Supplementation with omega-3 polyunsaturated fatty acids and effects on reproductive performance of sows

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1. Abstract

In studies in both humans and farm animals, the inclusion of omega-3 polyunsaturated fatty acids in the diet have been shown to have beneficial effects on many physiological processes including reproduction. The aim of this study was to examine the effects of supplementary omega-3 on sow reproductive performance and piglet survival. Salmon oil (1%) was fed to sows throughout gestation and lactation as a source of omega-3 and sows were followed through their subsequent parity when returned to a commercial gestation and lactation diet. It was hypothesised that sows fed omega-3 would show improved piglet survivability (+2%) and an increased litter size (one extra piglet born alive per litter) in the second experimental period compared with a soya oil supplemented control. Supplementation of 1% salmon oil across one parity increased the body weight of sows at weaning (p=0.01) and these sows maintained on average 4 kg ± 2.3 more over the lactation period than soya oil supplemented controls. Sows that were followed across a second un-supplemented reproductive period were heavier at farrowing (p<0.01) and weaning (p<0.05), had a higher condition score at farrowing and tended to have a higher condition score (p=0.063) and back fat at weaning (p=0.073) when they had received salmon oil in the previous reproductive cycle. However, salmon oil increased pre-weaning mortality by 2.4% in the first reproductive period (p<0.05) and significantly reduced litter weight at birth (*ca* 600g; p<0.05). Pre-weaning mortality was reduced by 3.4% in the second experimental period when supplementation of both salmon oil and the soya oil control had ceased (p<0.001). This effect tended to be greater for sows previously supplemented with omega-3. There was no effect on litter size, or the number of piglets born alive.

Supplementation of 1% salmon oil improved sow body weight at weaning and increased maternal stores across a second, un-supplemented reproductive cycle perhaps through effects on maternal nutrient partitioning. The increased mortality in the first experimental period and reduced mortality (across both treatment groups) when returned to a commercial diet suggests

a negative effect of omega 3 fatty acid supplementation on piglet survival when fed throughout gestation.

Key words: Salmon oil, sow, reproduction, piglet mortality, omega-3

2. Introduction

The modern sow shows improved prolificacy resulting in an increased litter size however there exists an antagonistic relationship with production metrics with decreased mean piglet birth weight, increased occurrence of stillbirths and an increase in pre-weaning mortality (Tanghe and De Smet, 2013). It is estimated that the proportion of low birth weight piglets (< 1 kg) in large litters (> 16 piglets) equates to a quarter of all piglets born (*ca* 23%) of which more than a tenth are still births (Quiniou et al., 2002). This represents both large economic losses to the industry and raises welfare concerns (Rutherford et al., 2013). There is much interest, therefore, in reducing the number of small birth weight piglets and improving both peri- and post-natal survival.

It is widely recognised in nutritional research of both humans and farm animals, that inclusion of omega-3 polyunsaturated fatty acids (PUFA), particularly those of marine origin (i.e. the long chain PUFA, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)), in the diet can have beneficial effects on many physiological processes (Millet and Delezie, 2013, Tanghe and De Smet, 2013). Omega-3 PUFA play a role in the molecular events that underpin reproduction, and although the exact mechanisms are unknown, it is believed that these may involve regulation of prostaglandin or cholesterol synthesis and endometrial gene expression (Abayasekara and Wathes, 1999, Wathes et al., 2007, Coyne et al., 2008). Omega-3 PUFA also play a role in immunity (Enke et al., 2008, Yaqoob, 2003). The supplementation of omega-3 PUFA to gestating sows may be able to enhance the general health of the sow and her piglets as well as improve piglet survivability, factors which are profitable to the pig industry (Tanghe and De Smet, 2013).

Previous studies have shown that supplementation of sows with omega-3 PUFA during mid-to-late gestation and subsequent lactation offer the potential to increase the number of pigs born alive per litter by 1 pig (Smits et al., 2011) and to reduce pre-weaning mortality by 2 % (Rooke et al., 2001). As follicle development occurs prior to weaning (Soede et al., 2011), omega-3 supplementation throughout lactation has the potential to enhance future reproductive success. The aim of this study was to examine the effects of supplementary omega-3 PUFA on sow reproductive performance and piglet survival. Omega-3 PUFA was fed to sows throughout gestation and lactation and sows were followed through their subsequent parity when returned to a commercial gestation and lactation diet. It was hypothesised that sows fed omega-3 would show improved piglet survivability in the first experimental gestation and an increased litter size in the second experimental gestation.

