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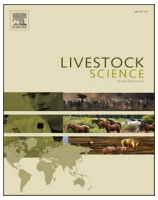

Dietary fibre supplemented pre-mating diets do not improve follicle development and litter characteristics in primiparous sows

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HIGHLIGHTS

- Dietary fibre affect feed intake and body protein mobilization during lactation.
- Dietary fibre did not reduce systemic 17β-oestradiol before ovulation.
- Dietary fibre did not affect follicle development and piglet birth weight.
- Metabolic hormone patterns after weaning showed the recovery of body mobilization.

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ABSTRACT

Piglet birth weight is an important factor for their survival and growth. As the pre-mating diet influences the sow's metabolic state, this may have an impact on follicle development after weaning and subsequent piglet birth weight. We investigated the pre-mating effect of dietary fibre (DF; sugar beet pulp (SBP) and microfibrillated cellulose (MFC)) on metabolic hormones and metabolites (IGF-1, non-esterified fatty acids (NEFA), creatinine, urea and leptin), follicle development, and litter characteristics at subsequent farrowing in 58 hyper-prolific primiparous sows farrowing 16.5 ± 0.4 piglets used in three consecutive batches. We supplemented commercial diets (CON) with SBP and MFC during the last week of lactation and the weaning-to-oestrus interval (WEI). We measured follicle diameters with ultrasound and collected preprandial blood samples at weaning, 3 days after weaning, and at oestrus. A tendency for higher average daily feed intake (ADFI; 5.69 *v.* 6.61 kg/day, $P < 0.07$) and significant lower backfat (BF; 1.1 *v.* 0.2 mm, $P < 0.05$) loss were observed in SBP sows than in MFC sows during one week before weaning. Total dietary fibre (TDF) intake during the last week of lactation was higher in SBP sows than in CON sows, whereas TDF intake in SBP sows was similar to MFC sows (775.0 vs. 900.6 vs. 840.9 g/day, respectively, for CON, SBP and MFC, $P < 0.05$). Creatinine concentration at weaning was higher in SBP sows than in MFC sows (162.9 *v.* 136.6 mmol/L, $P < 0.001$). Other hormones and reproductive parameters were not affected by pre-mating diets. At subsequent farrowing, there was no difference in litter characteristics ($P > 0.05$). In our study, the different types of DF fed pre-mating affected feed intake and body protein mobilization during lactation. However, the supplementation of DF before mating did neither improve follicle development nor litter characteristics in the hyper-prolific sows.

1. Introduction

Decreased mean piglet birth weight and increased within-litter birth weight variation in large litters (Wientjes et al., 2013; Han et al., 2021) are connected to higher pre-weaning piglet mortality (Milligan et al., 2002; Wientjes et al., 2012a). In sows, optimizing pre-mating diets can be one option to increase piglet birth weight and decrease within-litter piglet birth weight variation, as suggested previously (van den Brand et al., 2006, 2009; Peltoniemi et al., 2021). This is because pre-mating metabolic state affects not only follicle development (Costermans et al., 2020; Han et al., 2020) but also subsequent oocyte quality (Zak et al., 1997; Costermans et al., 2020), and eventually, piglet birth weight characteristics at subsequent farrowing (Wientjes et al., 2013; Han et al., 2021). Also, increased dietary fibre (DF) levels in pre-mating diets

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resulted in larger follicles, better oocyte quality and higher embryo survival in gilts (Ferguson et al., 2007; Weaver et al., 2013), and a larger litter size at subsequent farrowing in sows (Ferguson et al., 2004). This may be because DF could bind to circulating 17β-oestradiol (E2; Arts et al., 1991) and reduce circulating E2 concentration, and stimulate gonadotropin before ovulation, which is beneficial for oocyte quality and embryo survival (Ferguson et al., 2007). These improve oocyte quality and embryo survival which may be connected to larger mean piglet birth weight at subsequent farrowing (Ferguson et al., 2004). This is because oocyte and embryo development represent foetal and placental development in early gestation (reviewed by Peltoniemi et al., 2021), which largely affect piglet birth weight (van der Lende et al., 1990). Feed intake during lactation was negatively affected by inclusion of SBP in lactation diet. Krogh et al. (2017) reported previously that supplementation of sugar beet pulp (SBP; 120 g/kg) in lactation diets decreased feed intake in the 3rd week of lactation compared with a commercial diet. This decreased feed intake may result in higher body condition losses, which has been connected to impaired follicle development (Costermans et al., 2020; Han et al., 2020) and lower piglet birth weight at subsequent farrowing (Wientjes et al., 2013). Contrary to supplementation of SBP, supplementation of microfibrillated cellulose (MFC), which is a DF source (Serpa et al., 2016) and is derived from SBP, in pre-mating diets (the last week of lactation plus weaning-to-oestrus interval (WEI)) showed to numerically increase the total number of piglets born per litters (21 *v.* 19 for MFC and control sows; Han et al., 2021), without affecting feed intake and follicle development in these young sows (Han et al., 2020). Thus, the effect of different types of DF as pre-mating diets on sows' metabolic states and reproductive parameters remains unclear and needs to be investigated.

