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REPRODUCTION

Maternal nutrition during early and late gestation in gilts and sows under commercial conditions: impacts on maternal growth and litter traits[1]

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Abstract

The effects of two different feeding levels, offered in two phases during gestation, on body measurements and litter traits were evaluated in 152 gilts and 551 sows. The treatments consisted of the combination of two gestation phases (phase 1—days 22 to 42; phase 2—days 90 to 110) and two feed amounts (1.8 or 3.5 kg/d). Females were weighed on days 22, 42, 90, and 110 of gestation. Born alive and stillborn piglets were weighed within 12 h of birth. Total placental efficiency (ratio between litter weight and total placental weight) was measured in 518 females. Variables concerning body measurements at days 42 and 90 of gestation were analyzed considering the effects of feed amount, parity order (**PO**) and its interaction as a 2 × 2 factorial arrangement. Body measurements at day 110 of gestation and litter traits were analyzed considering the effects of feed amounts in phase 1, feed amounts in phase 2, PO and their interactions, as a 2 × 2 × 2 factorial arrangement. As expected, BW, backfat, and caliper units were greater at days 42, 90, and 110 ($P \leq 0.006$) for females fed 3.5 kg/d during the previous phase than those fed 1.8 kg. No differences were observed among feed levels in total number of piglets born, mummified fetuses, sum of born alive and stillborn piglets, and within-litter birth weight CV ($P \geq 0.118$). The percentage of stillborn piglets was affected by a three-way interaction (feed level at phase 1 × feed level at phase 2 × PO). Gilts fed 1.8 kg/d at phase 1 and 3.5 kg/d at phase 2 had fewer stillborn piglets than the other females ($P \leq 0.004$). Birth weight was not affected by feed levels ($P \geq 0.153$); however, sows had heavier piglets than gilts ($P < 0.001$). Females fed 3.5 kg/d during phase 2 tended to have heavier litters ($P = 0.054$) than those fed 1.8 kg/d. Feeding a high level at phase 2 reduced the occurrence of lightweight piglets in gilts, but not in sows (feed level phase 2 × PO; $P = 0.031$). Total placental weight, average placental weight, and total placental efficiency were not affected by feed level at phase 1, feed level at phase 2 or interactions ($P >$ 0.14). Sows had total placental weight and average placental weight greater ($P \leq 0.003$) than gilts. In conclusion, increasing feed intake during phase 1, phase 2, or both phases resulted in increased maternal BW gain, without expressive effects on litter traits. Feeding 3.5 kg/d to gilts during phase 2 reduced the occurrence of lightweight piglets.

Key words: birth weight, feeding, gilts, reproduction, sows

Introduction

Over the last decades, genetic improvements concerning pig litter size have created a problem due to the concomitant reduction in birth weight. Different efforts regarding nutritional strategies have been made to improve the birth weight of piglets or to compensate for the birth weight reduction resultant from larger litter sizes (De Vos et al., 2014; Gonçalves et al., 2016a).

Fetuses grow at an exponential rate during late gestation (McPherson et al., 2004), and the negative impacts of reduced intrauterine growth can persist during the lifetime of lightweight piglets. A common strategy to improve the birth weight of piglets is to feed females with higher feed amounts—bump feeding—in late gestation. However, our recent studies (Mallmann et al., 2018, 2019) and others presented in the literature (Gonçalves et al., 2016a) have not shown any benefits of the bump feeding practice, irrespective of the litter size (Mallmann et al., 2018).

One of the reasons for low piglet birth weight can be found earlier in gestation. In modern hyperprolific females, high ovulation rates and a consequently greater number of embryos on day 30 of gestation can compromise embryo development (Foxcroft et al., 2009; Da Silva et al., 2016). The availability of nutrients in utero can alter the expression of some genes during the peri-implantation period, with consequences for the growth of conceptuses. Among intrauterine environmental factors, nutrition affects the rapid placental development during the first trimester of gestation, playing a critical role in ensuring adequate uteroplacental blood flow and fetal growth (Wu et al., 2004). In this sense, the occurrence of conceptus losses between days 22 and 42 of gestation is likely due to the nutritional failures caused by insufficient placental development (Wright et al., 2016). The epitheliochorial placenta is established around days 26 to 30 of gestation (Dantzer, 1985) and is responsible for transporting nutrients, gases, and wastes between maternal and fetus systems (Reynolds and Redmer, 1995). In a molecular basis approach, higher energy levels throughout gestation have improved placental efficiency and reduced piglet birth weight variation (Che et al., 2017). Moreover, females fed lower energy amounts, based on the daily maintenance level, in different short time points during gestation (27 to 34, 55 to 62, and 83 to 90 d of gestation) had lighter piglets at birth (Ren et al., 2017).

