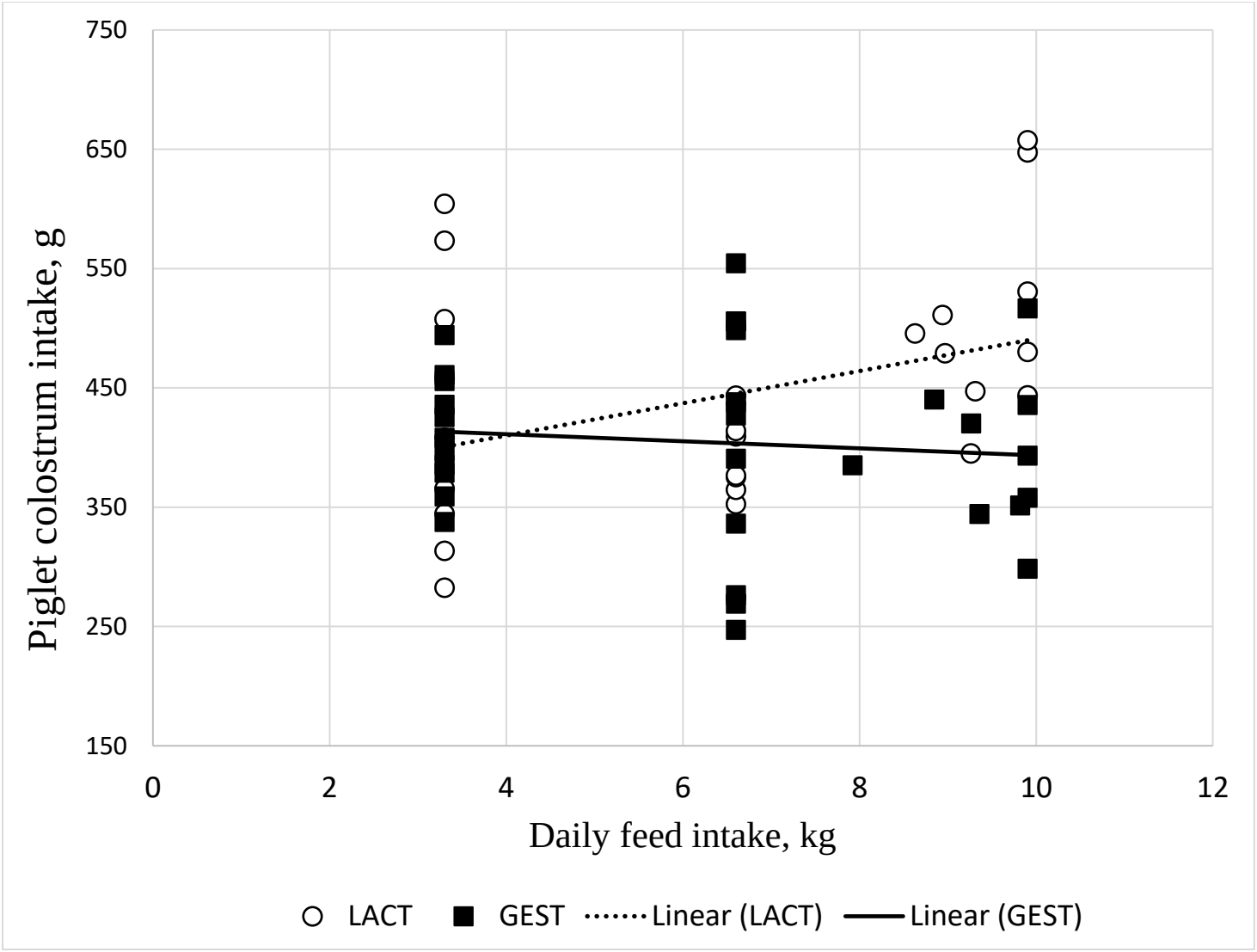

Figure 2.1 Piglet colostrum intake was increased (P=0.03) in EXP 1 when increasing levels of LACT but not GEST were fed from d 104 to farrowing.

