Effects of the feeding level in early gestation on body reserves and the productive and reproductive performance of primiparous and multiparous sows

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ABSTRACT

Early gestation may be the best period for sows to recover body reserve losses from previous lactation. The aim of this study was to investigate the effect of different levels of restricted feeding in early gestation on the body status, productive and reproductive performance, and hormonal-metabolic status of primiparous and multiparous sows. A total of 130 sows were randomly assigned to one of three feeding levels: Treatment I, which sows were fed at the level commonly used from day 3 to 28 of gestation (2.5 kg·d- 1 of a diet with 2.18 Mcal NE·kg- 1 and 13.72 g CP·kg- 1), and Treatments II and III, where feed was increased by 25% and 50%, respectively. Sow body status, litter size and weight, early mortalities, reproductive rates, weaning-to-estrus interval, and hormones linked to metabolism were recorded. The highest weight gain, body condition score, and backfat thickness were found in sows fed Treatment III compared to those fed the usual feeding level (Treatment I). No differences among treatment groups were found in litter size or litter weight, although a tendency for more live born piglets and fewer stillbirths was found in sows fed Treatment III. In contrast, litters from sows fed at higher feeding levels had a higher mortality at 72 h compared to those fed at the lowest feeding level (I), which was partly linked to a higher percentage of piglets culled at birth and piglets weighing less than 800 g. There were no differences in conception and farrowing rates, leptin, progesterone, insulin, or cortisol among treatment groups applied in early gestation. In conclusion, increasing the feeding level in sows during early gestation to improve their short-term productive and reproductive performance remains controversial. Further studies are needed to focus on how the restricted feeding level applied could affect the viability and proportion of low-weight piglets.

Keywords: feeding level, early gestation, sow, body reserves, performance, leptin

1. INTRODUCTION

Early gestation, which covers about the first 30 days, may be the best period for the sow to recover body reserve losses from previous lactation (Dourmad et al., 1996), and this is particularly relevant for gilts because they still have to grow to reach their mature body size. In addition, sows may be kept in individual crates in this period according to the European legislation (European Union, 2009/120/EC), which would allow specific feeding strategies to be adopted.

Knowledge of the nutrient requirements of modern sows and the feeding strategies to be applied to meet them under commercial conditions play an important role in achieving the best productive and reproductive performance. Furthermore, genetic selection for leanness has developed animals with lower fat reserves and limited feed intake. In fact, new hyper-prolific and leaner sows have higher culling rates than a few years ago, mainly due to reproductive failure (Sasaki and Koketsu, 2011).

This fact has been linked to both excessive losses of body weight and body reserves during lactation, and to a sub-optimal level of body reserves at weaning in these genotypes (Thaker and Bilkei, 2005; Ferreira et al., 2021). In this line, the restricted feeding programs commonly used during gestation do not always allow for the recovery of body reserves lost in the previous lactation. This is particularly problematic in primiparous sows, as they have lower body reserves and a 20% lower feed intake during lactation compared to multiparous sows (Eissen et al., 2000). In this sense, primiparous sows also show lower reproductive performance (a reduced farrowing rate, a lower litter size, or both) resulting from relatively higher weight losses during the first lactation (Thaker and Bilkei, 2005).

An increased feed intake during early gestation should help to ensure suitable levels of body reserves at farrowing and at weaning. However, the effect of the feeding level after insemination is controversial (Leal et al., 2019; Langendijk, 2021). Earlier studies with gilts diets supplying 32.5MJ DE·d^{-1} (Jindal et al., 1997) or 29.4MJ ME·d^{-1} (Dyck and Strain, 1983) in the first days after mating reduced the level of progesterone and impaired the uterine environment, reducing embryo survival. For this reason, it has been traditionally recommended to keep the feeding level low (without energy content greater than needed for body maintenance) in the first post-mating weeks. However, currently, increasing the level of feeding in hyper-prolific sows could positively affect embryo development and survival. Indeed, Leal et al. (2019) in a meta-analysis study about this topic, showed that restricted feed intake in early gestation is no longer relevant when using modern sow lines, as dietary energy of up to 54 MJ ME·d^{-1} had no detrimental effect on embryo survival. Otherwise, it is also well documented that increased levels of backfat at farrowing lead to a decrease in feed intake during lactation (Lavery et al., 2019). However, some studies suggest that higher body reserves at farrowing may play a protective role in sow performance against the adverse effects of excessive body weight loss during lactation, mainly in lean genotypes (Cerisuelo et al., 2008). In this sense, Schenkel et al. (2010) reported that a body weight loss higher than 10–12% decreases reproductive performance in the subsequent productive cycle.

From a hormonal point of view, the feeding level stimulates the growth of luteal tissue and increases the synthesis of progesterone by the ovaries in the pre-implantation period (Athorn et al., 2013), which is supplied directly to the uterine horns. The establishment and maintenance of luteal tissue in early gestation are critical to endometrial function, development, and embryo survival. Before implantation, the effects on formation of luteal tissue and progesterone secretion would be independent of the luteinising hormone (LH) and probably linked to metabolic signals via insulin and insulin-like growth factor 1 (IGF-1) (Langendijk et al., 2008). It is just during the first three days after ovulation when high feed intake can reduce systemic progesterone (while direct supply from the ovaries may still be low), and thus can also reduce embryo survival according to Jindal et al. (1997). After day 12 of gestation, the luteal function is dependent of LH, although variations in energy intake may not lead to gestation failure, but may affect nutrient supply to the embryos, as uterine capacity becomes limiting (Langendijk et al., 2016; Wang et al., 2017). Furthermore, to our knowledge, there is insufficient information about the effects of a feeding strategy applied in early gestation on the serum levels of some non-reproductive hormones, such as leptin, related to body reserves and feed intake in sows. Previous research has demonstrated that leptin is the principal regulator of energy balance during gestation, and the presence of leptin receptors in the placenta suggests effects on essential processes to ensure an adequate nutrient supply to the fetus (Saleri et al., 2015).

In summary, increasing the level of feeding in early gestation may offer advantages over later stages. Furthermore, the level of feeding in hyper-prolific sows during early gestation still needs to be refined in order to clarify some conflicting results found in the scientific literature on feeding management of sows. The aim of this study was to evaluate the effect of the feeding level from day 3 to 28 of gestation on body status and litter traits of primiparous and multiparous sows, as well as the effects on their hormonal-metabolic status.