The mentioned approaches are part of the current challenge, which is based on the following question: how can piglet birth weight be improved if females submitted to bump feeding do not transfer the extra energy ingested to fetal growth? It has been suggested that earlier placental development is necessary to support higher blood flow and, consequently, later greater energy exchange between maternal uterus and fetuses (Meschia, 1983; Reynolds and Redmer, 1995). We hypothesize that higher amounts of feed during the exponential placental development period (days 22 to 42) may improve placental efficiency, allowing a better nutrient exchange later in gestation in females submitted to bump feeding. Our objective is therefore to evaluate the bump feeding effects on maternal growth and litter traits using two feed amounts (1.8 or 3.5 kg) and two different phases (days 22 to 42 and 90 to 110) during gestation of gilts and sows under commercial conditions.

Materials and Methods

The protocol used in the present study was approved by the Ethics Committee of Animal Utilization of the Federal University of Rio Grande do Sul, under the process no. 36267.

Location

The study was conducted in a pig farm with 5,500 females, located in the Midwest of Paraná State, Brazil (24°55′04″ S, 50°05′50″ W), between January and April (average, minimum, and maximum temperatures were 23.5, 16.1, and 34.0 °C, respectively, with an average relative humidity of 86.7%, corresponding to summer and early autumn in the southern hemisphere.

Housing and Feeding

Females were moved to gestation pens after the last insemination (1.8 ± 0.8 d later) and were housed in static groups during gestation (around 70 females per pen), which means with no movements of newly bred sows into the pen until the entire group reached 110 d of gestation. Pens with 140 m^2 provided 2.0 m^2 per animal, for both gilts and sows, and were equipped with one electronic feeding station (**ESF**; SowComp, WEDA Dammann & Westerkamp GmbH, Germany), allowing space for up to 70 females. All females were fed by ESF and could enter the equipment as often as they wished. The ESF system recorded daily feed intake during the experimental period. The amount of feed recorded by the system was assumed to be consumed by the females before they left the feed station. Nipples provided ad libitum access to water.

Feed content was calculated monthly based on the analysis of ingredients. Dietary samples were collected every 2 wk for 4 mo and analyzed in triplicates for CP, total AA, and DM (methods described in CBAA, 2017, based on **AOAC**—Official Methods of Analysis of AOAC International Methodologies, 19th edition, 2012). Samples were also analyzed for crude fiber, ash, ether extract, calcium, and phosphorus (AOAC Int., 2012; CBAA, 2017).

Experimental and Treatment Design

From days 0 to 21 and from days 43 to 89 of gestation, all females were fed 1.8 kg/d of a corn–soybean-based meal with 3.15 Mcal ME/kg, 15.0% CP, and 0.68% standardized ileal digestible (**SID**) lysine (Table 1). The analyzed diet was considered consistent with the formulated values based on analytic variability (Table 1). During the other gestational periods, females were fed according to the groups cited below.

On day 20 of gestation, a total of 152 gilts and 551 sows, with PO 0 to 5 (PIC Camborough, Hendersonville, TN, Landrace × Large White crossbred) were selected according to the general health status and a body condition score between 2.5 and 4.5 (1 to 5 scale; Young et al., 2004). Females were individually weighed and assigned to two treatments, in a completely randomized design, to be fed a corn–soybean-based diet: 1.8 kg/d (5.7 Mcal ME and 12.2 g/d SID Lys) and 3.5 kg/d (11.0 Mcal ME and 23.8 g/d SID Lys). On day 89 of gestation, females of each group were again randomly assigned to receive two different feed levels: 1.8 or 3.5 kg/d. From that moment onward, the treatments consisted of the combination of two feed amounts (1.8 or 3.5 kg/d) offered in two gestation phases (phase 1—days 22 to 42; phase 2—days 90 to 110) for both gilts and sows. Females were moved to farrowing rooms on day 110 of gestation and fed 1.8 kg/d of a corn–soybean-based meal (3.30 Mcal ME/kg, 20.0% CP, and 1.20% SID Lysine) until farrowing.

All females were weighed and submitted to backfat (**BF**) and caliper evaluations at the beginning and the end of each phase (22, 42, 90, and 110 d of gestation). All weight measurements were performed with a 500-g precision scale (EW6, Tru Test, Auckland, New Zealand). Backfat measurements were performed at the P2 point (6.5 cm away from the midline of the vertebral column at the last rib level) with A-mode ultrasonography (Renco Lean

Table 1. Composition of the experimental gestation[1] diet (as-fed basis)