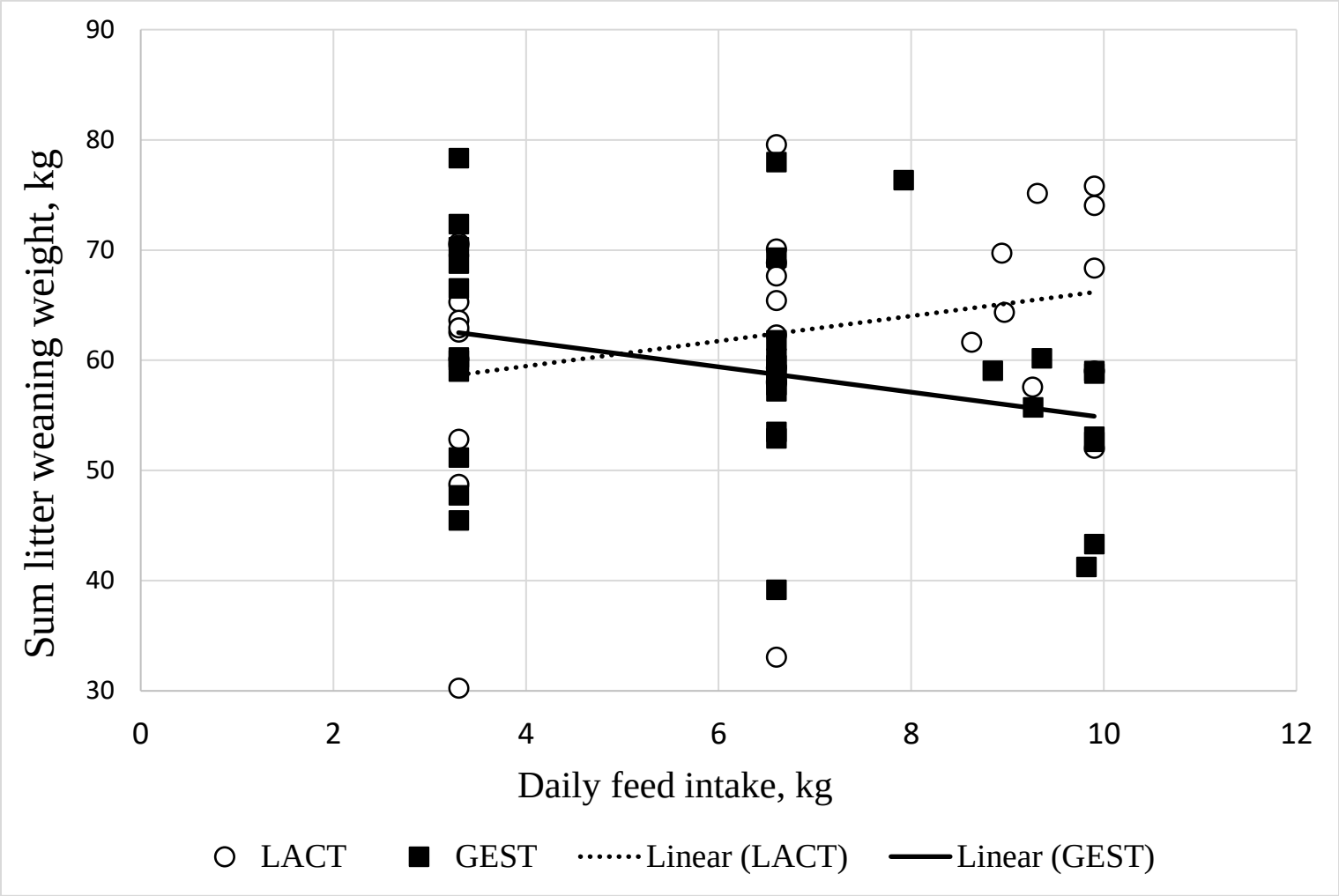

Figure 2.2 Litter weaning weight was increased (P=0.02) in EXP 1 when increasing levels of LACT but not GEST were fed from d 104 to farrowing.