We hypothesized that supplementation of DF sources reduces E2 concentration and positively affects follicle development before ovulation, and thereby improves subsequent litter characteristics. Therefore, the objective of this study was to evaluate effects of the different types of DF supplemented pre-mating diets (the last week of lactation plus WEI) on feed intake during lactation, metabolic hormones and metabolites (IGF-1, NEFA, creatinine, urea and leptin), E2 and follicle development before ovulation in primiparous sows.

2. Material and methods

Experimental procedures were reviewed and approved by the Animal Experiment Board (ELLA; ESAVI/2325/04.10.07/2017) in Finland.

2.1. Animals and management

This experiment was conducted in March 2020 on a research herd in western Finland. Primiparous sows ($N = 58$; DanAvl, alternate cross between Landrace (L) and Yorkshire (Y), either YLY or LYL) were used in three consecutive batches ($N = 21$, $N = 22$ and $N = 15$, respectively).

One week prior to parturition, sows were transferred to the farrowing and lactation unit, where they were housed in individual farrowing crates. Within 2 days after farrowing, litters were standardized to 13–17 piglets based on number of functional teats. The average litter size at birth was 16.5 ± 0.4, at 1 week before weaning 13.2 ± 0.1 and at weaning 13.1 ± 0.1. After weaning at 29.7 ± 0.4 day of lactation, the sows were moved into the insemination units with individual stalls. From weaning onwards, oestrus detection was performed daily at 1100 and 1800 h by a farm technician using fence-line boar contact and sows were artificially inseminated once on every day of oestrus with a commercial dose of semen (2×10^9 sperm cells; DanAvl; Finnpig, Finland). Pregnancy check with ultrasound was performed by a farm technician at 35 days after the first insemination. Sows were then moved to the gestation unit with a group housing system (4–6 sows per pen). One week prior to parturition, sows were transferred to the farrowing and lactation unit.

2.2. Feeding and dietary treatment

In the farrowing and lactation unit, sows were provided liquid feed (1:3.35, feed to water ratio) and water *ad libitum*. Before farrowing and in the first 2 weeks of lactation, sows received a standard commercial lactation diet (9.2 MJ net energy (NE)/kg DM, 13.8% CP, 4.4% crude fat, 6.7% crude fibre and 0.8% lysine, Imetys Pekoni 1; Hankkija Oy, Hyvinkää, Finland) twice a day. The dry feed allowance before farrowing was 2.99 kg/day, and this was gradually increased to 6.89 kg/day during the first 2 weeks of lactation. After 2 weeks of lactation until weaning, sows received another commercial lactation diet (9.9 MJ NE/kg DM, 16.0% CP, 5.4% crude fat, 4.7% crude fibre and 0.95% lysine, Imetys Pekoni 2; Hankkija Oy, Hyvinkää, Finland) four times a day. After the first 2 weeks of lactation until treatment allocation, the dry feed allowance was 7.21 kg/day. At last week of lactation, sows were assigned to one of three dietary treatments given during the last week of lactation and during the WEI. Allocation to treatments was stratified based on body weight (BW) loss (kg) between farrowing and allocation, the number of piglets at allocation and the expected lactation length. During the last week of lactation1 week before weaning, control group (CON; commercial diet; $N = 19$) and microfibrillated cellulose group (MFC) sows ($N = 19$) received 7.73 kg/day of dry feed allowance. Of commercial diets, 50 g were replaced with 50 g of microfibrillated cellulose (MFC; Betulium® Microfibrillated cellulose, Espoo, Finland; Table 1) for MFC sows. Sugar beet pulp (SBP) sows ($N = 20$) were fed 7.81 kg/day of dry feed allowance, in which 520 g of commercial diets were replaced with 600 g of SBP-rich diet (Table 1), without affecting NE intake. During lactation, daily feed allowance of individual sows was reduced with 10% when feed residuals remained in the trough. During the WEI, CON sows were provided 4.79 kg/day of commercial gestation diet (9.1 MJ NE/kg DM, 12.3% CP, 3.7% crude fat, 7.3% crude fibre and 6.1 g/kg lysine, Tiineys Pekoni 1; Hankkija Oy, Hyvinkää, Finland). The MFC sows were fed 4.79 kg/day in which 50 g of commercial gestation diet was replaced with 50 g of MFC (Table 1) and SBP sows were fed 4.82 kg/day in which 570 g of commercial gestation diet was replaced with 600 g of SBP-rich diet (Table 1), without affecting NE intake. During the whole gestation period, all experimental sows had the same amount of feed allowance based on farm management system similar to that in Han et al. (2020). The experimental diets were analysed for DM (EU 152/2009), CP (Dumas methods), crude fat (EU 98/64), crude fibre (EU 92/89), NDF (AOAC 2002:04/ISO 16472:2005), ADF (ISO

Table 1.
Chemical composition of the commercial diets (CON), sugar beet pulp (SBP)-rich diet, and microfibrillated cellulose diet (MFC) of sows.