2. MATERIAL AND METHODS

The experimental procedures and handling of animals, following the European regulations (European Union, 2010/63/EU Directive) for the protection of animals used for scientific purposes, were approved by the Ethics Committee of Animal

Experimentation of the University of Murcia and the Administrative Authorities (A-13170805).

2.1 Location and Animals

The trial was carried out in a commercial farm located in the southeast of Spain (Murcia, Spain). A total of 130 sows (Landrace x Large-white; Topigs Norsvin TN70), 61 primiparous (second gestation sows) and 69 multiparous (from third to eighth parity), were used for this experiment. When estrus was detected, sows were blocked by parity, body weight, and body condition status (by decreasing order of preference) and assigned randomly to one of three gestation feeding programs (described below). Sows were then inseminated with semen from Duroc boars, after following the standard procedure for assessing sperm motility, which included total sperm motility (percentage showing any form of motility), progressive sperm motility (percentage showing rapid, linear movement) and sperm velocity (on a scale of 0 to 4, from immotile to rapidly motile). The estrus detection and insemination protocol are described below.

2.2 Experimental Design and Treatments

The feeding program during gestation was divided into two periods: early gestation (from day 3 to day 28) and the rest of the gestation period until a few days before farrowing (from day 29 to day 110). All sows were fed the same commercial gestation diet, which was formulated according to the standard recommendations of the Spanish Foundation for the Development of Animal Nutrition (FEDNA, 2013) and manufactured in a dry mash form. The ingredients and chemical composition of the gestation diet are summarized in Table 1. All sows were fed once a day (at 07:00 h). Three feeding levels were assessed in the early gestation period. In Treatment I, sows were fed at the level commonly used on this farm (2.5 kg·d^{-1} of a diet with 2.18 Mcal NE·kg^{-1} and 13.72

g CP·kg^{-1}), whereas feed was increased by 25% and 50% in Treatments II and III, respectively (3.125 and 3.750 kg·d^{-1}, respectively). From day 29 onwards, all sows were fed the same amount (2.5 kg·d^{-1} until day 110), regardless of the feeding level applied in early gestation. Sows were kept in the gestation facilities during the weaning-to-estrus interval and the first 28 days, including gestation diagnosis; which was performed at 25 days after first insemination by transabdominal ultrasonography (Echoscan T-300 S, Barcelona, Spain). They were housed in individual crates (0.60 m × 2.00 m). Non-pregnant sows were removed from the study when they returned to estrus (n = 9). Water was offered ad libitum by a drinking nipple, while feed was restricted in an individual feeder according to the experimental design (as described above). Feed refusals in early gestation were monitored to check that all sows ate the total amount of feed offered. Room temperature was kept at approximately 20 ◦C, and ventilation was thermostatically controlled. On day 29 of gestation, sows were moved to outdoor pens (5 m × 8 m) and kept loose in mixed-treatment groups of 15 sows each, in which they were also fed in a restricted way but with the same amount of feed, as noted previously. The feeder was a long common cement trough with access to water by means of nipple drinkers. Throughout lactation and the first post-weaning days, the feeding regime was also common for all sows. When sows were moved to individual crates (0.60 m × 2.20 m) about one week before farrowing (day 110 of gestation), they were fed 2.0 kg·d^{-1} of a commercial lactation diet (Table 1). After farrowing, sows were fed three times a day: at 7:00, at 12:00, and at 18:00 h. The initial amount of feed was adjusted for each lactating sow by gradually increasing the daily amount supplied by 0.5 kg when no refusal was observed for 2 consecutive days, until the maximal feed intake was reached (about day 10 of lactation). From weaning (at 25 days of lactation) to the next heat period, sows were fed 4.0 kg·d^{-1} of the gestation diet (Table 1).

2.3 Measurements

Body status traits of sows were monitored during gestation and lactation. Body weight (BW), body condition score (BCS), backfat thickness (BF), and loin depth (LD) were recorded individually at days 0 (d0), 28 (d28), 60 (d60), 90 (d90), and 110 (d110) of gestation and at weaning (dW). The changes in body condition during gestation (d110-d0) and from day 0 until weaning (dW-d0), known as the global balance, were also calculated. The BCS was always evaluated by the same person on an ordinal scale from 1 (very thin) to 5 (very fat) according to Bonde et al. (2004); BF and LD were measured by ultrasound scan equipment with a linear probe (SF1, Wireless Backfat and Loin Depth Scanner, Sonivet, Beijing, China) at the P2 position (last rib, 65 mm from the center line of the back). The measurements were repeated three times, and their average was used for further calculations, following previous protocols (Maes et al., 2004). The productive performance per sow (litter size and weight) was recorded at farrowing. Live born piglets, stillborn, and mummies were recorded and weighed within 24 h after birth. Piglets of litters born from 9:00 to 18:00 h were individually weighed the following day in the morning (at 7:30 h), while those born during the night were weighed at 15:00 h. The mortality rate at birth (percentage of stillborn in relation to total born) and within-litter birth weight coefficient of variation were calculated. The number of dead piglets during the first three days was also recorded to calculate the mortality rate at 72 h as a percentage of live piglets at birth. In addition, piglets culled at birth, as they are unlikely to survive and unable to reach market weight at the same rate as normal-weight littermates (low vitality, crushed but still alive, malformations, cannibalism, etc.), and piglets born weighing less than 0.8 kg were recorded to calculate their proportions within each litter. Reproductive parameters, such as the conception rate and the farrowing rate, were calculated within treatment. The conception rate was calculated as the proportion of sows that did not return to estrus relative to the total number of sows inseminated, while the farrowing rate was calculated as the proportion of inseminated females that farrowed. The weaning-to-estrus interval (WEI) of sows in the next reproductive cycle, defined as the interval from weaning to the first standing heat reflex, was also determined. Sows were checked for estrus twice a day (at 08:00 and at 16:00 h) using the back-pressure test in the presence of a mature teaser boar. They were inseminated twice by a post-cervical artificial insemination method, 16–24 h after onset of standing heat and again 24 h later; considering the first insemination as day 0 of gestation.