Item	Gestation
Ingredient, %	
Corn	49.6
Oats	14.0
Soybean meal, 46% CP	11.1
Wheat, 14.5% CP	10.0
Rice bran defatted, 17% CP	5.0
Corn DDGS, 6% fat	5.0
Molasses	1.2
Vitamin and mineral premix[2]	0.2
Monocalcium phosphate	0.35
Limestone	1.02
Salt	0.25
Sodium bicarbonate	0.30
L-Lys	0.29
DL-Met	0.02
L-Thr	0.09
Soybean oil	1.2
Phytase[3]	0.02
Others	0.36
Total	100.00
Calculated analysis	
SID Lys, %	0.68
SID Met: Lys, %	37
SID Met and Cys: Lys, %	78
SID Thr: Lys, %	81
SID Trp: Lys, %	23
SID Val: Lys, %	110
CP, %	15.03
Ca, %	0.73
STTD P, %	0.40
Na, %	0.25
Cl, %	0.20
ME, Mcal/kg	3.15
Proximate analysis, %	
DM	88.55 (87.78)
CP	14.89 (15.03)
Crude fiber	5.23 (3.85)
Fat	3.38 (4.38)
Ash	5.87 (4.87)
Ca	0.99 (0.73)
P	0.64 (0.40)
Total AA, %[4]	
Lys	0.77 (0.78)
Ile	0.71 (0.58)
Leu	1.29 (1.37)
Met	0.26 (0.28)
Met and Cys	0.56 (0.57)
Thr	0.64 (0.63)
Trp	0.15 (0.16)
Val	0.67 (0.75)
His	0.29 (0.40)
Phe	0.82 (0.64)

[1]Diet was fed during the entire gestation.
[2]*Vitamin composition per kilogram of diet*: Vitamin A: 12,500 IU; vitamin D_3: 2,500 IU; vitamin E: 125.0 IU; vitamin K_3: 4.5 mg; vitamin B_1: 2.5 mg; riboflavin (B_2): 7.5 mg; pyridoxine (B_6): 3.5 mg; vitamin B_{12}: 33.8 µg; niacin: 50.0 mg; pantothenic acid: 25.0 mg; folic acid: 2.4 mg; biotin: 0.26 mg; choline: 1.25 g. *Mineral composition:* selenium: 0.64 mg; iron: 75.0 mg; copper: 21.7 mg; manganese: 61.4 mg; zinc: 183.4 mg; iodine: 1.5 mg.
[3]Aela (Auster Animal Nutrition, São Paulo, Brazil) provided 1,000 phytase units per kilogram of diet, with a release of 0.19% STTD P.
[4]Values in parentheses indicate those calculated from the diet formulation and are based on the values from the NRC (2012).
SID = standardized ileal digestible; STTD = standardized total tract digestible.

Meter—Renco Corporation, Minneapolis, MN) within a range of 2 mm. Caliper unit was taken on the same BF point with the caliper equipment in a unit range from 1 to 25 (Knauer and Baitinger, 2015). The birth weight of the piglets born alive and stillborn was recorded within 12 h of birth, using a 1-g resolution scale. Mummified fetuses were not weighed; however, the number was recorded and included in the total number of piglets born.

Placental Efficiency

The total weight of placentas was recorded after farrowing in 518 females. The average placental weight was calculated dividing the total weight of placentas by the sum of piglets born alive and stillborn piglets. According to Wilson et al. (1999), placental efficiency is determined as a ratio between individual piglet birth weight and respective placental weight. In the present study, a total placental efficiency was obtained as a ratio between the litter weight and the respective total placental weight, as reported by Dallanora et al. (2017).

Statistical Analysis

Statistical analysis was performed using the Statistical Analysis System software, version 9.3 (SAS Inst. Inc., Cary, NC). The models for analysis of variables concerning the responses of phase 1 included PO (gilts or sows), feed amounts (1.8 or 3.5 kg/d), and their interaction as fixed effects, in a 2 × 2 factorial arrangement. From phase 2 onward, the analysis considered a 2 × 2 × 2 factorial arrangement, including PO, feed amounts of phase 1, feed amounts of phase 2, and their interactions as fixed effects.

The following variables were analyzed using the GLIMMIX procedure fitted assuming a normal distribution: BW, BF, and caliper unit at different time points and their respective gains and losses, total number of piglets born, born alive piglets, sum of born alive and stillborn piglets, litter weight, piglet weight at birth, total placental weight, average placental weight, and placental efficiency. The sum of born alive and stillborn piglets was used as a covariate for the analysis of litter weight, piglet weight at birth, total placental weight, average placental weight, and total placental efficiency. The results of differences in body measurements (i.e., gain or loss) are presented in intervals during gestation: days 22 to 42, 42 to 90, 90 to 110, and for the overall period (days 22 to 110).

The percentages of stillborn piglets, mummified fetuses, and piglets weighing <1,000 g were analyzed using the GLIMMIX procedure fitted assuming a binomial distribution. The total number of piglets born was significant as a covariate in the analysis of stillborn piglets and mummified fetuses. The within-litter birth weight CV was analyzed as a beta distribution using the GLIMMIX procedure.

Week of treatment onset and pen nested within PO were included as random effects. Differences were considered significant at $P \leq 0.05$, and P-values between 0.05 and 0.10 were designated as a tendency. Each female was considered as an experimental unit.