Item	CON lactation	CON gestation	SBP[1]	MFC[1]
Energy, MJ NE/kg DM[2]	9.9	9.1	8.6	
Analysed composition, g/kg, as-is basis				
DM, %	87.8	87.1	89.6	97.2
CP, g/kg	168	129	127	89
Crude fat, g/kg	51	32	42	3
Crude fibre, g/kg	51	73	152	199
NSP, g/kg	108	152	412	360
ADL, g/kg	17	17	23	65
TDF, g/kg[3]	125	179	435	425
NDF, g/kg	155	208	290	400
ADF, g/kg	42	86	159	250
Ca, g/kg	9.1	6.6	16.0	7.3
P, g/kg	5.5	3.5	3.3	0.7

NE = net energy, NSP = Non-starch polysaccharides, TDF = total dietary fibre.
[1] 600 g of SBP replaced the 520 g of CON lactation diet and 570 g of CON gestation, respectively. 50 g of MFC were replaced the 50 g of both CON lactation and gestation.
[2] Calculated value. The energy of MFC was not applicable, but its energy value was considered as similar to CON due to low supplementation level (50 g).
[3] Sum of NSP and ADL.

13906:2008), non-starch polysaccharides (NSP; similar to Jonathan et al. (2013)), acid detergent lignin (ADL; ANKOM method) and Ca and P (ISO 11885:2009). Total dietary fibre (TDF) intake was calculated as sum of NSP and ADL.

2.3. Body weight, backfat and loin muscle depth

Sows' BW, backfat thickness (BF) and loin muscle depth (LM) were measured at 1 day after farrowing, at 1 week before weaning and at weaning. Sows' BF and LM was measured at P2 on the right and left side of the sow (at 6 cm from the midline straight above the last rib bone) using a B-mode ultrasound with a 10.0 MHz linear array probe (MyLab One VET; Esaote, The Netherlands), similar to Han et al. (2020).

2.4. Follicle development, oestrus and ovulation

Trans-rectal ultrasonography with an 8-MHz linear array probe (MyLab One VET; Esaote, The Netherlands) was performed to assess follicle diameter on the day of weaning, 3 days after weaning and at 12-h intervals during oestrus until ovulation. The time interval between weaning and first onset of oestrus (standing response) was regarded as the WEI. The time of ovulation was defined as 6 h before the first scan when no pre-ovulatory follicles were found, and used to calculate the weaning-to-ovulation interval (WOI). The oestrus rate was calculated as the percentage of sows that showed oestrus by day 7 after weaning. Ultrasound clips were taken from one ovary only due to bilaterally synchronized ovarian function in sows (Soede N. M., unpublished results). The clips were exported in DICOM format and analysed using the DICOM viewer Horos (Version 3.3.2, available at www.horosproject.org). Follicle diameter was determined as the mean of the five largest follicles. The largest measured follicle diameter of the five largest follicles during oestrus was defined as the follicle diameter at ovulation.

2.5. Blood sampling

All blood samplings were taken from the *vena coccygea* 30 min before feeding. Blood samples for IGF-1, NEFA, creatinine, urea and leptin were taken at 1 week before weaning, weaning, 3 days after weaning and at the second day of oestrus, whereas the blood samples for 17β-oestradiol (E2) were collected on the day of weaning, 3 days after weaning and on the second day of oestrus. The samples for IGF-1 were collected into 3-ml EDTA tubes (VACUETTE® K2EDTA, Greiner Bio-One Italia, Cassina de Pecchi, Italy), immediately placed on ice and centrifuged at 1710 × g for 10 min at 4 °C. Non-esterified fatty acids, creatinine, urea, leptin and E2 were collected into 3-ml serum tubes (VACUETTE® TUBE, Greiner Bio-One Italia, Cassina de Pecchi, Italy) and then incubated for 1 h at 4 °C and centrifuged at 1710 × g for 10 min at 4 °C. Both plasma and serum samples were stored at -20 °C until further analysis

2.6. Blood analysis

Sensitivity and intra- and inter-assay coefficients of variation for IGF-1, NEFA, creatinine, urea, leptin and E2 were presented in Supplementary Material S1.

Plasma IGF-1 concentrations were analysed using a commercial kit (IRMA IGF-1 A15729®; Immunotech, Marseille, France) after extraction of the samples with ethanol and HCl, as described in Han et al. (2020). For the NEFA analysis, a commercial kit (Randox NEFA kit; Randox Laboratories Ltd., Crumlin, UK) was used. Creatinine and urea were analysed using the same commercial kit (Konelab™ / T Series CREATININE (Enzymatic) 981896, Thermo Fisher Scientific, Vantaa, Finland). Leptin concentration was analysed using a commercial kit (Multi-Species Leptin XL-85K, EMD Millipore Corporation, Billerica, MA, USA). Serum E2 concentrations were analysed by using an Ultra-sensitive Estradiol RIA (Beckman Coulter, Brea, CA, USA) with ether extraction. One millilitre of plasma sample was extracted with 5 ml of diethyl ether (AnalR Normapur PDH, Prolabo, Leuven, Belgium). Extraction was repeated twice. Dried extracts were re-suspended into 200 μl of 0.1% gelatine in PBS, and E2 was measured by using the above-mentioned commercial kit.