2.4 Blood Samples and Hormone Analysis

Blood samples, from ten sows per treatment, were taken from the cranial vena cava in sterile tubes without additives (Vacuette®, Greiner Bio-One, Kremsmünster, Austria), at the day of first artificial insemination (d0) and at days 28, 60, and 110 of gestation. Sows within each treatment were chosen according to their BW as being close to the average weight of the treatment at day 0; the same sows were subsequently bled over time. The serum was separated by centrifugation (1600 ×g for 10 min), and it was then frozen at □ 80 ◦C until further analysis of leptin, progesterone, insulin, and cortisol. The serum samples were submitted to the Interdisciplinary Laboratory of Clinical Analysis of the University of Murcia (Interlab-UMU, Spain) and were analyzed in duplicate with an automated chemiluminescent immunoassay (Immulite System, Siemens Health Diagnostics, Deerfield, IL, USA). Leptin concentration was analyzed at days 0, 28, 60 and 110 using RIA (Multi-species Leptin Assay Kit, Linco Research, St. Louis, MO, USA), previously validated for porcine plasma (Govoni et al., 2005). Paired differences in leptin relative to the initial concentration (d0) were calculated taking into account the sow effect ([Leptin]d28- [Leptin]d0, [Leptin]d60-[Leptin]d0, and [Leptin]d110-[Leptin]d0). The other hormones were determined at day 28. Progesterone concentrations were analyzed using the Immulite System (Siemens Health Diagnostics, Deerfield, IL, USA). Insulin was determined by an Enzyme- Linked Immuno Sorbent Assay (ELISA) Kit (Mercodia, Porcine Insulin ELISA ref. 10–1200-01, Winston Salem NC, USA). Cortisol was analyzed with an automated chemiluminescent immunoassay (Immulite System, Siemens Health Diagnostics, Deerfield, IL, USA). All methods showed an inter- and intra-assay coefficient of variation lower than 15%.

2.5 Statistical analysis

Data were analyzed using SPSS version 24.0 for Windows (SPSS Inc., Chicago, IL, USA). Body measurements of sows at different days throughout the study, and their changes in gestation and lactation (d110-d0 and dW-d0), were analyzed through an ANOVA model using the General Linear Model procedure. For the productive performance of sows at farrowing, an ANOVA model was also used. Both models included treatment (feeding level in early gestation) and parity order (primiparous vs. multiparous) as main factors as well as their first-order interaction. The value of each body variable measured at day 0 and the total born were used as a covariate for body status measurements and the productive performance of sows (litter data), respectively. Piglet mortality rates, the proportions of piglets culled at birth and of piglets of low birth weight, and the reproductive rates of sows were coded as binary variables within litter (sow) and treatment, respectively, and then analyzed by logistic regression. Therefore, a binomial distribution (either the number of events occurring in a set of trials or a binary response) with a logit model was fitted to evaluate them, where treatment, parity order, and their first-order interaction were used as dependent variables. Furthermore, correlations by Spearman rank correlation analysis were examined for ordinal categorical variables, such as the number of piglets dead at 72 h, the number of piglets culled at birth, and the number of low-weight piglets within litters. For hormone analyses, paired differences in leptin within sow relative to the initial concentration (d0) were calculated to ignore the intra-individual variability and analyzed with a model including treatment and parity order as main factors as well as their first-order interaction. The same model was used for the rest of the hormones (progesterone, insulin, and cortisol), which were measured only at day 28. The sow (or litter) was considered the experimental unit. Results are presented as least square means or as percentages (reproductive rates and piglet mortalities). A pairwise comparison of means was performed by using the least significance difference (LSD) test. The significant value was set at $p \leq 0.05$, while $0.05 < p \leq 0.10$ was considered as a tendency.

3. RESULTS

3.1 The Body Status and Body Changes of Sows

At the beginning of the study (day 0), there were no differences in sow BW and BCS among dietary treatments ($p > 0.05$) (Fig. 1A). However, differences in both traits were found at day 28 and throughout gestation ($p \leq 0.05$). Sows fed the highest level of feed (III) showed a higher BW at 28 and 60 d of gestation than those fed the lower feeding levels (I and II). On days 90 and 110 of gestation and at weaning, sows fed Treatment III had also a higher BW than those fed Treatment I, although without differences compared to sows fed Treatment II. Sows fed Treatment III had a higher BCS than sows fed Treatments II and I at days 28, 60, and 90. There were also differences in BCS between Treatments I and II at day 28. However, no differences between Treatments I and II were found from day 60 onwards. At 110 d of gestation and at weaning, there were also differences in BCS between Treatments I and III, whereas Treatment II showed intermediate scores. The BF and LD results of the treatments were not different at day 0 ($p > 0.05$) (Fig. 1B). On day 28, sows fed Treatments III and II had a higher BF thickness than those fed Treatment I ($p \leq 0.05$). These differences were found between Treatments I and III ($p \leq 0.05$) at days 60, 90, and 110 and at weaning, while the BF of sows fed Treatment II was not different from the above-mentioned treatments ($p > 0.05$). For LD at day 28 of gestation, sows fed Treatment I showed a lower average than those fed Treatments II and III ($p \leq 0.05$). On day 60, these differences were found in sows fed Treatments I and III, but there were no differences between Treatments I and II. On day 90, Treatment I resulted in a lower LD than Treatment III. However, no differences in LD were found between treatment groups at day 110 and at weaning. Similar results to those described above were partly reflected in body changes (Table 2). From day 0 to day 110 of gestation, sows improved their body status. The highest BW gain, BCS, and BF thickness were found in sows fed Treatment III compared to those fed the usual restricted feeding level (I), whereas sows fed Treatment II showed intermediate averages. As for changes in LD during gestation, there was a trend ($p = 0.087$) in which sows fed Treatment III showed the greatest LD. When results were examined by parity, BW and LD changes in primiparous sows were higher than in multiparous sows ($p \leq 0.05$). In addition, no interaction effects between feeding level and parity were found for any variable mentioned above ($p > 0.05$). Regarding changes during the global period (including lactation losses), differences among treatment groups were found ($p \leq 0.05$); sows fed Treatment III showed the best balance in BW, BCS, and BF. Furthermore, there were differences in BW and BF thickness according to parity order ($p \leq 0.05$). While primiparous sows showed higher weight gain compared to multiparous sows, they also had higher losses in BF. There were no significant interactions for body changes during the global period between feeding level and parity.