3. Methods

The experiment described below was performed at two sites (University of Leeds Pig Research Centre – Site 1 and Harper Adams University Farm Pig Unit– Site 2). Ethical approval for the protocol was granted by the Animal Welfare and Ethical Review Body at both sites.

3.1 Animals and Housing

3.1.1 Site 1

A total of 200 Large White x Landrace sows with an average body weight of 205.6 ± 51.75 kg (± SD) and parity of 4.1 ± 2.54 (range 1-10) were used in this study. Dry sows were housed in straw pens with feeding stalls (Period 1) and straw pens with dump feed (Period 2). During gestation, sows were fed individually (2.4 ± 0.2 kg) once daily in feeding stalls but when not eating were kept in straw yards in groups of 8 to 10. Each pen contained sows from both treatment groups. From approximately 3 days prior to farrowing until weaning each sow was housed in an individual farrowing crate with fully slatted floor. Sows received their allocated gestation ration until farrowing and then were fed twice daily according to a step up programme following farrowing, through to weaning (7.4 ± 0.6 kg per day). At weaning sows returned to a communal straw kennel area and were fed individually in stalls once daily until service. Sows were then followed through a second parity during which all received the same standard commercial diets and normal farm management. Cross fostering occurred within 24 hour of birth and where possible, within a treatment.

3.1.2 Site 2

At Site 2, 219 Large White x Landrace sows with an average body weight of 227.3 ± 56.13 kg and parity of 4.6 ± 3.03 (range 1-16) were used. Dry sows were housed in straw pens with open access feeding stalls with dunging passage. During gestation, sows were fed 3.4 kg per day for 8 days post weaning and then 2.6 ± 0.1 kg per day to farrowing. From 7 days prior to farrowing until weaning, sows were housed in an individual farrowing crate with fully slatted floor. Sows received their allocated gestation ration until farrowing and then were fed twice daily according to the Stotfold scale programme from farrowing, through to weaning (6.5 ± 0.7 kg per day). At weaning sows returned to dry sow accommodation and were fed once daily following the same regime as in Period 1. Sows were followed through a second parity where all sows received the same commercial diet and normal farm management.

3.2 Experimental design and treatments

The same trial diets were fed at both experimental sites. All diets were formulated to meet or exceed nutrient requirements of gilts and sows (BSAS, 2003). Sows were fed either a diet supplemented with 1% omega-3 PUFA derived from salmon oil (Optomega-50 (Anpario); N = 101 and 111 for Site 1 and Site 2 respectively) or a control diet containing 1% soya oil in the same carrier matrix (N = 99 and 108 for Site 1 and Site 2 respectively), from the start of the dry period (gestation), through lactation, to the next service (approximately 22 weeks; referred to herein as Period 1). For the second parity (Period 2), sows all received the same commercial gestation and lactation diets used in normal farm management at each site. Feed refusals were weighed daily. At both sites, seven consecutive batches of sows were used with an average of 28.3 ± 1.70 and 31.3 ± 1.38 sows per batch for Sites 1 and 2 respectively. The composition of the experimental gestation and lactation diets is shown in Table 1. Treatment groups were balanced for live weight, parity, body condition and fat (P2) and previous litter history at the start of the experiment.

[Insert Table 1 here]

3.3 Measurements and sampling

Sows were individually weighed and both body condition and P2 back fat (mm) were recorded at the start of the experimental period, farrowing, weaning for Period 1 and service (Site 1 only) farrowing and weaning for Period 2. Sow weights, body condition and P2 back fat were only recorded at service at Site 1. Body condition was measured by the same trained personnel on each site on a five-point scale, allowing for half point measures, where a higher number indicates a fatter animal (AHDB, 2017). The number of piglets born, number of piglets born alive, pre-weaning survival, weaning to service interval, litter weight at birth, litter weight at weaning and number of piglets weaned per sow were recorded.