2.7. Litter characteristics

At subsequent farrowing, the total number of piglets born per litters was calculated by summing the number of live born and stillborn piglets. Within 12 h after birth, all live born and stillborn piglets were weighed individually, and SD and CV of birth weight were calculated for these piglets. The proportions of piglets weighing $< 1\,000$ g and $> 1\,800$ g in the same litters were calculated. We discarded one sow (MFC) who had two piglets and one sow (SBP) who died during gestation from the analysis.

2.8. Statistical analysis

SAS 9.4 (SAS Institute Inc., Cary, NC, USA) was used for statistical analyses of all data. Normality of the parameters was checked with UNIVARIATE procedure using the Shapiro-Wilk test. Normally distributed parameters (body condition during lactation, feed intake, follicle diameter, IGF-1 concentrations, total number of piglets born per litter, litter weight at birth, mean birth weight, and SD and CV of birth weight) were analysed with the MIXED procedure (Supplementary Material S2). Non-normally distributed parameters (oestrus and ovulation characteristics, E2, NEFA, creatinine, urea, leptin and proportions of piglets $\langle$ 1 000 g and piglets $\rangle$ 1 800 g) were analysed with the GLIMMIX procedure (Supplementary Material S3). A binomial distribution with a logit link function was fitted to the GLIMMIX procedure to evaluate the effects of treatment on oestrus rate and proportions of piglets $< 1\,000$ g and piglets $> 1\,800$ g. A gamma distribution with a log link function was fitted to the GLIMMIX procedure to identify the effects of treatment on WEI, WOI and oestrus-to-ovulation interval (EOI). In both models, treatment (CON, SBP, MFC) was used as a fixed effect, and batch (1, 2 and 3) and breed (YLY and LYL) were included as random effects. Significant differences between treatment were tested using the

Repeated measure was used in MIXED and GLIMMIX procedures to assess the effects of treatment (CON, SBP, MFC) on IGF-1 and on NEFA, creatinine, leptin and urea concentrations, respectively (Supplementary Material S4). In these models, the concentrations at 1 week before weaning were added as a covariate to account for pre-treatment differences. Tukey-Kramer procedure. Normally distributed parameters were presented as least square mean, and non-normally distributed parameters as means.

3. Results

3.1. Feed intake and body condition losses

During 1 week before weaning, SBP sows tended to have lower ADFI than MFC sows (5.69 *v.* 6.61 kg/day, $P < 0.07$; Table 2), whereas no difference in ADFI was observed between SBP and CON sows ($P > 0.05$). However, treatment did not affect ADFI during lactation ($P > 0.05$; Table 2). Higher TDF intake during 1 week before weaning was observed in SBP sows compared to CON sows, while TDF in SBP and MFC sows were similar (775.0 vs. 900.6 vs. 840.9 g/day, respectively, for CON, SBP and MFC, $P < 0.05$; Table 2). During the WEI, TDF intake in SBP sows was higher than CON and MFC sows (857.4 vs. 1021.8 vs. 869.7 g/day, respectively, for CON, SBP and MFC; Table 2). Sugar beet pulp sows had higher BF loss during 1 week before weaning than MFC sows, whereas SBP sows were similar to CON sows (0.6 *v.* 1.1 *v.* 0.2 mm, respectively for CON, SBP and MFC$P < 0.05$; Table 2).

Table 2
Average daily feed intake (ADFI), body conditions and their changes in sows fed either commercial diet (CON), sugar beet pulp (SBP)-rich diet, or micro-fibrillated cellulose diet (MFC) during 1 week before weaning and the weaning-to-oestrus interval (WEI).