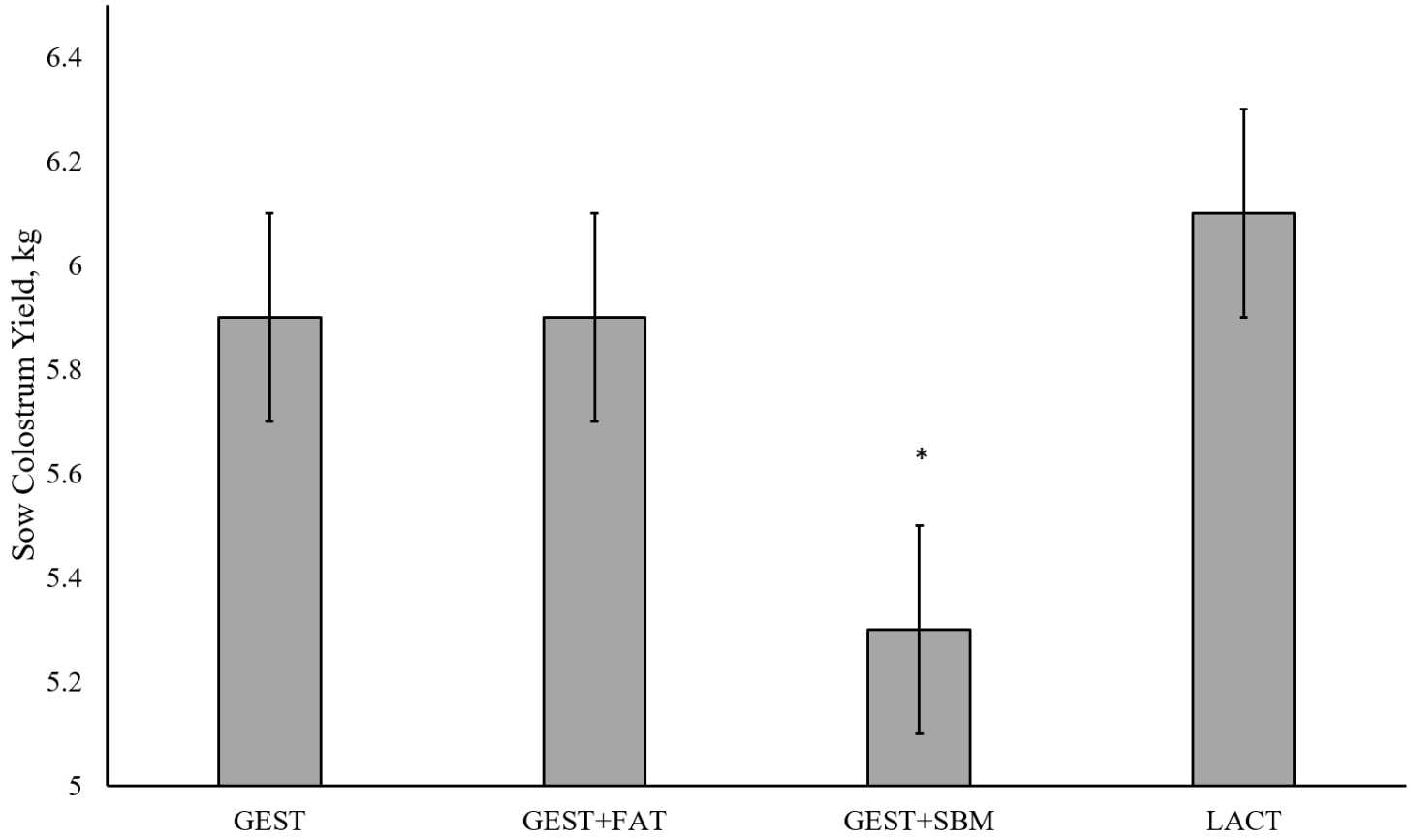

Figure 2.3 The average colostrum yield of sows consuming GEST+SBM in EXP 3 was reduced (P<0.05) compared to sows consuming GEST, GEST+FAT, or LACT.