3.2 The Productive Performance of Sows: Litter Traits

No differences among dietary treatments were found in the total born at farrowing ($p > 0.05$) (Table 3), nor when piglets at birth segregated into live born, stillborn, and mummies ($p > 0.05$). However, a tendency for more live born piglets and fewer stillbirths was found in sows fed Treatment III ($p = 0.069$ and $p = 0.071$, respectively). In addition, the number of live born piglets was higher among primiparous sows than among multiparous sows ($p \leq 0.05$), while a reverse trend was found in mummies ($p = 0.070$). There were no differences in any variable of litter weight analyzed ($p > 0.05$), either between treatment groups or between parity order. Moreover, there were also no interaction effects between feeding level and parity order on litter size or litter weight ($p > 0.05$). No differences in mortality rate at birth were found among dietary treatments (Table 3), while litters from sows fed at higher feeding levels (II and III) had a higher mortality at 72 h compared to those fed at the lowest feeding level (I) ($p \leq 0.05$). An unfavorable effect was also found in litters fed Treatments II and III on the percentage of piglets culled at birth and those weighing less than 800 g ($p \leq 0.05$). The mortality rate at 72 h included the rate of piglets culled at birth, so the number of piglets dead at 72 h was positively correlated with both the number of piglets culled at birth and the number of low-weight piglets ($p < 0.001$) (Spearman rank correlations of 0.759 ± 0.052 and 0.535 ± 0.077, respectively). In addition, piglets culled at birth were correlated with low-weight piglets ($r_s = 0.669 \pm 0.068$, $p < 0.001$). When results were examined by parity order, primiparous sows tended to have a higher piglet mortality at 72 h than multiparous sows ($p = 0.086$), and there was a significant interaction effect between feeding level and parity order on the mortality rate at 72 h, the piglet culling rate, and the rate of low weights at birth. Differences between primiparous and multiparous sows on the mortality at 72 h were observed in Treatment I. However, on the piglet culling rate at birth, these differences in parity order were found in sows of Treatment I and III. On the low weight piglet rate, differences between primiparous and multiparous were only found in sows of Treatment II (Supplementary Fig. 1). Despite the mortality results described above, no differences in litter size at 72 h were found for any of the factors analyzed (Table 3).

3.3 Reproductive Performance and Serum Hormonal Concentrations

There were no differences ($p > 0.05$) among the three different levels of restricted feeding applied in early gestation in terms of reproductive rates, either the conception rate or the farrowing rate ($p > 0.05$) (Table 4). Neither an effect of parity order nor a first-order interaction with the feeding level was found in regard to reproductive rates ($p > 0.05$). Similarly, no factor affected the WEI ($p > 0.05$), whose mode and median was 4 days in all treatments. Preliminary analyses of the serum leptin showed no differences among treatment groups at d0 ($p > 0.05$; data not shown). Paired differences in leptin (within-sow from the initial concentration at day 0) increased significantly as gestation progressed ([Leptin]d60-[Leptin]d0), returning to baseline values at d110 ([Leptin]d110-[Leptin]d0) (Fig. 2). In any case, no effect was found on leptin concentration among treatment groups ($p > 0.05$). Furthermore, no effect of parity order or first-order interaction with feeding level on paired differences in leptin was found ($p > 0.05$). Regarding the rest of the hormones (progesterone, insulin, and cortisol), measured at d28, none of the factors examined in this study was associated with their serum concentrations (Table 5), except for the first-order interaction for progesterone concentration ($p = 0.011$). The highest serum concentrations were found in multiparous sows fed at the intermediate feeding level (II), compared to primiparous sows in Treatment II, or in multiparous sows in Treatment I, while the other sows showed intermediate concentrations (Supplementary Fig. 2).

3. DISCUSSION

4.1 The Body Status and Body Changes of Sows

Sows require intensive nutritional management due to a genetic for prolificacy and a leaner body condition. A sub-optimal level of body reserves at weaning in hyper-prolific sows has been related to a lower productive and reproductive performance (Dourmad et al., 1996; Thaker and Bilkei, 2005; Lavery et al., 2019). Increasing feeding levels during gestation should preserve higher levels of body reserves at farrowing and at weaning. This study showed that a greater feeding level from 3 to 28 d of gestation in primiparous and multiparous sows increased body reserves throughout gestation. The weight gain of sows fed at the highest level was an increase of about 20% (+10.4 kg) compared to sows in the control group, which was reflected in the higher BCS (+0.48 points) and BF thickness (+1.43 mm). Furthermore, these improvements were also confirmed from a global point of view when accounting for lactation losses, where sows at the highest level maintained the differences compared to those in the control group (+9.49 kg, +0.49 points, and + 1.53 mm for BW, BCS, and BF, respectively). This is consistent with previous findings about increased levels of restricted feeding in early gestation (Virolainen et al., 2004; Hoving et al., 2011; Mallmann et al., 2020), where this feeding strategy improved BW gain and body reserves throughout gestation and at farrowing. Likewise, the extent of these differences in BW (+8.7 kg) and BF (+1.5 mm) compared to the standard feeding level was similar to that found by Hoving et al. (2011) in first and second parity sows with a higher feed intake (+30%, 3.25 $\text{kg}\cdot\text{d}^{-1}$) from day 3 to day 32 after insemination. More recently, Seoane et al. (2020), by increasing the feeding level during the first month of gestation (from 2.5 to 3.5 $\text{kg}\cdot\text{d}^{-1}$ of a diet with 2.11 Mcal $\text{NE}\cdot\text{kg}^{-1}$ and 13.85 g $\text{CP}\cdot\text{kg}^{-1}$), showed an increase in sow BW from previous weaning to farrowing, but this effect was not found between two successive weanings. In this line, Ren et al. (2017b), who changed feeding levels in three 7 d periods throughout gestation (by modifying the amount of maintenance energy intake from a common corn-soybean meal-based diet with 3.30 Mcal ME·kg^{-1} and 15.70 g CP·kg^{-1}), showed that both BW gain and BF change (from day 27 to day 109) increased linearly with increasing feeding levels; however, during lactation, BW gain and BF loss decreased and increased linearly, respectively, due to the reduction of feed intake. Thus, a negative relationship was described by linear regression between BF at farrowing and feed intake during lactation, mainly in the first week (Dourmad, 1991). Although it is well known that an excessive increase in BF levels at farrowing leads to a decreased feed intake during lactation (Mullan and Williams, 1989; Sinclair et al., 2001), this negative relationship could be not linear; and there is no agreement in the literature on the threshold level above which feed intake during lactation is reduced. In addition, this threshold may have changed in the current genotypes, as suggested by Cerisuelo et al. (2008). Current findings showed that BF losses during lactation ranged from 2 to 2.5 mm and BF never fell below 14 mm at weaning, regardless of the dietary treatment applied. In this line, data from several studies showed that BF levels below 16 mm at weaning may compromise the next reproductive cycle (Schenkel et al., 2010), although this threshold value could also be dependent on the sow genotype. On the other hand, global balance results also demonstrate that sows can gain BW and lose BF simultaneously, indicating the limited practical usefulness of BW changes to predict changes in BF. In addition, our study showed that weight gain and fat loss was more pronounced in primiparous sows compared to multiparous sows. These results are in agreement with Cerisuelo et al. (2009), who suggested that BW gain in pregnant gilts was mainly in the form of protein and less as fat. It is also worth highlighting the fact that the degree of improvement in body reserves throughout gestation was close to that of global changes, suggesting that the mobilization or loss of reserves during lactation was similar among treatment groups. Massive tissue mobilization could be expected from farrowing to weaning in sows with higher milk production (Strathe et al., 2017), which would suggest no differences between treatment groups; nevertheless, milk production was not measured in this study.