	Treatment				
	CON	SBP	MFC	RMSE	*P*-value
Number of sows, n	19	20	19		
ADFI					
During lactation, kg/day	5.31	5.21	5.38	0.15	0.72
Until treatment allocation, kg/day	5.18	5.19	5.16	0.19	0.98
During 1 week before weaning, kg/day	6.20^{A}	5.69^{B}	6.61^{A}	0.31	<0.07
TDF intake during 1 week before weaning, g/day	775.0^{b}	900.6^{a}	840.9^{ab}	38.9	<0.05
TDF intake during WEI, g/d[1]	857.4	1021.8	869.7		
Body weight					
After farrowing, kg	212	214	211	5	0.84
At treatment allocation, kg	202	205	201	6	0.80
At weaning, kg	195	193	197	5	0.85
Loss during until 1 week before weaning, kg	10	10	10	3	0.99
Loss during 1 week before weaning, kg	7	11	3	4	0.10
Loss during lactation, kg	16	20	13	3	0.24
Loss during lactation, %	7.7	9.5	6.1	2	0.24
Backfat					
After farrowing, mm	14.0	13.9	13.1	0.6	0.42
At treatment allocation, mm	11.4	11.3	10.5	0.6	0.37
At weaning, mm	10.8	10.2	10.3	0.6	0.66
Loss during until 1 week before weaning, mm	2.6	2.6	2.6	0.4	0.99
Loss during 1 week before weaning, mm	0.6^{ab}	1.1^{a}	0.2^{b}	0.2	<0.05
Loss during lactation, mm	3.2	3.7	2.8	0.4	0.33
Loss during lactation, %	22.4	26.3	21.7	2.7	0.41
Loin muscle depth					
After farrowing, mm	51.5	51.6	50.7	1.1	0.73
At treatment allocation, mm	46.5	46.2	45.7	0.9	0.82
At weaning, mm	45.6	44.1	45.4	0.9	0.44
Loss during until 1 week before weaning, mm	5.1	5.5	5.1	1.6	0.95
Loss during 1 week before weaning, mm	0.8	2.0	0.3	1.1	0.35
Loss during lactation, mm	5.9	7.5	5.3	1.4	0.38
Loss during lactation, %	11.1	14.0	10.2	2.5	0.40

TDF = total dietary fibre.
1 Sows received the same amount of feed allowance during the WEI within treatments.
a,b,c Means within a row without a common superscript are different ($P \leq 0.05$).
A,B Means within a row without a common superscript are different ($P > 0.05$, $P \leq 0.10$).

3.2. Metabolic hormones

Plasma IGF-1 and serum NEFA, urea and leptin were not affected by treatment ($P > 0.05$; Fig. 1A, B, D, E). Creatinine concentration at weaning was higher in SBP sows than in MFC sows (162.9 *v.* 136.6 mmol/L, $P < 0.001$; Fig. 1C), whereas CON sows had a similar creatinine concentration than SBP and MFC sows ($P > 0.05$; Fig. 1C). After weaning, creatinine concentrations were not affected by treatment (Fig. 1C). Within treatments, IGF-1 concentrations were similar throughout WEI (231.2 *v.* 249.0 *v.* 224.5 ng/ml, respectively, for weaning, 3 days after weaning and oestrus, $P > 0.05$; Fig. 1A). Both NEFA and creatinine concentrations were highest at weaning, decreasing thereafter ($P < 0.001$; Fig. 1B and C). Urea concentration increased from weaning until 3 days after weaning, then increasing again at oestrus ($P < 0.001$; Fig. 1D). Leptin concentrations were lowest at weaning, increasing thereafter ($P < 0.001$; Fig. 1E).

3.3. Follicle development and reproductive parameters

Similar E2 concentrations were observed between treatments ($P > 0.05$). 17β-oestradiol concentrations increased from weaning until 3 days after weaning, then decreasing at oestrus ($P < 0.05$; Fig. 2). Follicle diameters during the WOI, oestrus and ovulation characteristics and pregnancy rate at 35 days after the first insemination were unaffected by treatment ($P > 0.05$; Table 3).

3.4. Body condition gain during gestation and litter characteristics

During gestation (on average 118.4 ± 1.0 day; Table 4), sows gained on average 38.7 ± 2.8 kg of BW, 2.3 ± 0.3 mm of BF and 0.8 ± 0.7 mm of LM. Pre-mating diets did not affect these characteristics ($P > 0.05$; Table 4).

Sows farrowed on average 19.9 ± 0.6 total born (range 8–25), 19.6 ± 0.6 born alive (range 8–25) and 0.7 ± 0.1 stillborn piglets (range 0–3). The mean piglet birth weight was 1344 ± 33 g, and SD and CV of piglet birth weight were 271 ± 9 g and 20.7 ± 0.8%, respectively. Pre-mating diets did not affect these characteristics ($P > 0.05$; Table 4). When corrected for the total number of piglets born per litter, mean piglet birth weight in SBP sows tended to be lower than in MFC sows ($P = 0.12$; Table 4).

4. Discussion

Types of DF differently affected sows' feed intake metabolic state during late lactation. Sows fed SBP-rich diet had lower feed intake during lactation and higher creatinine concentration at weaning than MFC sows. However, there were no treatment effects on follicle development and litter characteristics.

4.1. Feed intake and metabolic state

Our primiparous SBP sows had lower feed intake than CON and MFC sows. Also, SBP sows had higher BF loss during 1 week before weaning than MFC sows, whereas BF loss during 1 week before weaning was similar to CON sows. Reduced feed intake in the SBP-rich diet was also observed during lactation. Krogh et al. (2017) observed that second parity sows fed SBP-rich diets had significantly lower feed intake than sows fed control diets on days 15–21 of lactation (6.1 *v.* 6.8 kg/day), whereas feed intake was similar between the two diets in late lactation (days to 22–28). Presumably, a reduced gastrointestinal flow of digesta by SBP (Bach Knudsen, 2001) in primiparous sows with lower gastric capacity than multiparous sow (Theil et al., 2012) can be a reason for lower feed intake during late lactation. Thus, supplementation with a high amount of SBP may reduce the feed intake during lactation especially in young sows. In our previous study, no effects of MFC on feed intake or reproductive parameters were detected in young sows (parity 1 and 2; Han et al., 2020 and 2021). Thus, the reason for the increased feed intake in MFC sows compared with SBP sows is not clear and warrants further research.