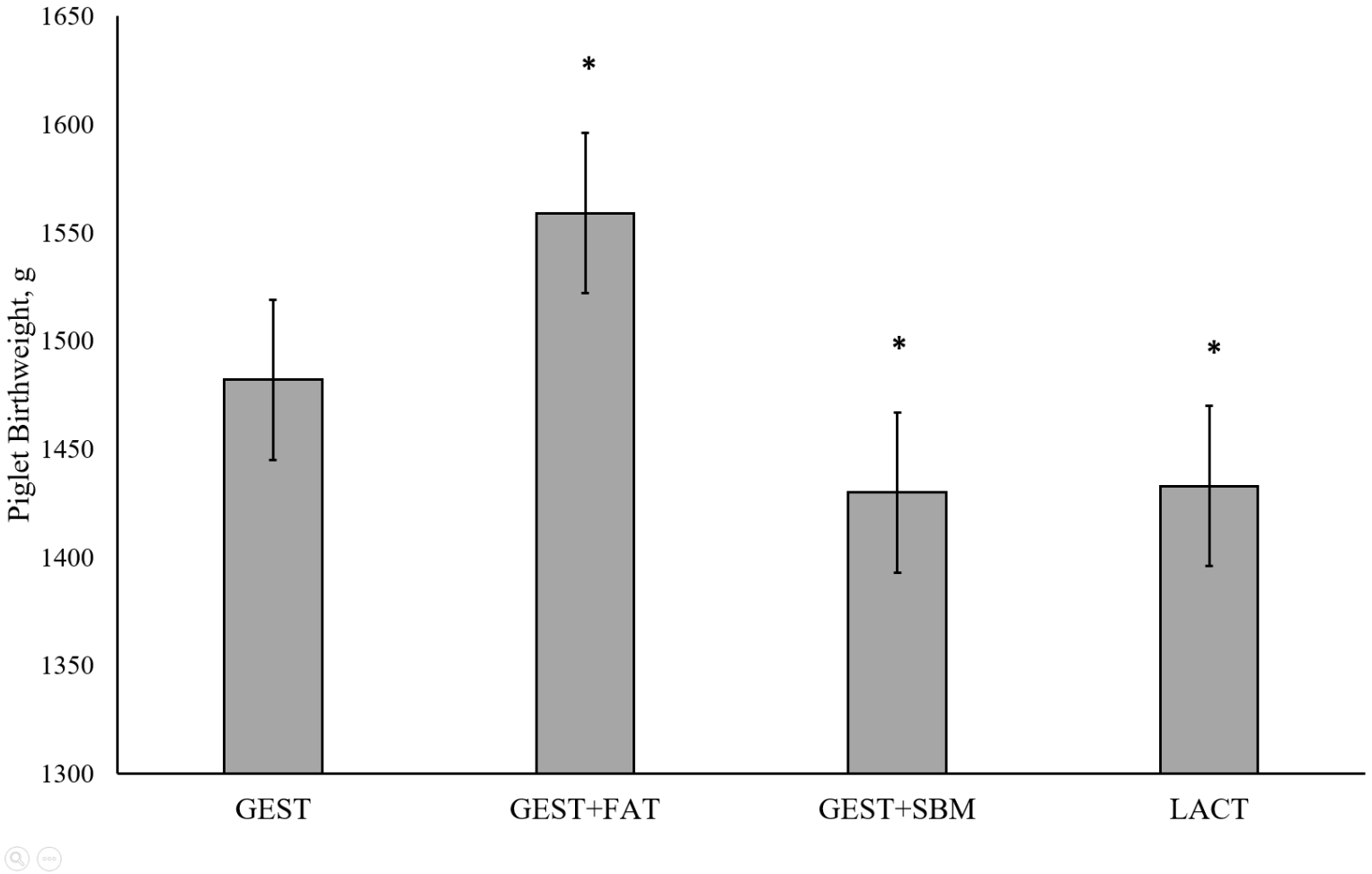

Figure 2.4 The average birth weight of piglets born to sows consuming GEST+FAT in EXP 3 was greater (P<0.02) than sows consuming GEST+SBM or LACT, but was not different (P=0.12) from sows consuming GEST.