4.2 The Productive Performance of Sows: Litter Traits

Our results showed that the level of feeding after insemination had no influence on the productive performance of sows, assessed by litter size and litter weight. The average of the total born was 15.5, with no differences between treatment groups. In contrast, studies conducted to assess the impact of feeding during early gestation reported an associated increase in litter size. In this line, Hoving et al. (2011) found an increased litter size by 2 total piglets born in the plus-feed group (+30%) in comparison with those in the control group (3.25 kg·d^{-1} vs. 2.5 kg·d^{-1}, respectively). However, they reported that birth weight of piglets was similar in both groups, suggesting improved embryonic and/or placental development. Sørensen and Thorup (2003) also found significant effects on litter size (+0.5 piglets) when the daily energy supply to sows (49.9 vs. 31.2 MJ ME·d^{-1}) was higher in the first 28 d after insemination. Nevertheless, our data are in agreement with several studies that showed no effect of feeding levels during gestation on productive performance (Dwyer et al., 1994; Ren et al., 2017a, 2018; Mallmann et al., 2019). Furthermore, a higher level of feeding in hyper-prolific Large White gilts during early gestation (50 vs. 25 MJ ME·d^{-1}), 7 d after insemination, did not affect embryonic survival, size, or variability (Quesnel et al., 2010). There was also no effect of feeding level on any of the litter weight variables tested. This lack of effect of increasing feeding levels during early gestation is in line with findings on the average weight of piglets at birth (Hoving et al., 2011; Mallmann et al., 2019). Nissen et al. (2003) also found no effect on average piglet birth weight when sows were fed ad libitum at different stages of gestation (25–50 and 25–70 days of gestation) compared to a control group (restricted diet), suggesting no beneficial effect on fetal growth. However, several authors have shown that increasing feeding levels during short periods throughout gestation or in late gestation increased piglet birth weight linearly or quadratically (Cromwell et al., 1989; Ren et al., 2017b, 2018). Consequently, heavier piglets are generally expected to be associated with higher levels of feeding during late gestation, when fetal growth occurs. Thus, the time during which higher levels of feeding were applied in our study could have been determinant of a failure to influence fetal growth, since no differences in the average birth weight of piglets at birth were found. Differences in litter size and litter weight among studies could be related to either the sow genotype or the feeding program, i.e., the amount of feed (energy and/or nutrients supplied), the length of time of extra feed, and the gestation period in which a higher feeding level is applied. On the other hand, an increase above the standard restricted feeding level was associated with higher piglet mortality at 72 h, although no differences in litter size or litter weight were found among treatment groups. When disaggregating the reasons recorded for early piglet mortality, this finding was partly linked to a higher percentage of piglets culled at birth, which, in turn, was also related to the proportion of piglets weighing less than 800 g. This relationship between early mortality and the proportion of small piglets has been previously reported in the literature (Quiniou et al., 2002), where a lower percentage of survival until weaning was observed in piglets weighing less than 1 kg (with more stillbirths and more piglets dead within 24 h). Quiniou et al. (2002) also described an increased proportion of smaller piglets in larger litters and a simultaneous decrease in average piglet birth weight and litter homogeneity, which had negative effects on piglet viability. Thus, differences in early mortality and low-weight piglets of our study may also be in line with the trend found for the higher number of live born piglets from sows fed the highest feeding level (+0.5 piglets), as well as the greater numerical variation in within-litter weight of sows fed Treatments II and III compared to the control group (+1.8%). In fact, within-litter birth weight variation is an economically important trait due to its positive correlation with piglet losses from birth to weaning (Campos et al., 2012), which was also previously described in hyper-prolific Large White sows by Wolf et al. (2008). Furthermore, Moreira et al. (2020) recently reported, in a review and meta-analysis study, an increase in the coefficients of variation in piglet birth weight of around 4% for sows with high prolificacy compared to sows with low prolificacy.