The higher BF loss in SBP sows during 1 week before weaning can be explained by their reduced feed intake. Surprisingly, the higher BF loss did not result in a higher NEFA concentration at weaning in SBP sows, although they did have a higher creatinine concentration at weaning. Similarly, in primiparous sows, Costermans et al. (2020) found similar NEFA concentration at weaning between sows that were full-fed and restricted fed during the last 2 weeks of lactation, but creatinine concentration was higher in the restricted-fed sows. Thus, in primiparous sows, high body mobilization due to low feed intake during lactation seems to be connected to protein utilization. Nevertheless, NEFA concentration at weaning in SBP sows tended to be higher compared to MFC sows in this study (0.523 *v.* 0.365, $P = 0.12$). Thus, it seems that lower feed intake in SBP sows results in both higher body protein and lipid mobilization during lactation than in MFC sows.

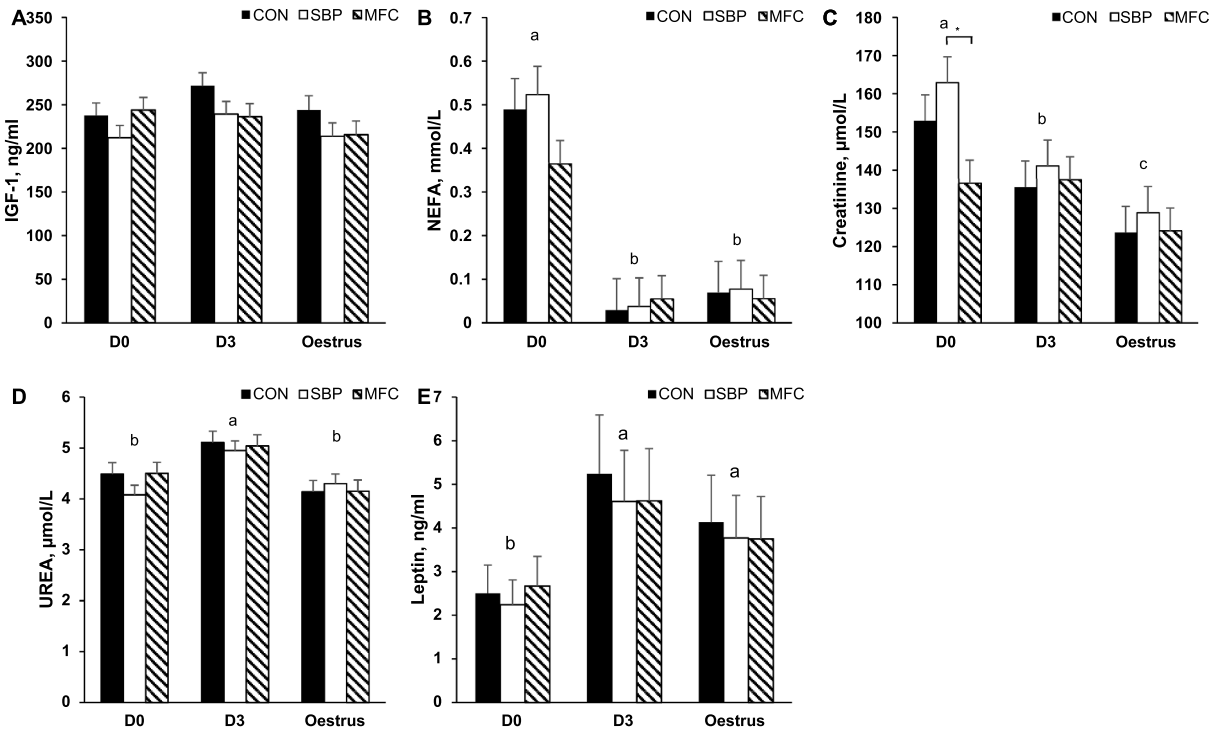

Fig. 1. Plasma Insulin-like growth factor-1 (IGF-1; A; ng/ml), and serum NEFA (B; mmol/L), creatinine (C; µmol/L), UREA (D; mmol/L) and leptin (E; ng/ml) profiles during the weaning-to-oestrus interval corrected for pre-treatment concentrations in sows fed either commercial diet (CON), sugar beet pulp (SBP)-rich diet, or microfibrillated cellulose (MFC) during 1 week before weaning and the weaning-to-oestrus interval. D0 = at weaning, D3 = at 3 days after weaning; *$P \leq 0.001$, [a,b,c]days with different superscript differ, $P \leq 0.0001$.