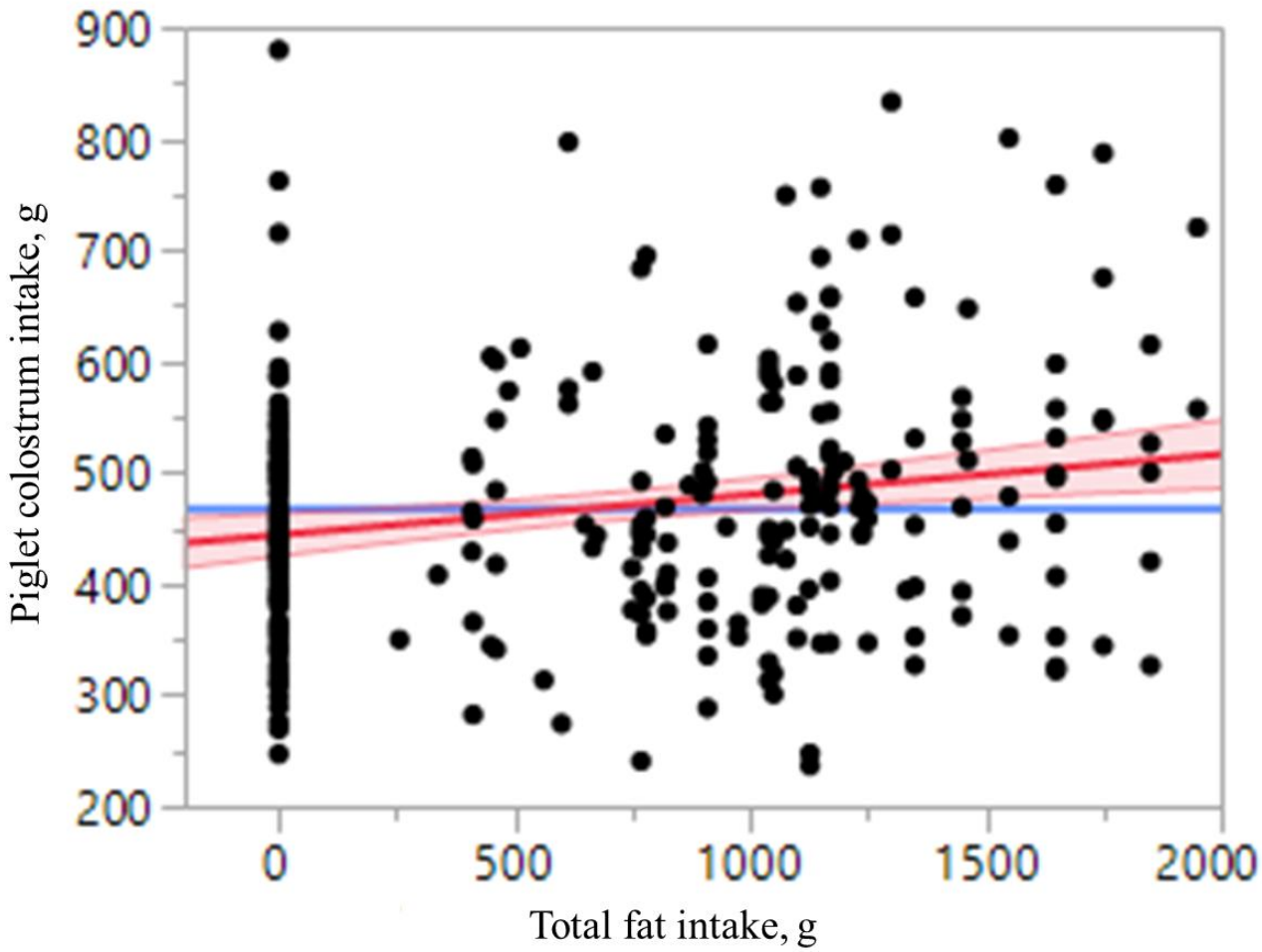

Figure 2.5 Effects of increasing sow added fat intake from day 93 of gestation to farrowing on piglet colostrum intake (P=0.02). Each dot represents the mean piglet colostrum intake of one sow (n=290 sows).