4.3 Reproductive Performance and Serum Hormonal Concentrations

Our findings showed no differences among the three different levels of restricted feeding applied in early gestation in terms of reproductive rates ($p > 0.05$); nevertheless, the farrowing rate was lower, albeit non-significantly, in sows fed Treatment III in comparison with other groups (close to □ 8%). It is worth noting that Hoving et al. (2011) also found that the increased feeding level (+30%) numerically reduced the farrowing rate (□ 13%). In contrast, Virolainen et al. (2004) showed that a high feeding level during early gestation improved the percentage of pregnant gilts at day 34 post-insemination (54 vs. 27 MJ·d□ 1 for those 34 days using a commercial diet with 13 MJ DE·kg□ 1 and 14.5 g CP·kg□ 1) . However, this study was conducted with a reduced number of gilts (three groups of eight females) of lower weight (7–8 months old and 127 kg of BW), and no data on body status were reported. These results emphasize the importance of managing body reserves throughout gestation and at farrowing and their influence on fertility rates. In fact, further studies should examine how the farrowing rate can be affected by increased feeding levels as a function of body reserves in new leaner genotypes. Few studies on gestational feeding levels have provided information on the WEI. For instance, Whittemore et al. (1988) and Ren et al. (2017a, 2017b) found no differences between sows fed different feeding levels, while Dourmad (1991) reported that the WEI was extended in sows fed higher levels during gestation. Furthermore, Whittemore et al. (1988) described a positive association by regression analysis between readiness to rebreed (days from weaning to conception) and body fat at weaning, as well as with the BW of the sow at weaning. In this line, the different results could be explained by the extent of BW and BF gains during gestation, body reserves at farrowing and weaning, and the degree of body reserve mobilization. The current findings show that there were no differences in the effects of dietary treatment groups on blood metabolites measured at day 28: progesterone, insulin, and cortisol. When serum concentrations of different reproductive hormones were reported in studies on feeding levels in early gestation, they mainly referred to progesterone and LH (Virolainen et al., 2004). It is well known that the feeding level has a positive effect on the formation of luteal tissue and progesterone secretion in the pre-implantation period, which is essential for endometrial remodeling (Langendijk and Peltoniemi, 2013). Before implantation, these effects are independent of LH and probably triggered by metabolic signals, such as insulin and IGF-1, but the potential of nutritional strategies in these pathways remains to be investigated (Langendijk, 2021). On the other hand, sow stress (or elevated cortisol) before or during the pre-implantation phase is associated with reproduction disruption (Du et al., 2020). Thus, there is evidence that stress may interfere with the release of LH at the pituitary level (Dobson and Smith, 2000). No effect was found on leptin throughout gestation, regardless of dietary treatment, sow parity order, or their interaction. To our knowledge, there are no data on the effect of the feeding level in early feed intake. In fact, leptin is recognized as a major regulator of fat mass and energy balance during gestation (Grattan et al., 2007). In gestation, the placenta is the main source of leptin, which is an important factor linking metabolic status to reproduction (Schneider, 2004). Prunier et al. (2001), who assessed two feeding levels from day 23 of gestation (high (H) vs. medium (M)) in primiparous sows, reported that leptin on days 4, 11, 18, and 25 of lactation was higher in H than in M sows. Regarding leptin concentrations, Saleri et al. (2015), monitoring this hormone in Large White×Landrace multiparous sows, found that plasma levels increased from day 72 of gestation and remained high until farrowing, reaching the highest concentrations at day 107 and at farrowing. These authors suggested that hyperleptinemia with gestational progression in restrictively fed pregnant sows confirms the presence of leptin resistance, which contributes mainly to allowing increased nutrient availability for the fetus. This increasing evolution of leptin concentrations throughout gestation are in line with those described by Superchi et al. (2019) in groups of sows with high and low BF, although no differences were found between them. However, the evolution described above differed from our results, as a higher concentration was found at mid-gestation (d60), and a lower concentration was found at days 0 (insemination) and 110 (pre-partum). These lower leptin levels in the peripartum period, also described by Papadopoulos et al. (2009), could be related to the negative energy balance of sows due to the increased energy requirements in the last 12 days of gestation (up to 60% according to Feyera and Theil (2017)). Therefore, the mechanisms by which leptin concentrations are modified in pregnant sows need to be investigated.

5. CONCLUSION

No clear productive or reproductive benefits of increasing the amount of feed in early gestation, other than an improvement in the body reserves of sows throughout gestation and at weaning, were found. Therefore, increasing the level of restricted feeding during early gestation to improve the short-term productive and reproductive performance of sows remains controversial. Further research is needed to establish which feeding strategy and what level of restricted feeding best fits the increasing demands of modern genotypes and to assess how a restricted feeding level could affect the viability or proportion of low-weight piglets. Supplementary data to this article can be found online at https://doi. org/10.1016/j.rvsc.2022.05.002.

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ETHICAL STATEMENT

This study was carried out according to the protocol approved by the Animals Experimentation Ethics Committee of the University of Murcia and the Authorities of the Region of Murcia (4 August 2017, No. A-13170805), and following the European Union guidelines for the care and use of research animals (Directive 2010/63/EU of the EU Parliament and of the Council of 22 September 2010 on the protection of animals used for scientific purposes).

RESEARCH DATA

Data sharing is not applicable to this article.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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Table 1. Ingredients and composition of diets (as-fed basis).

Item	Diets	
	Gestation	Lactation
Ingredients, %		
Barley	45.00	18.77
Wheat flour, 30% starch	18.00	12.00
Sunflower seed 28	12.00	2.95
Sunflower seed 35	-	0.88
Wheat	6.69	32.00
Corn	6.00	10.00
Sugar beet	5.00	2.50
Colza 34	2.11	-
Soybean meal 47% CP	2.00	14.57
Calcium carbonate	1.35	1.43
Calcium phosphate	0.40	0.71
Fat 3/5	0.40	2.25
Salt	0.35	0.20
Vitamin-mineral premix 0.3 FIT EC[1]	0.30	0.30
L-lysine	0.24	0.41
Sodium bicarbonate	0.11	0.66
L-threonine	0.05	0.18
DL-Methionine	-	0.10
L-Valine	-	0.09
Composition calculated, %[2]		
Net Energy, Mcal· kg^{-1}	2.18	2.35
Crude Protein (CP)	13.72	16.80
Lys	0.72	1.06
Ca	0.80	0.85
P	0.61	0.59

[1] Nutrients supplied per kilogram: Vitamin A, 4,000,000 UI; Vitamin D_3, 666,666 mg; Vitamin E, 13,333 mg, Vitamin B_{12}, 6.67 mg, Vitamin B_6, 666.00 mg; Vitamin K_3, 333.00 mg; Vitamin B_1, 333.00 mg; Vitamin B_2, 1.33 mg; Folic acid 666.00 mg; Nicotinic acid 6.66 g; Pantothenate, 3.00 mg; Biotin, 83.00 mg; Choline Chloride , 41.67 g; Anhydrous betaine 19.20 g; Iron (Iron sulphate monohydrate), 33.33 g; Manganese (manganese oxide), 10.67 g; Selenium E_2 (Sodium selenite), 100.00 mg; Zinc (Zinc oxide), 30.00 g; Copper (copper sulphate), 3.33 g; Iodine (potassium iodate), 333.00 mg.

[2] According to FEDNA (2010).

Figure 1. Effect of the feeding level in early gestation on body weight (BW, red color), body condition score (BCS, blue color) (Figure 1A), backfat thickness (BF, red color), and loin depth (LD, blue color) (Figure 1B) of sows at Days 0, 28, 60, 90, and 110 and at weaning (dW).