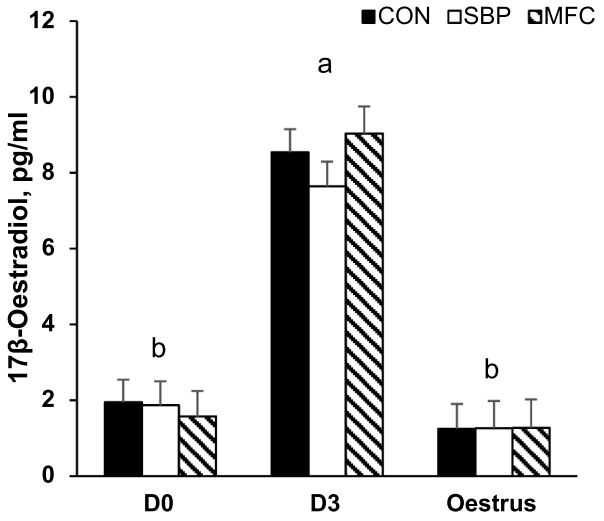

Fig. 2. Serum 17β-oestradiol (E2; pg/ml) concentrations during the weaning-to-oestrus interval (WEI) in sows fed either commercial diet (CON), sugar beet pulp (SBP)-rich diet, or microfibrillated cellulose diet (MFC) during 1 week before weaning and the weaning-to-oestrus interval. D0 = at weaning, D3 = at 3 days after weaning, [a,b,c]days with different superscript differ, $P \leq 0.0001$.

Table 3
Follicle development, and oestrus and ovulation characteristics of sows fed either commercial diet (CON), sugar beet pulp (SBP)-rich diet, or microfibrillated cellulose diet (MFC) during 1 week before weaning and the weaning-to-oestrus interval (WEI).

	Treatment CON	SBP	MFC	RMSE	*P*-value
Number of sows, n	19	20	19		
Follicle diameter, mm					
At weaning[1]	4.11	3.97	4.03	0.06	0.21
At 3 days after weaning[1]	6.68	6.35	6.52	0.16	0.32
At ovulation[1]	7.34	7.22	7.26	0.12	0.75
Oestrus and ovulation					
Oestrus rate ≤ 7 days, %	79.4 (15/19)	85.2 (17/20)	84.6 (16/19)	9.3	0.87
WEI, h[1,2]	101.6	105.9	109.3	2.7	0.15
WOI, h[1,2]	128.4	128.8	129.8	2.9	0.92
EOI, h[1,2]	27.0	23.0	22.0	2.7	0.38
Pregnancy rate at 35 days, %[3]	100	100[4]	100		1.00

WOI = weaning-to-ovulation interval; EOI = oestrus-to-ovulation interval.
[1] Of sows showing oestrus ≤ 7 days.
[2] Data were presented as mean.
[3] Of all sows inseminated.
[4] One sow culled after pregnancy check (SBP).

Interestingly, IGF-1 concentration at weaning was not lower than after weaning (at 3 days after weaning and oestrus). Most studies show that sows have the lowest IGF-1 concentrations at weaning, thereafter rapidly increasing (Mejia-Guadarrama et al., 2002; Wientjes et al., 2012b; Han et al., 2020) because sows are in the catabolic state during lactation and the somatotropic axis becomes uncoupled (reviewed by Lucy 2008). In the current study, IGF-1 concentration at weaning was higher than in our earlier study (230.8 v. 198.8 ng/ml in Han et al., 2020). This may be because BW loss during lactation in this study was lower (7.8 v. 12.2% in Han et al., 2020). Generally, 10–12% of BW loss is considered indicative of severe body condition losses and subsequent reduced reproductive parameters (Thaker and Bilkei, 2005). Thus, sows with mild body condition losses during lactation as in the present study, may have higher IGF-1 concentrations at weaning that do not subsequently increase.

The metabolic hormone patterns during WEI indicated a quick recovery of sows' body condition after weaning in this study. Non-

Table 4
Gestation length, body condition at farrowing, body condition gain during gestation and litter characteristics at subsequent farrowing of primiparous sows fed either commercial diet (CON), sugar beet pulp (SBP)-rich diet, or micro-fibrillated cellulose diet (MFC) during 1 week before weaning and during the weaning-to-oestrus interval.