3.4 Statistical analysis

Data was initially analysed by Select Statistical Services (Exeter, UK). Analysis was repeated and built upon in-house and the in-house analysis is shown below unless otherwise stated. For Period 1, data were analysed using the mixed linear model procedure of IBM SPSS Statistics 21 with sow as the experimental unit. A total of 174 sows were included from Site 1 and 217 from Site 2. Diet and parity were included as an interaction term with diet and parity as main effects. A random effect of batch nested within herd was also included under the assumption that sows within the same batch were likely to be more similar as well as sows from the same herd. Where possible, all weights, condition and fat measurements included the score at the previous time period (e.g. farrow weight at weaning) as a covariate in the model. Weaning age was included as a covariate for weaning weight. For mortality, the total number of piglets born and the change in the sow's body condition from farrowing to weaning were included in the model. Odds-ratio for mortality was performed by Select Statistics after fitting a logistic regression mixed-effects model to the data in R.

For Period 2, only sows which had successfully farrowed in both Period 1 and 2 were included. This resulted in the inclusion of 125 sows from Site 1 and 152 sows from Site 2. A total of 114 sows were removed from this second part of the analysis with 49 sows removed from Herd 1 and 65 from Herd 2. These sows were either not in heat, returned or were culled from the breeding herds. Data were again analysed using the mixed linear model procedure of IBM SPSS Statistics 21 with sow as the experimental unit. Models were run as for Period 1 above and the same covariates were used.

Interactions between diet and period were also examined for those sows that successfully farrowed in both Period 1 and Period 2 and the main effect of experimental time period were also explored. These models included diet and period as an interaction, with diet, period and parity as main effects. A random effect of sow nested within batch, nested within site was also included. Only those sows that farrowed in both Period 1 and 2 were included in this analysis resulting in the same number of sows as for the Period 2 analysis above.

Where an interaction, main effect or covariate was found to have no significant effect in the model, it was removed, and the model was re-run. Results were considered significant if $p < 0.05$ and a trend if $p < 0.1$. Data are presented as least square means ± SEM. All sows of parity 7 or over were grouped into the same category (7+) due to low replication.

4. Results

4.1 The effect of supplementing omega-3 on sow reproductive performance (Period 1)

In the first experimental period, during which sows were fed either an omega-3 supplement or a soya oil control, it was found that sows fed omega-3 were significantly heavier at weaning compared to the control group (234.8 *vs* 230.9 kg; ± 2.0; $p = 0.01$). The sows fed omega 3 retained on average *ca* 4 kg more live weight than those on the soya oil control ($p < 0.01$; Table 2). Although numbers born and born alive were similar for both treatments, the litter birthweight from sows fed omega-3 was significantly lighter than that from sows on the control treatment (19.3 *vs* 19.9 kg; ± 0.36; $p < 0.05$). Litter weight gain to weaning was similar for both treatments (66.2 *vs* 65.9 kg; ± 2.15 for omega-3 and soya oil treatments respectively). Litter weight gain increased with parity up to parity 3 and then decreased with each subsequent parity thereafter.

There was a significant effect of omega 3 supplementation on piglet mortality (16.6 *vs* 14.2 % ± 1.0; $p < 0.05$ for omega-3 and soya oil respectively). Supplementation with omega-3 increased mortality by 2.4% with both the number of piglets born ($p < 0.001$) and the change in the sow's body condition from farrowing to weaning ($p < 0.018$) having significant effects on the model. Higher numbers of piglets born increased the mortality rate and sows that maintained their body condition showed increased piglet mortality to weaning. Higher parity sows (7+) maintained body condition better than lower parity sows ($p < 0.05$) with the exception of parities 4 and 5 (Figure 1). This difference in mortality between treatments equated to an odds-ratio of 1.28. This means that if a sow not fed omega-3 would have a pre-weaning mortality of 10%, a supplemented sow from this study would be expected to have a pre-weaning mortality of around 12.5%. Effectively an increase of 25% (not percentage points).