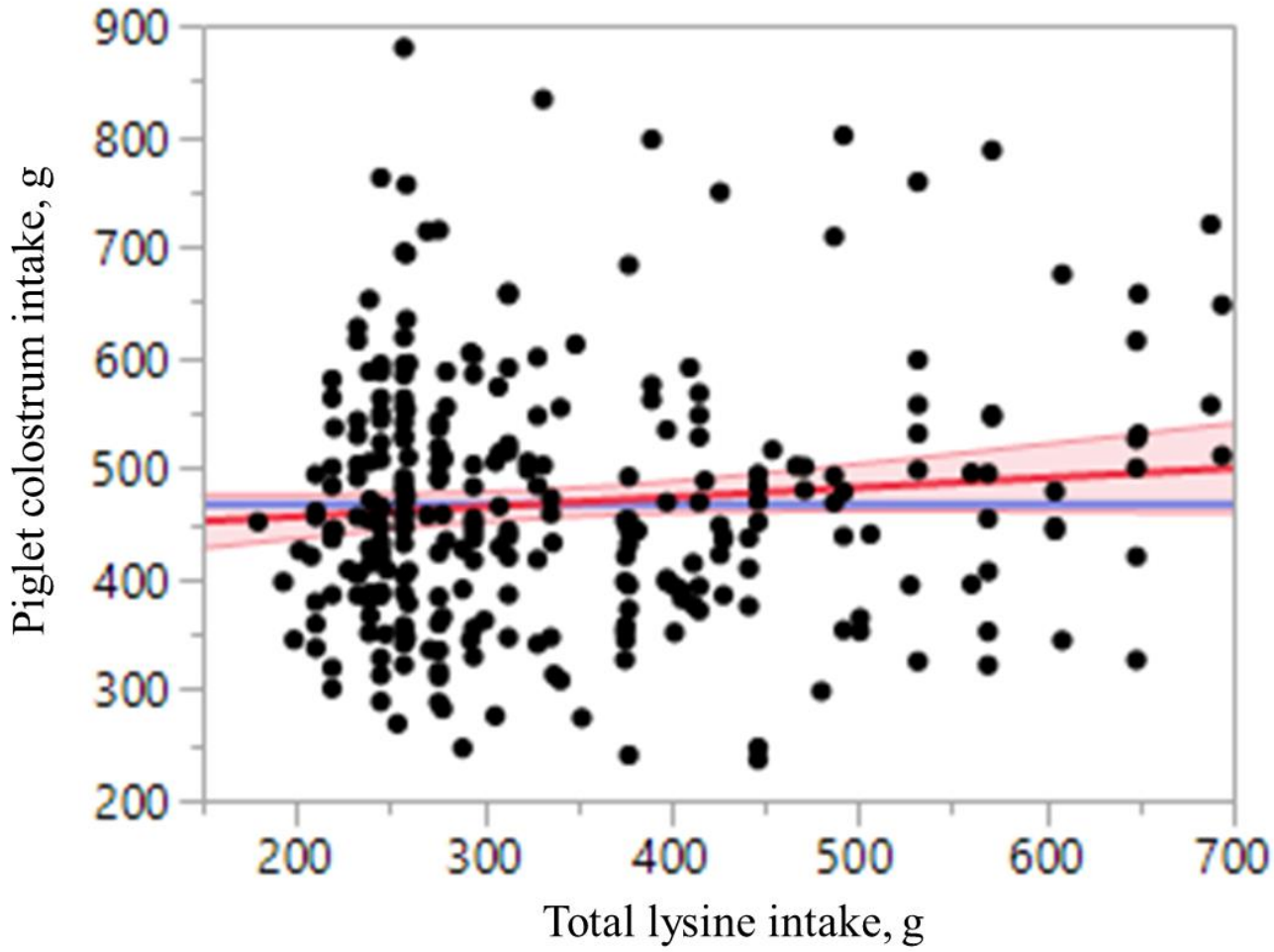

Figure 2.6 Effects of increasing sow lysine intake from day 93 of gestation to farrowing on piglet colostrum intake (P=0.10). Each dot represents the mean piglet colostrum intake of one sow (n=290 sows).