	CON	HDF	MFC	RMSE	*P*-value
Number of sows, n	14	15	15		
Gestation length, day	118.2	118.4	118.6	0.4	0.61
BW, kg					
At farrowing	242	235	228	8	0.28
Gain during gestation	41	44	31	5	0.14
BF, mm					
At farrowing	13.2	12.9	11.8	0.6	0.26
Gain during gestation	2.1	2.9	1.8	0.6	0.34
LM, mm					
At farrowing	45.6	46.5	45.5	1.1	0.78
Gain during gestation	0.2	2.4	0.0	1.3	0.32
Farrowing rate, %	87.8	88.2	100	6.8	0.99
Litter characteristics					
Total born[1], n	19.7	18.6	20.1	1.3	0.58
Litter weight at birth, kg	26.2	24.1	26.9	1.4	0.25
Mean birth weight, g[3]	1369	1333	1395	100	0.67
SD of birth weight, g[3]	247	297	281	18	0.20
CV of birth weight, %[3]	18.7	21.3	21.0	2.2	0.33
Piglets < 1 000 g, %[2]	14.4	16.2	16.9	5.2	0.83
Piglets > 1 800 g, %[2]	6.6	2.5	7.4	3.9	0.34

All data presented as least square (LS) means, unless otherwise stated.
[1] Total number of piglets born per litter.
[2] Data presented as means.
[3] When corrected for total born, mean birth weight: 1370 *vs.* 1300 *vs.* 1409 g, P = 0.13; SD of birth weight: 247 *vs.* 286 *vs.* 278 g, P = 0.14; CV of birth weight: 18.7 *vs.* 22.1 *vs.* 20.6%, P = 0.33; respectively for CON, SBP, and MFC.

esterified fatty acids and creatinine concentrations, which are markers for lactation body lipid and protein mobilization (Mosnier et al., 2010), were high at weaning, decreasing afterwards. This indicates that sows restore their body lipid and protein during WEI. Restoration of sows' fat storage was also observed by the increasing leptin concentration after weaning (this study; Costermans et al., 2020).

4.2. Follicle development and litter characteristics

We did not find any treatment effect on sows' reproductive parameters after weaning and litter characteristics at subsequent farrowing, consistent with our previous study (Han et al., 2020 and 2021). We expected that the pre-mating DF would have a beneficial impact on sows' follicle development after weaning, as in earlier studies (Ferguson et al., 2007; Weaver et al., 2013), and thereby increase piglet birth weight and decrease within-litter birth weight variation similar to Ferguson et al. (2004). Ferguson et al. (2007) observed lower E2 concentrations in gilts fed a high fibre diet during the pre-mating period. Also, Ferguson et al. (2007) and Weaver et al. (2013) found a similar follicle size but better oocyte quality (higher metaphase 2) at 19 days of the first oestrus cycle and increased embryo survival at 28 days of pregnancy in gilts. Similarly, increased litter size was observed in sows fed SBP-rich diet (Ferguson et al., 2004). However, we did not observe differences in follicle diameter, E2 concentration and litter characteristics. This might be related to differences in sows' parity (primiparous sows *v.* gilts; this study and Ferguson et al., 2007; Weaver et al., 2013) and type of fibres (SBP *v.* lupin; this study and Weaver et al., 2013). Besides, multiparous sows (parity 1–7) were used in the study of Ferguson et al. (2004), while we used primiparous sows. Gilts never experience negative energy balance (NEB) and multiparous sows have low chances to have severe NEB during lactation, respectively. Strathe et al. (2017) showed that multiparous sows (parity > 2) had lower BW loss (%; 7.8 *v.* 10.1%, respectively for primiparous and multiparous sows) compared to primiparous sows because of higher ADFI during lactation (6.4 *v.* 5.4 kg/day). Because 10–12% of BW loss during lactation can be considered as severe NEB (Thaker and Bilkei, 2005), it seems that multiparous sows are not easily experienced severe NEB during lactation. Thus, the beneficial impact of DF as a pre-mating diet on follicle development and litter characteristics may be more effective in sows with mild NEB during lactation. On the other hand, pre-mating diets have a less (or no) impact on reproductive parameters in primiparous sows who easily experienced severe NEB during lactation, as shown before (Han et al., 2020 and 2021). Another possibility of lack of fibre on E2 concentration and reproductive parameters may be different duration of treatment period. In the study of Ferguson et al. (2004, 2007), the duration of treatment period was more than 3 weeks prior to oestrus, whereas we supplemented DF around 10 days before mating. Thus, longer feeding period of DF with sows did not experience severe NEB may be beneficial for reproductive parameters, which is not the case in this study.

In conclusion, higher SBP supplementation level negatively affected ADFI and body mobilization in hyper-prolific sows during late lactation compared to MFC, whereas no different body mobilization during 1 week before weaning was observed between CON and SBP, and CON and MFC. However, sows recover their body condition around the time of oestrus as indicated by metabolic hormone profiles. Neither SBP nor MFC affected reproductive parameters or litter characteristics at subsequent farrowing compared to the control group. Thus, our results imply that DF supplemented pre-mating diets do not impact on subsequent fertility in hyper-prolific primiparous sows.

Author contributions

T. Han: Conceptualization, Methodology, Data curation, Writing - Original draft preparation; S. Björkman: Methodology, Writing - Reviewing and Editing, Supervision; N.M. Soede: Methodology, Writing - Reviewing and Editing, Supervision; C. Oliviero: Methodology, Writing - Reviewing and Editing, Supervision; O.A.T. Peltoniemi: Methodology, Writing -Reviewing and Editing, Supervision.

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Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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Supplementary materials

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