Figure 1A

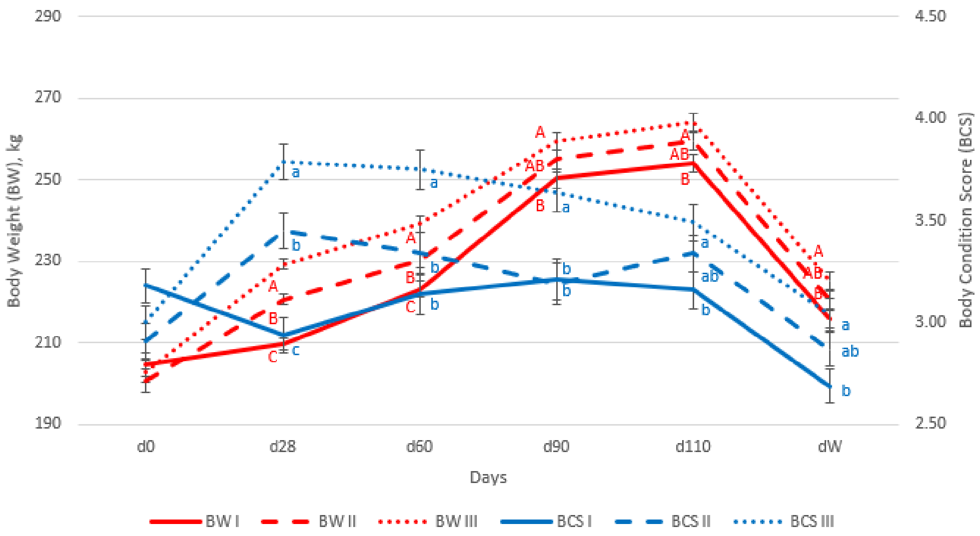
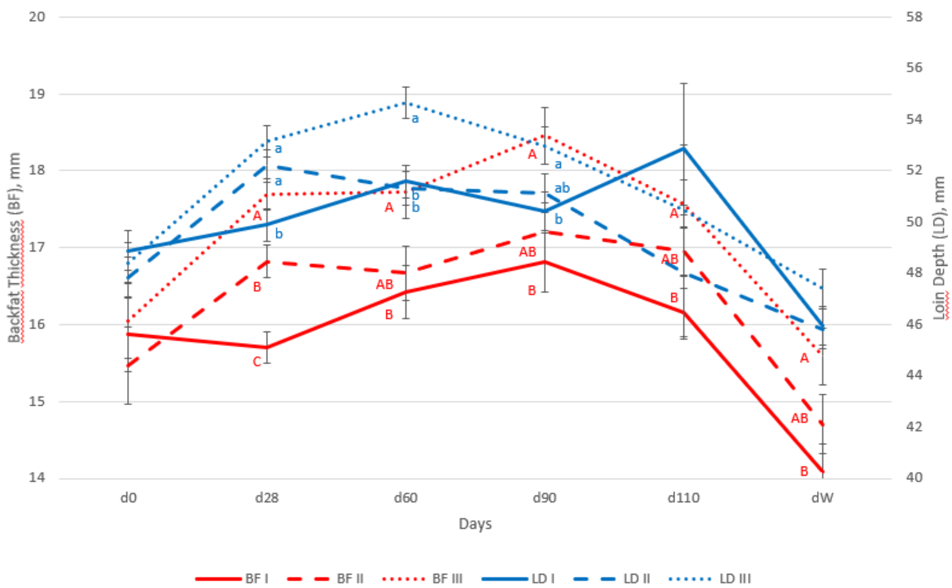
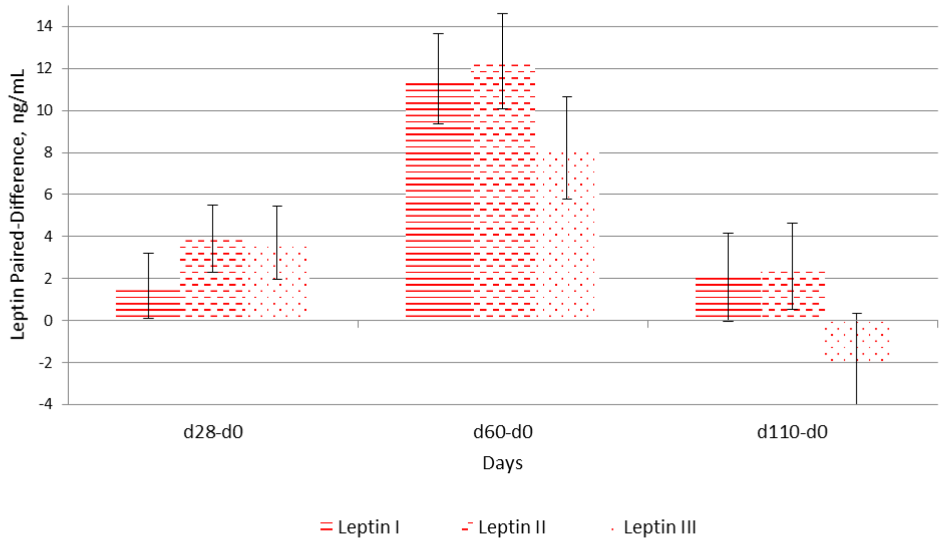


Figure 1B



Treatments I, II, and III: The feeding level from Day 3 to Day 28 of gestation was increased by 25 and 50% in Treatments II and III (dashed and dotted lines), respectively, in comparison to Treatment I (solid lines). Different capital and lowercase letters for left and right y-axis means, respectively, indicate significant differences at $p \leq 0.05$ between treatment groups within a day.

Figure 2. Effect of the feeding level in early gestation on paired differences in leptin concentration in relation to the initial concentration at Day 0 ($[Leptin]_{d28}$-$[Leptin]_{d0}$, $[Leptin]_{d60}$-$[Leptin]_{d0}$, and $[Leptin]_{d110}$-$[Leptin]_{d0}$).



Treatments I, II, and III: The feeding level from Day 3 to Day 28 of gestation was increased by 25 and 50% in Treatments II and III (bars with dashed and dotted lines), respectively, in comparison with Treatment I (bar with solid lines). A non-significant effect of the feeding level was observed ($p > 0.05$).

Table 2. Effect of the feeding level in early gestation and parity (primiparous vs. multiparous) on body weight (BW), body condition score (BCS), backfat thickness (BF), and loin depth (LD) changes in gestation (d110-d0) and the global balance of sows.