Results

Body Measurements

No differences were observed between the feed levels for BW, BF, and caliper units on day 22 (Table 2; $P > 0.458$). However, gilts and sows differed ($P < 0.006$) in BW (153.5 ± 4.7 and 213.8 ± 3.1 kg) and caliper unit (14.2 ± 0.2 and 13.5 ± 0.1), respectively, with no

Table 2. Effects of feed intake (**FI**; 1.8 or 3.5 kg/d) during phase 1 (days 22 to 42) on maternal body measurements in gilts and sows under commercial conditions

	Gilts			Sows			P-values		
	1.8 kg	3.5 kg		1.8 kg	3.5 kg				
Item	*n* = 74	*n* = 78	SEM	*n* = 280	*n* = 271	SEM	FI	PO1	FI × PO1
BW, kg									
Day 22	153.0	153.9	5.2	213.4	214.3	3.4	0.730	<0.001	0.978
Day 42	164.1	174.8	4.9	220.2	237.2	3.1	<0.001	<0.001	0.209
Day 90	189.0	194.6	4.8	236.3	245.2	3.1	0.002	<0.001	0.488
BF, mm									
Day 22	12.5	12.2	0.4	12.6	12.6	0.2	0.592	0.501	0.698
Day 42	13.3	13.9	0.5	13.1	14.4	0.3	0.001	0.739	0.224
Day 90	13.4	13.9	0.5	13.9	15.1	0.3	0.006	0.135	0.198
Caliper unit									
Day 22	14.1	14.4	0.2	13.5	13.5	0.1	0.458	0.006	0.333
Day 42	13.8	15.5	0.3	13.5	14.7	0.2	<0.001	0.192	0.171
Day 90	13.4	14.4	0.3	13.5	14.3	0.2	<0.001	0.902	0.710
Changes, days 22 to 42									
BW, kg	11.1	20.9	0.9	6.7	22.9	0.5	<0.001	0.218	<0.001
BF, mm	0.9	1.7	0.5	0.3	1.7	0.3	<0.001	0.642	0.038
Caliper unit	-0.2	1.2	0.3	-0.02	1.2	0.2	<0.001	0.689	0.470
Changes, days 42 to 90									
BW, kg	24.9	19.8	1.2	16.2	8.0	0.8	<0.001	<0.001	0.020
BF, mm	0.1	0.1	0.5	0.7	0.7	0.4	0.343	0.280	0.670
Caliper unit	-0.4	-1.1	0.3	0.0	-0.5	0.3	<0.001	0.118	0.120

[1]PO, parity order

difference in BF (12.4 ± 0.3 and 12.6 ± 0.2 mm; $P = 0.501$). The BW, BF, and caliper units were greater on days 42 and 90 in females fed 3.5 kg/d ($P \leq 0.006$; Table 2). Only BW was different between gilts and sows on days 42 and 90 ($P < 0.001$).

The gains of BW and BF from days 22 to 42 were affected by the interaction between feed amount and PO ($P < 0.04$; Table 2). Within females fed 1.8 kg/d, gilts gained 4.4 kg more weight than multiparous sows ($P < 0.001$); however, no differences were observed between gilts and sows fed 3.5 kg/d. The BF gain was greater in gilts fed 3.5 kg/d than in multiparous sows fed 1.8 kg/d ($P = 0.032$). Both gilts and sows fed 3.5 kg/d showed greater BF gain than those fed 1.8 kg/d, with no difference between parities within the feed levels ($P \geq 0.722$). Females fed 3.5 kg/d in phase 1 gained more caliper units between days 22 and 42 than those fed 1.8 kg/d ($P < 0.001$).

The BW gain between 42 and 90 d of gestation was affected by the interaction between feed intake in phase 1 and PO. Gilts fed 3.5 kg/d and sows fed 1.8 kg/d had similar BW gain ($P > 0.05$; Table 2), whereas gilts fed 1.8 kg/d gained more BW than sows fed 3.5 kg ($P < 0.001$). Within each feed level, gilts gained more BW than sows ($P < 0.001$), and both gilts and sows fed 1.8 kg/d had greater BW gain from days 42 to 90 than those fed 3.5 kg/d between 22 and 42 d ($P < 0.001$). The change in BF from days 42 to 90 was not affected by feed intake, PO, and their interaction ($P \geq 0.280$; Table 2). The females fed 3.5 kg/d between 22 and 42 d showed greater caliper loss from 42 to 90 d of gestation than those fed 1.8 kg/d ($P < 0.001$).

The mean and SEM values concerning the effects of feed levels offered at both phases are presented in Table 3, while the probabilities values are shown in Table 4. High feed intake during phase 1 or phase 2 resulted in greater BW, BF, and caliper unit levels on day 110 ($P \leq 0.006$). Sows were 50.6 kg heavier than gilts on day 110 (258.9 vs. 208.3 kg; $P < 0.001$), respectively. An interaction between feed intake in phase 2 and PO was observed for changes in BW and BF between 90 and 110 d ($P \leq 0.016$). Within the 3.5 kg/d feed level, sows gained 4.0 kg more than gilts ($P = 0.029$), with no difference when fed 1.8 kg/d ($P = 0.938$). The interaction for BF change showed that gilts fed 3.5 kg/d during phase 2 gained more BF from days 90 to 110 than sows fed 1.8 kg/d ($P < 0.001$). Both gilts and sows fed 3.5 kg/d during phase 2 gained more BF from days 90 to 110 than gilts and sows fed 1.8 kg/d, respectively ($P < 0.001$). Within each feed level in phase 2, no effect of PO was observed for BF changes ($P \geq 0.291$). Although the change in caliper unit was affected by feed intake in phase 1 ($P = 0.026$), it was more significantly affected by feed intake in phase 2 ($P < 0.001$). The females fed 3.5 kg/d lost 0.14 and gained 0.53 units, whereas females fed 1.8 kg/d gained 0.06 and lost 0.60 units when considering feed levels at phase 1 and phase 2, respectively.