Parity had a significant effect on all measures with the exception of piglet mortality, gestation length and wean to service interval. All data can be seen in Table 2. Parity tended to affect farrowing live weight and farrowing back fat ($P < 0.1$) both measures increasing with each subsequent parity. Supplementation of omega-3 did not affect feed intake during lactation with both treatment groups consuming on average 6.9 ± 0.167 kg per day ($p = 0.752$).

[Insert Table 2 here]

4.2 The carry-over effect of omega-3 supplementation into a second, un-supplemented, experimental reproductive cycle (Period 2)

Sows were followed through a second gestation and lactation after the treatment diets had been withdrawn to determine if there was any carry over effect of omega-3 supplementation when sows were returned to an un-supplemented commercial diet. Sows that were fed omega-3 during the previous reproductive cycle were found to be significantly heavier at farrowing than soya oil supplemented controls (290.0 *vs* 282.3 kg ± 3.13 respectively; $p < 0.01$; Table 3) and also had a higher body condition score (3.5 *vs* 3.3 ± 0.11; $p < 0.001$). These results, however, should be interpreted with caution as weight and condition could not be included as co-variates in their respective models as these were not measured for the second service period at Site 2 and body condition score is a subjective measure.

The sows that were previously supplemented with omega-3 were *ca* 3.5 kg heavier at weaning ($p < 0.05$) and tended to have a higher body condition score (3.3 *vs* 3.1 ± 0.07; $p = 0.063$). When returned to a commercial diet, sows fed omega-3 in the previous period lost a similar amount of live weight, back fat and body condition from farrowing to weaning as control sows. All data can be seen in Table 3.

There was an interaction between diet and parity for both litter weight at birth ($p < 0.05$; Figure 2a) and pre-weaning mortality ($p < 0.05$; Figure 2b). Gilts that were supplemented with omega-3 in Period 1 tended to have both a lower litter weight (19.5 *vs* 21.6 kg ± 0.60; $p = 0.079$) and higher piglet mortality (9.5 *vs* 5.7% ± 1.27; $p = 0.052$) compared to controls following an un-supplemented second parity. The opposite was shown for second parity sows, which showed significantly higher litter weight at birth (21.7 *vs* 19.2 kg ± 0.63; $p < 0.05$) and tended to show lower mortality (5.6 *vs* 11.0% ± 1.50; $p = 0.087$) when supplemented with omega-3 throughout the previous reproductive cycle. No differences were observed for parities 3 to 7 ($p > 0.1$).

[Insert Table 3 here]

4.3 The interactive effect of omega-3 supplementation across two reproductive cycles

The interactive effect of diet and time period, and the effect of time period alone were also examined. Only those sows that farrowed in both reproductive periods were included in this analysis. All data is shown in Table 4. There was a significant interaction between diet and period ($p < 0.01$) for weight at farrowing with sows fed omega 3 heavier than control sows at Period 2 (291 *vs* 283 kg ± 2.1 respectively; Table 4). Both groups had had similar weights during farrowing at Period 1 (258 kg ± 2.1). A similar pattern was shown for the sow's body condition at farrowing whereby significant interaction was also observed ($p < 0.05$). The body condition of the previously omega-3 supplemented sows was significantly higher than that of soya supplemented controls during Period 2 (3.6 *vs* 3.3 ± 0.06 respectively; $p < 0.05$). Again, these were similar in Period 1 (3.1 *vs* 3.0 ± 0.06).

There was a trend towards an interaction between diet and period for pre-weaning mortality ($p = 0.089$; Figure 3). There appeared to be a detrimental effect of omega-3 supplementation on piglet mortality in the first time period (15.5 *vs* 13.9 % ± 0.9) but at the second time period, when sows were returned to a commercial diet, mortality was similar, if not improved for the sows that had received omega-3 in the first reproductive period (10.7 *vs* 11.9 % ± 0.9 for omega 3 and the control diet respectively). Piglet mortality was significantly greater in the first experimental time period than in the second (14.7 *vs* 11.3 respectively; $p < 0.001$) irrespective of experimental diet.