	Feeding level[1] (A)			**Parity**[2] (B)		**SEM**[3]	***P*-value**		
	I	II	III	P	M		A	B	AxB
Sample size, sows	37	36	39	50	62				
Gestation changes									
BW, kg	50.25^{b}	56.60^{ab}	60.65^{a}	62.25	49.42	2.293	**0.007**	**0.000**	0.894
BCS	0.00^{b}	0.38^{ab}	0.48^{a}	0.31	0.26	0.109	**0.006**	0.718	0.373
BF, mm	0.54^{b}	1.41^{ab}	1.97^{a}	0.99	1.62	0.329	**0.009**	0.101	0.884
LD, mm	0.04	0.18	2.14	1.65	-0.08	0.748	0.087	**0.048**	0.248
Global balance[4]	37	36	36	52	57				
BW, kg	12.67^{b}	18.35^{ab}	22.16^{a}	20.92	14.53	2.293	**0.015**	**0.018**	0.351
BCS	-0.46^{b}	-0.10^{a}	0.03^{a}	-0.22	-0.13	0.100	**0.002**	0.448	0.413
BF, mm	-1.61^{b}	-0.92^{ab}	-0.08^{a}	-1.58	-0.16	0.368	**0.015**	**0.001**	0.917
LD, mm	-2.52	-2.28	-0.92	-1.76	-2.05	0.808	0.324	0.762	0.293

[1] Treatments I, II, and III: The feeding level from Day 3 to Day 28 of gestation was increased by 25 and 50% in Treatments II and III, respectively, in comparison with Treatment I (2.5 $kg \cdot d^{-1}$).

[2] Parity: P (primiparous) and M (multiparous) sows.

[3] SEM: standard error of the mean.

[4] Changes from Day 0 until weaning (calculated as dW-d0).

Table 3. Effect of the feeding level in early gestation and parity (primiparous vs. multiparous) on sow productive performance, i.e., the litter size and litter weight of sows, and on mortality and low birth weight rates within litters.

	Feeding Level[1] (A)			**Parity**[2] (B)		**SEM**[3]	***P*-value**		
	I	II	III	P	M		A	B	A*B
Sample size, litters	38	37	39	52	62				
Litter size									
Total born, n	15.21	15.39	16.00	15.77	15.30	0.527	0.532	0.442	0.585
Live born[4], n	14.57	14.59	15.05	14.94	14.54	0.164	0.069	**0.036**	0.716
Stillborn [4], n	0.67	0.84	0.40	0.52	0.76	0.135	0.071	0.124	0.570
Mummies[4], n	0.28	0.08	0.07	0.06	0.22	0.076	0.103	0.070	0.543
Piglets alive at 72 h[4], n	13.99	13.37	13.60	13.79	13.52	0.133	0.158	0.312	0.456
Litter weight									
Total born weight[4], kg	22.92	22.46	22.14	22.62	22.39	0.466	0.497	0.663	0.351
Average live born weight[4], kg	1.53	1.50	1.47	1.50	1.50	0.031	0.402	0.949	0.308
Within-litter variation[4], %	19.92	21.70	21.77	21.27	21.00	0.009	0.275	0.800	0.277
Mortality and low birth weight rates[5]									
Mortality rate at birth, %	4.14	5.23	2.73	3.29	4.62	0.485	0.170	0.117	0.412
Mortality rate at 72 h, %	2.96[a]	8.26[b]	9.93[b]	7.59	5.20	0.693	**0.000**	0.086	**0.045**
Piglet culling rate at birth[6], %	2.12[a]	5.04[b]	5.46[b]	4.82	3.14	0.535	**0.029**	0.120	**0.010**
Low birth weight rate[7], %	2.85[a]	4.99[b]	6.76[b]	4.49	4.70	0.547	**0.013**	0.845	**0.050**

[1] Treatments I, II, and III: The feeding level from Day 3 to Day 28 of gestation was increased by 25 and 50% in Treatments II and III, respectively, in comparison with Treatment I (2.5 kg·d^{-1}).
[2] Parity: P (primiparous) and M (multiparous) sows.
[3] SEM: standard error of the mean.
[4] Adjusted mean: Total born was used as a covariate for these variables in the statistical model.
[5] Data analyzed by logistic regression.
[6] Piglets culled at birth, as they are unlikely to survive and unable to reach market weight at the same rate as normal-weight littermates.
[7] Piglets with low weight at birth (alive born weighing less than 0.8 kg)

Table 4. Effect of the feeding level in early gestation and parity (primiparous vs. multiparous) on sow reproductive performance: fertility rates and weaning-to-estrus interval (WEI).

	Feeding Level[1] (A)			**Parity**[2] (B)		**SEM**[3]	***P*-value**		
	I	II	III	P	M		A	B	A*B
Sample size, sows	42	41	47	61	69				
Conception rate[4], %	93.24	95.12	92.39	90.97	95.62	2.235	0.878	0.306	0.731
Farrowing rate[4], %	90.48	91.41	82.75	85.70	91.15	2.964	0.414	0.360	0.722
WEI, days	4.00	4.09	4.34	4.29	4.00	0.184	0.397	0.180	0.397

[1] Treatments I, II, and III: The feeding level from Day 3 to Day 28 of gestation was increased by 25 and 50% in Treatments II and III, respectively, in comparison with Treatment I (2.5 kg/d).
[2] Parity: P (primiparous) and M (multiparous) sows.
[3] SEM: standard error of the mean.
[4] Data analyzed by logistic regression.

Table 5. Effect of the feeding level and parity (primiparous vs. multiparous) on some hormonal parameters: the progesterone, insulin, and cortisol of sows.

	Feeding level[1]			**Parity**[2]		**SEM**[3]	***P*-value**		
	I	II	III	P	M		A	B	A*B
Sample size, sows	10	10	10	15	15				
Hormonal parameters									
Progesterone, $ng \cdot mL^{-1}$	15.40	18.97	17.32	16.57	17.89	1.206	0.133	0.358	**0.011**
Insulin, $\mu UI \cdot mL^{-1}$	48.39	57.91	43.48	54.47	45.39	4.729	0.460	0.346	0.222
Cortisol, $\mu g \cdot mL^{-1}$	2.67	2.86	2.94	2.73	2.94	0.279	0.919	0.712	0.475

[1] Treatments I, II, and III: The feeding level from Day 3 to Day 28 of gestation was increased by 25 and 50% in Treatments II and III, respectively, in comparison with Treatment I (2.5 kg/d).
[2] Parity: P (primiparous) and M (multiparous) sows.
[3] SEM: standard error of the mean.