Considering the overall changes (days 22 to 110; Tables 3 and 4), the interactions between feed level in phase 1 and PO and between feed level in phase 2 and PO ($P \leq 0.012$) affected the overall BW. Within both gilts and sows, 3.5 kg/d in phase 1 or phase 2 resulted in a greater BW gain than 1.8 kg/d. Within 3.5 kg/d, gilts and sows did not differ ($P > 0.065$), whereas a greater BW gain was observed in gilts than in sows fed 1.8 kg/d ($P < 0.001$). The changes in BF and caliper unit were affected by feed intake offered in both phase 1 and phase 2 ($P < 0.001$). Females fed 3.5 kg/d had greater BF and caliper gain than those fed 1.8 kg/d. Overall, caliper changes were also affected by PO ($P = 0.002$), with gilts losing (–0.36) and sows gaining (0.29) caliper units.

Litter Traits

The mean and SEM values concerning the effects of feed levels offered at both phases are presented in Table 3, while the

Table 3. Effects of feed intake during phase 1 (days 22 to 42) and phase 2 (days 90 to 110) of gestation on maternal body measurements, farrowing performance, and characteristics related to the offspring in gilts and sows under commercial conditions[1]

	Gilts					Sows				
	Phase 1 (days 22 to 42)					Phase 1 (days 22 to 42)				
	1.8 kg		3.5 kg			1.8 kg		3.5 kg		
	Phase 2 (days 90 to 110)					Phase 2 (days 90 to 110)				
Item	1.8 kg n = 37	3.5 kg n = 37	1.8 kg n = 37	3.5 kg n = 41	SEM	1.8 kg n = 137	3.5 kg n = 143	1.8 kg n = 135	3.5 kg n = 136	SEM
BW, kg										
Day 90	189.3	188.7	193.8	195.3	5.7	237.6	235.1	245.0	245.4	3.5
Day 110	199.8	212.1	202.4	219.0	6.1	246.5	262.9	253.5	272.5	3.9
BF, mm										
Day 90	13.6	13.2	13.6	14.1	0.7	13.9	13.9	14.7	15.5	0.4
Day 110	13.7	15.1	13.8	16.3	0.6	13.7	15.1	14.9	16.6	0.4
Caliper unit										
Day 90	13.4	13.5	14.4	14.3	0.3	13.4	13.6	14.3	14.2	0.2
Day 110	13.0	14.2	13.7	14.6	0.3	12.8	14.1	13.6	14.7	0.2
Changes (days 90 to 110)										
BW, kg	10.5	23.4	8.6	23.7	1.3	9.0	27.9	8.5	27.2	0.9
BF, mm	0.0	1.9	0.1	2.1	0.5	–0.1	1.2	0.2	1.1	0.3
Caliper unit	–0.4	0.7	–0.7	0.3	0.2	–0.6	0.6	–0.7	0.5	0.1
Overall changes (days 22 to 110)										
BW, kg	52.0	65.2	54.9	70.0	2.8	32.4	51.3	40.1	59.4	1.2
BF, mm	1.3	3.0	1.9	3.7	0.6	1.1	2.6	2.3	4.1	0.3
Caliper unit	–1.2	0.2	–0.6	0.2	0.3	–0.7	0.5	0.1	1.3	0.1
Farrowing performance										
Total born piglets, n	14.8	14.6	14.7	14.4	0.6	14.6	15.3	14.9	14.6	0.4
Born alive piglets, n	13.5	13.7	13.4	13.2	0.6	13.3	13.8	13.3	13.1	0.3
Born alive + stillborn piglets, n	14.6	13.9	14.0	14.0	0.6	14.2	14.7	14.3	14.1	0.3
Stillborn piglets, %	5.3	1.8	4.8	5.4	1.0	5.9	5.6	7.4	6.5	0.6
Mummified fetuses, %	3.1	3.8	2.6	2.3	1.0	2.0	2.5	2.0	2.3	0.4
Litter traits										
Average birth weight, g	1,370.5	1,381.1	1,359.1	1,359.1	35.0	1,487.4	1,509.0	1,473.7	1,542.0	19.2
Litter weight, kg	19.2	19.5	18.9	19.3	0.5	20.4	20.9	20.5	21.2	0.3
Piglets weighing <1,000 g, %	18.4	12.3	19.1	14.6	2.3	14.9	14.5	14.5	12.6	1.2
Birth weight CV, %	21.1	18.6	20.5	19.8	1.3	21.6	21.9	22.0	20.9	0.8
Total placental weight[2], kg	3.1	3.1	3.1	2.9	0.2	3.4	3.2	3.3	3.4	0.9
Average placental weight[2], g	214.6	216.3	209.9	197.5	13.3	235.0	226.0	227.6	240.4	6.6
Total placental efficiency[2,3], g/g	6.7	6.8	7.1	7.4	0.4	6.7	7.1	6.8	6.8	0.2