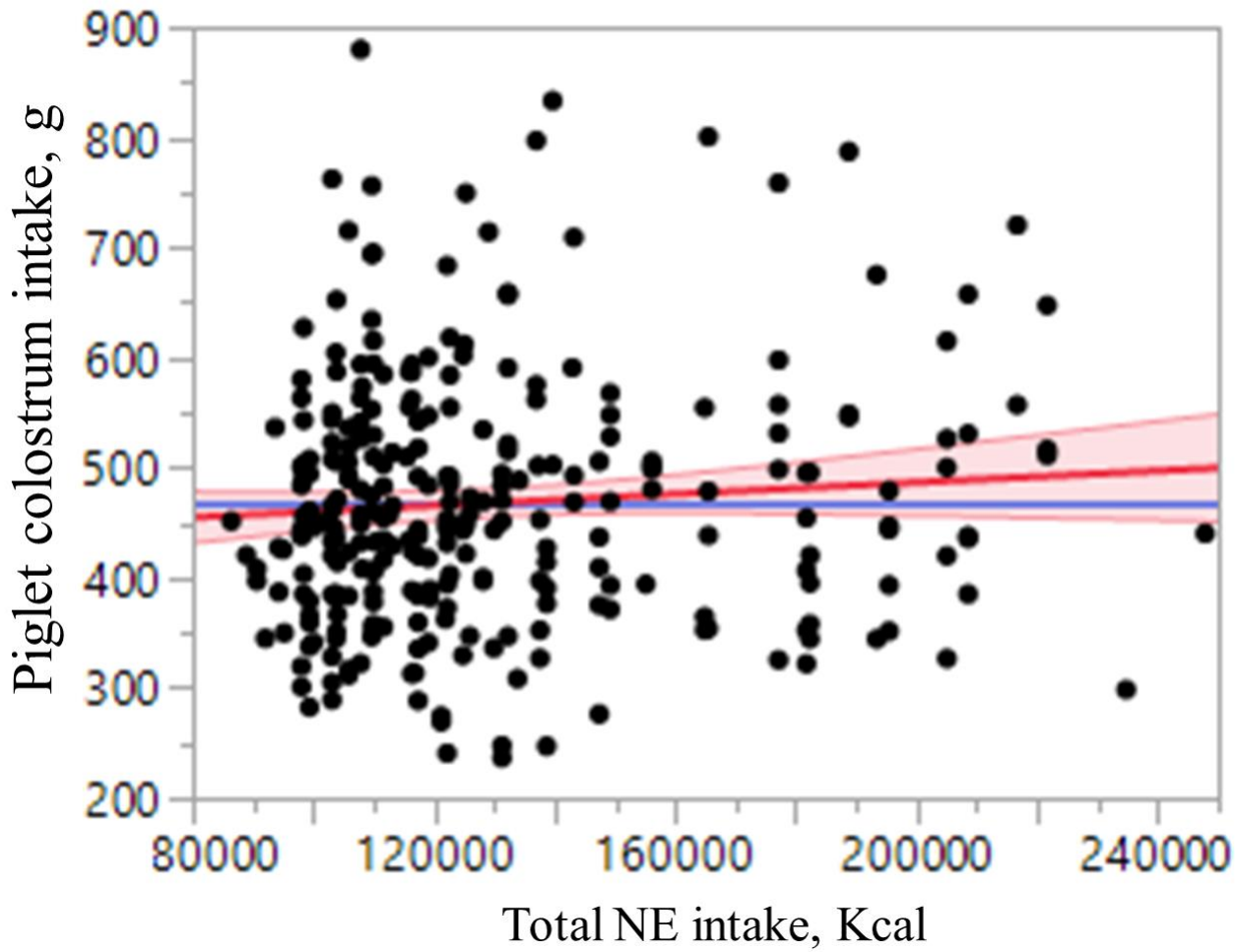

Figure 2.7 Effects of increasing sow net energy intake from day 93 of gestation to farrowing on piglet colostrum intake (P=0.19). Each dot represents the mean piglet colostrum intake of one sow (n=290 sows).

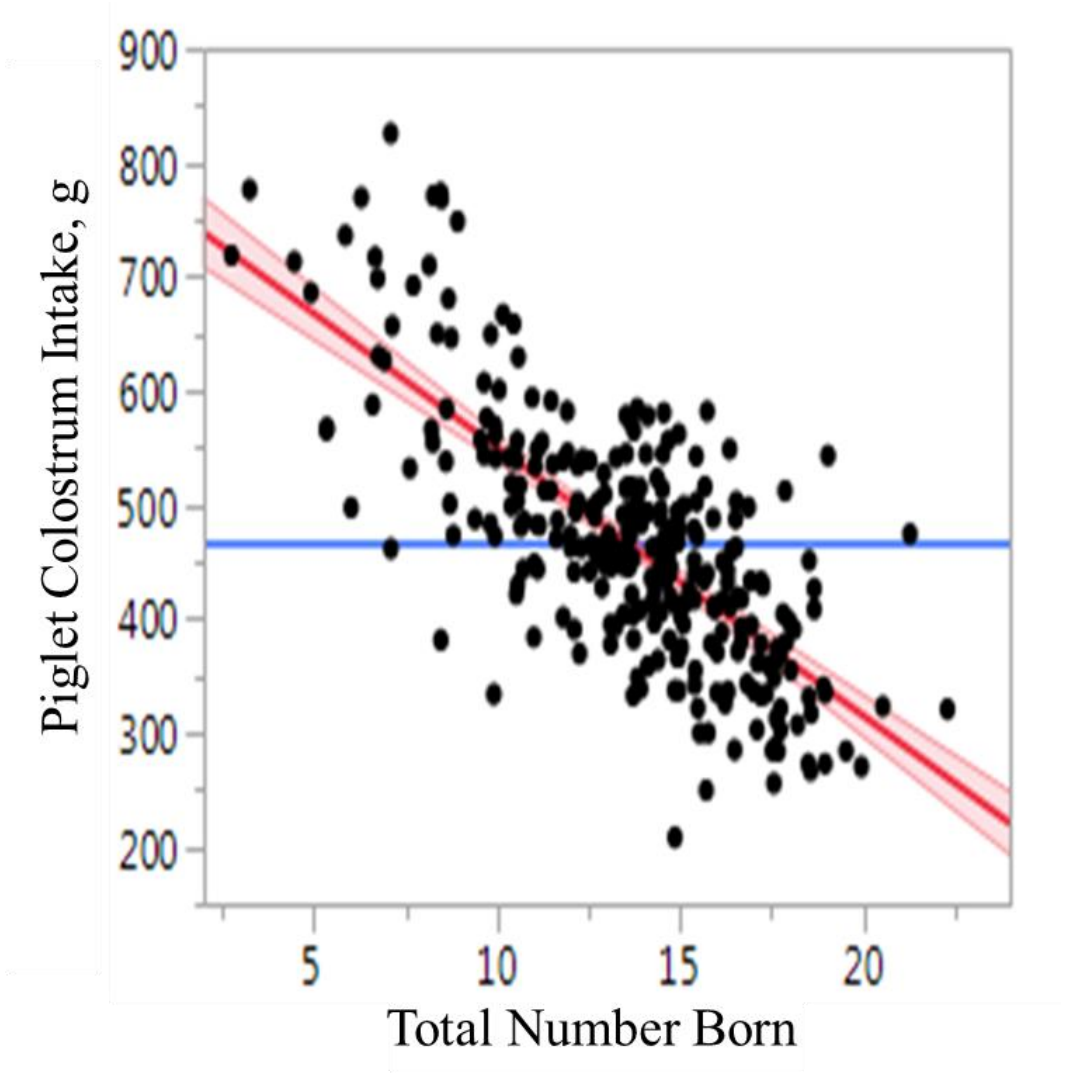

Figure 2.8 The impact of the total number of piglets born on piglet colostrum intake (P<0.01). Each dot represents the mean piglet colostrum intake of one sow (n=290 sows).

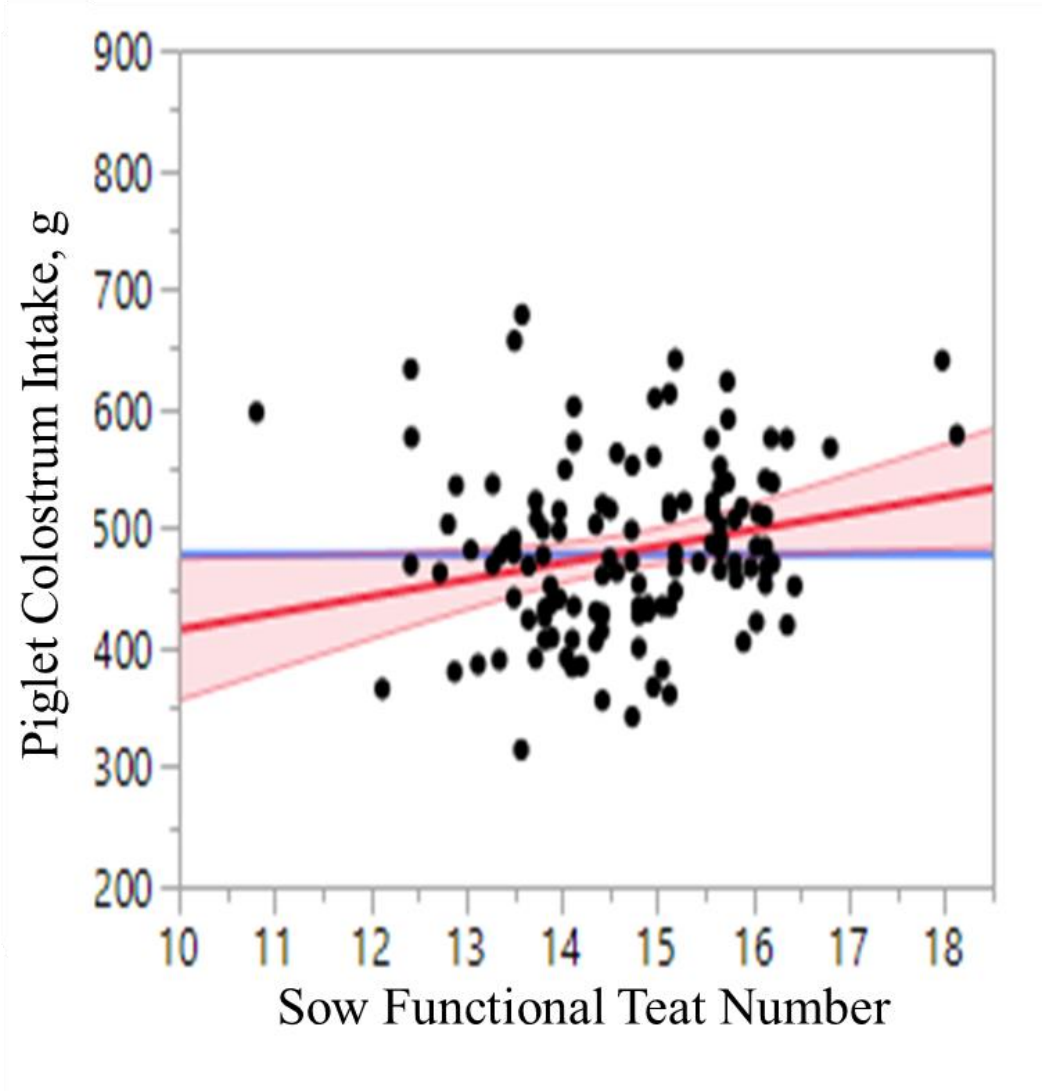

Figure 2.9 The impact of sow functional teat number on piglet colostrum intake (P=0.07). Each dot represents the mean piglet colostrum intake of one sow (n=122 sows).

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