[1]Probability values are presented in Table 4.
[2]A subsample of 518 females (24 to 32 gilts and 98 to 105 sows per treatment) were used for this analysis.
[3]Calculated as a ratio between litter weight and total placental weight.

probabilities values are shown in Table 4. The number of total piglets born, born alive, the sum of piglets born and born alive, and the percentage of mummified fetuses were not affected by feed levels, PO or their interactions ($P \geq 0.135$). The three-way interaction (feed level at phase 1 × feed level at phase 2 × PO) affected the percentage of stillborn piglets ($P = 0.008$). Gilts fed 1.8 kg/d at phase 1 and 3.5 kg/d at phase 2 had fewer stillborn piglets than the other females ($P \leq 0.007$). The sows fed 3.5 kg/d at phase 1 and 1.8 kg/d at phase 2 had a greater percentage of stillborn piglets than either gilts fed the same feed levels and sows fed 1.8 kg/d at phase 1 and 3.5 kg/d at phase 2 ($P \leq 0.043$).

Sows had heavier piglets ($P < 0.001$; 1,367.5 vs. 1,503.0 g) and heavier litters ($P < 0.001$; 20.8 vs. 19.2 kg) than gilts. Although birth weight was not affected by feed amount in any phase ($P > 0.150$), total litter weight was marginally greater in females fed 3.5 kg/d (20.2 vs. 19.7 kg) during late gestation ($P = 0.054$). Even though the within-litter birth weight CV was not affected by feed level or PO ($P \geq 0.118$), the percentage of piglets weighing <1,000 g was affected by the interaction between the feed level at phase 2 and PO ($P = 0.031$). Gilts fed 3.5 kg/d had a lower percentage of lightweight piglets than those fed 1.8 kg/d ($P = 0.006$; 13.4 vs. 18.8%, respectively), with no difference in sows ($P = 0.419$; 13.5% vs. 14.7%, respectively).

Total placental weight, average placental weight, and total placental efficiency were not affected by feed level at phase 1, feed level at phase 2 or interactions ($P > 0.14$). Although sows had total placental weight and average placental weight greater ($P \leq 0.003$) than gilts (3.3 vs. 3.0 kg and 232.2 vs. 209.6 g, respectively), the total placental efficiency was not different ($P = 0.604$) between sows and gilts (6.9 vs. 7.0).

Table 4. Probability values corresponding to main effects and interactions among feed intake (1.8 or 3.5 kg) in phase 1 (FI1—days 22 to 42), feed intake in phase 2 (FI2—days 90 to 110), and PO of high-performing gilts and sows on maternal body measurements, piglet birth weight, and farrowing performance under commercial conditions[1]

	Interactions						
Item	FI1 × FI2 × PO	FI1 × PO	FI2 × PO	FI1 × FI2	FI1	FI2	PO
BW day 90, kg	0.945	0.488	0.749	0.593	0.002	0.907	<0.001
BW day 110, kg	0.847	0.461	0.481	0.460	0.006	<0.001	<0.001
BF day 90, mm	0.858	0.192	0.512	0.167	0.006	0.506	0.135
BF day 110, mm	0.606	0.366	0.555	0.311	0.004	<0.001	0.427
Caliper unit day 90	0.702	0.714	0.943	0.510	<0.001	0.948	0.902
Caliper unit day 110	0.947	0.534	0.685	0.449	<0.001	<0.001	0.757
Changes (days 90 to 110)							
BW, kg	0.156	0.802	<0.001	0.289	0.107	<0.001	0.270
BF, mm	0.462	0.750	0.016	0.618	0.400	<0.001	0.343
Caliper unit	0.569	0.078	0.548	0.870	0.026	<0.001	0.964
Overall changes (days 22 to 110)							
BW, kg	0.636	0.012	0.002	0.432	<0.001	<0.001	0.002
BF, mm	0.862	0.140	0.723	0.677	<0.001	<0.001	0.957
Caliper unit	0.332	0.053	0.660	0.163	<0.001	<0.001	0.002
Farrowing performance							
Total born, *n*	0.525	0.916	0.499	0.466	0.597	0.848	0.656
Born alive, *n*	0.798	0.845	0.802	0.364	0.359	0.836	0.813
Born alive + stillborn piglets, *n*	0.330	0.958	0.476	0.945	0.468	0.740	0.657
Stillborn piglets, %	0.008	0.188	0.103	0.020	0.004	0.016	0.002
Mummified fetuses, %	0.645	0.264	0.544	0.425	0.135	0.405	0.281
Litter traits							
Average birth weight, g	0.416	0.455	0.261	0.609	0.842	0.153	<0.001
Litter weight, kg	0.829	0.378	0.562	0.715	0.920	0.054	0.001
Piglets weighing <1,000 g, %	0.309	0.123	0.031	0.951	0.849	0.003	0.315
Birth weight CV, %	0.223	0.679	0.311	0.849	0.993	0.118	0.131
Total placental weight[2], kg	0.198	0.357	0.586	0.742	0.685	0.566	0.003
Average placental weight[2], g	0.197	0.271	0.603	0.780	0.551	0.800	0.001
Total placental efficiency[2,3], g/g	0.487	0.148	0.835	0.904	0.320	0.389	0.604

[1]A total of 703 females were used, with 37 to 41 gilts and 135 to 143 sows per treatment.
[2]A subsample of 518 females (24 to 32 gilts and 98 to 105 sows per treatment) were used for this analysis.
[3]Calculated as a ratio between litter weight and total placental weight.

Discussion

Effects on Body Measurements

We demonstrated that increasing the feed amount in one or two different phases during gestation significantly increased BW, BF, and caliper units. Conventional gestating feeding programs are established to fulfill the requirements for maintenance, maternal growth, and fetal and mammary gland growth, in addition to the development of the uterus and the placenta (NRC, 2012). Early-mid gestation is the best opportunity to recover the body reserves lost in the previous lactation phase, whereas in late gestation, the objective is to provide adequate nutrients for fetal and mammary gland growth (Goodband et al., 2013; Menegat et al., 2017). Assuming the equation proposed by the NRC (2012) to calculate the energy necessary for maintenance under thermoneutral conditions (100 kcal × $BW^{0.75}$), gilt and sow requirements on day 20 were 4.4 and 5.6 Mcal/d, increasing to 5.2 and 6.1 Mcal/d on day 90, respectively. Similar results have been reported by Thomas et al. (2018a), who showed increases of 20% and 14% in the maintenance of gilts and sows as gestation progressed. The lysine requirements increase in a greater proportion, from 6.8 to 15.3 g/d, as gestation progresses (Kim et al., 2009), based on fetal tissue gain (Mc Pherson et al., 2004) and mammary gland development (Ji et al., 2005). Considering the feeding levels used in the present study, females fed 1.8 kg/d ingested 5.7 Mcal/d and 12.2 g/d SID Lys, while the 3.5 kg/d treatment provided 11.0 Mcal/d and 23.8 g/d SID Lys. When fed 1.8 kg/d, sows had their maintenance energy requirements fulfilled on day 20 of gestation. Even though the energy provided by 1.8 kg/d was 0.4 Mcal below the level recommended for maintenance on day 90 of gestation, the sows had an overall BW gain.

However, it is necessary to consider that slight losses in caliper units occurred in gilts and sows, mostly during late gestation, when 1.8 kg/d was provided in both phases or only in phase 2, indicating that fat and protein were mobilized. Knauer and Baitinger (2015) observed that caliper measurement is correlated with loin depth (i.e., protein reserves; $r = 0.51$) and BF ($r = 0.62$), which agrees with the correlation of 0.61 with BF (data not shown) observed in the present study. Mallmann et al. (2019) also observed losses of BF (−0.1 mm) and caliper unit (−0.8) when gilts were fed 1.8 kg/d during late gestation, even though they had whole BW gain (15.0 kg). If the BW gain in females fed 1.8 kg/d during late gestation (~9 kg) and their litter weight at farrowing (~19 kg) are considered, we can attribute the BW increase to whole BW gain instead of gain in maternal weight. In general, sows will only lose BW when a severe restriction is applied; however, they will use fat and protein reserves to meet the energy requirements for fetal growth (Goodband et al., 2013). In a recent study performed in sows, BW losses were observed when the feed level was set at 50% of the maintenance level in three different short gestational periods, whereas females fed the maintenance level during the entire gestation gained 24 kg between 27 and 109 d (Ren et al., 2017).

In the present study, gilts gained 54.8 kg in BW during the overall gestation, which is close to the recommendation of 55 kg reported previously (Ji et al., 2005; NRC, 2012). Thomas et al. (2018b) reported no BF gain during gestation in gilts, whereas we observed a BF gain of 2.5 mm. It should, however, be noted that our gilts were thinner at the onset of the experimental period when compared with the gilts in their study (12.4 vs. 18.2 mm).

Effects on Litter Traits and Birth Weight

Bump feeding is a common and controversial feeding strategy used in breeding herds and consists of increasing the feed amount after day 90 of gestation to meet the requirements of females and to increase piglet birth weight (Gonçalves et al., 2016a). Based on recent studies that used this strategy, our attempt was to verify the effects of bump feeding late in gestation in females that received a greater feed amount between 22 and 42 d of gestation, which includes the period of placental establishment (Dantzer, 1985), and is also considered a critical phase for embryo survival and development (Geisert and Schmitt, 2002). Furthermore, if the intention is to have a greater maternal-fetal exchange during late gestation, an adequate vascular bed development earlier in gestation is necessary (Meschia, 1983). In our earlier studies (Mallmann et al., 2018, 2019), we inferred that one of the reasons why the birth weight was not increased in bump-fed females might be the metabolic state earlier in gestation, as suggested by Foxcroft (2009). However, even though a better metabolic state was provided by increasing the feed amount during the placenta establishment, placental efficiency, and birth weight were not improved in the present study. Some studies tried to improve placental efficiency (Dallanora et al., 2017) or angiogenesis (Mateo et al., 2007) by changing the AA profile. Individual placental weight was increased when the AA profile was changed in different moments during gestation, although no effects were found on placental efficiency and piglet birth weight (Dallanora et al., 2017). Krombeen et al. (2018) studied the different factors that contribute to placental efficiency variation and reported 6.73 as the most efficient placental unit and 4.85 as the least efficient one; the associated fetuses differed in placental weight by 24.95%, contrasting with a difference of only 4.15% in BW (Krombeen et al., 2018). This indicates that there are compensatory mechanisms that ensure adequate fetal growth when the placenta size is restricted, and these are not only restricted to the placenta (Vallet et al., 2013).

In the present study, there were no improvements in litter traits in females with a greater feeding level in both phases. Musser et al. (2006) reported that piglet birth weight was not statistically improved when the feed level was increased from 1.81 to 3.61 kg/d, between 30 and 50 d of gestation, even with piglets from females fed 3.61 kg/d being numerically 50 g heavier. However, birth weight was significantly increased when the energy level was increased (from 0.5 to 1, 1.5, and 2 × maintenance) in three different short periods, at 27 to 34, 55 to 62, and 83 to 90 d of gestation (Ren et al., 2017). Using 14 gilts per group, Che et al. (2017) increased the energy level in 0.4 Mcal DE/d during the entire gestation, which resulted in an increase in birth weight by 150 g, with a reduction from 20.9% to 12.0% in within-litter variation. In the present study, although the treatments did not affect within-litter variation, there was a reduction by 5.3% in lightweight piglets when gilts ingested more feed during late gestation. In a previous study, the occurrence of lightweight piglets reduced by 2.4% following the increase in feed amount from 1.8 to 2.3 kg/d in late gestating gilts, with no improvements when the feed amount increased to 2.8 and 3.3 kg/d (Mallmann et al., 2019).

The total numbers of piglets born or born alive piglets were not affected by changing the amount of feed in any of the gestational phases. In agreement, litter size was not affected when different feeding levels were provided during specific (days 25 to 50, 25 to 70, and 45 to 85) phases (Nissen et al., 2003; Cerisuelo et al., 2008). Based on the maintenance requirements, Ren et al. (2017) changed the feeding levels, in three different periods of 7 d during gestation, and no effects were observed in total piglets born, born alive piglets, and stillborn piglets. However, in females with fewer piglets born (10.5 piglets per litter) than in the current study, a greater amount of feed (1.81 vs. 3.63 kg/d), provided between 30 and 50 d of gestation, resulted in a reduction by 1.2 piglets (Musser et al., 2006). In recent studies, bump feeding has been associated with more stillborn piglets. For example, Gonçalves et al. (2016b) reported an increased stillborn rate in sows fed a high-energy level. In another study, gilts fed 1.8 kg/d had a lower percentage of stillborn piglets than gilts fed 2.3, 2.8, or 3.3 kg/d late in gestation (Mallmann et al., 2019). In the present study, however, gilts that received 1.8 kg/d from 22 to 42 d and 3.5 kg/d in late gestation had a stillborn rate unexpectedly lower than the other groups, with unexplained underlying reasons.

Against this background, it is necessary to better understand the placental functions and to develop economically viable strategies to improve its development and functions in order to increase litter uniformity and piglet birth weight (Vallet et al., 2013). Based on our findings and on those of other studies performed in a commercial perspective, providing greater feed levels (Mallmann et al., 2018, 2019) or greater energy or lysine levels (Gonçalves et al., 2016b) is not justified because productive returns do not compensate them. In general, the benefits obtained with different feeding strategies are not substantial, and in our understanding, the way to solve this issue is to change the traits considered in selection programs. Including new traits in breeding selection indices will provide an excellent opportunity to mitigate some antagonisms (Amer et al., 2014), such as the relationship between litter size and piglet birth weight.

Conclusions

In gilts and sows with a suitable body condition, the BW and BF gains during gestation increased as the feed amount increased in phase 1 (days 22 to 42), phase 2 (days 90 to 110), or in both phases. Piglet birth weight was not increased with greater feed amounts; however, a lower occurrence of lightweight piglets was found when gilts ingested greater feeding levels during late gestation. Placental efficiency was not affected by feed amounts.

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Conflict of interest statement

None declared.

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