Total litter weight was lighter in the first time period than in the second (19.5 *vs* 20.5 kg respectively; $p < 0.001$) with a trend towards an interaction between diet and period ($p = 0.066$). Omega-3 supplemented sows produced litters *ca* 700g lighter than control sows in the first reproductive period with similar weights in the second time period (20.5 kg for both groups).

Period had a significant effect on gestation length (and by association, wean to service interval) with an additional 0.3 days of gestation in Period 2 ($p = 0.01$). Sows maintained significantly more live weight between farrowing and weaning in Period 1 when compared to Period 2 (-25.5 *vs* - 36.5 kg ± 1.65; $p < 0.001$). However, they also lost more back fat (- 4.3 *vs* - 1.5 mm ± 0.24; $p < 0.001$). This is likely due to the fact that the P2 back fat measurement was significantly higher at farrowing for the sows in Period 1 than Period 2 to begin with (20.0 *vs* 19.2 mm ± 0.25; $p < 0.05$).

[Insert Table 4 here]

5. Discussion

The inclusion of omega-3 polyunsaturated fatty acids derived from salmon oil in the diet of sows is thought to improve reproductive performance but reports in the literature present conflicting results, some indicating benefit (Rooke et al., 2001, Smits et al., 2011) and others not (Posser et al., 2018). In addition, when a performance benefit was observed the type of benefit varied between studies. This may be due to the considerable variation in the level and period of feeding between different experiments making it difficult to identify the optimum period or inclusion level for feeding omega-3 PUFA. In farming practice, it is often only possible to feed one diet through gestation and one through lactation therefore in this experiment multiparous sows were fed omega-3 salmon oil at 1% of the diet throughout both periods for one parity and then followed for a further parity after the omega-3 feeding had ended. The salmon oil fed was incorporated onto a carrier for ease of mixing into the diets and therefore the control diet contained an equivalent amount of soya oil incorporated onto the same carrier to ensure that the carrier itself was not a confounding factor.

The initial hypotheses behind this experiment were that supplementation of sows with omega-3 PUFA from salmon oil throughout gestation and the subsequent lactation would increase number of pigs born alive per litter by 1 pig and reduce pre-weaning mortality by 2 %. In this experiment the number of piglets born alive was similar for both treatments, 13.6 versus 13.5 for omega-3 fed sows versus control fed sows respectively in the first parity and 13.5 versus 13.4 respectively in the second parity and therefore the first hypothesis must be rejected. Feeding omega-3 PUFA supplemented diets from service through gestation and then through to the following service did not improve numbers born alive in either that or the subsequent parity. This is in contrast to the findings of Smits et al. (2011) who found that supplementing sows with 3g omega-3 PUFA per kg diet during the last part of gestation and lactation increased the number of pigs born alive in the subsequent litter by an average of one pig, thought to be due to improved oocyte quality and embryo survival. However, omega-3 supplementation in the form of linseed oil has been shown to have a detrimental effect on both the quality of embryos and on related hormonal and fatty acid metabolism in the uterus of gilts prior to placentation (Chartrand et al., 2003). Prostaglandin (PG) E_2 and $PGF_{2\alpha}$ were both lower in the uterine fluid of gilts fed linseed oil compared to a hydrogenated tallow control which the authors suggested may be due to interference of the *n-3* PUFA with desaturase and/or cyclooxygenase enzymes required for PG synthesis. Bilby et al. (2006) observed no difference in oocyte quality when supplementing PUFA (vegetable or linseed oil) or MUFA (sunflower oil) to dairy cattle.

Soya oil was supplemented as a control in the current study. Soya oil contains PUFA, which can be classified into a subgroup of PUFA (including sunflower oil and corn oil) that are made up of MUFA and linoleic acid (LA) and has a *n*6-*n*3 ratio of 6.7 (Dubois et al., 2007). The lack of difference in litter size could perhaps be attributed to a similar action of the two oils.

Alternatively, it may be that the concentration of PUFA supplemented to the sow was unsuitable. Indeed, there are limited dose-response studies using fish oil in the literature with inconsistent experimental design (Tanghe et al., 2015) which makes determining a suitable inclusion rate difficult. Therefore, more dose response studies in this area may be of use. In addition to this, EPA and DHA are usually considered together as one entity. As there is evidence that they have different effects on cell function including gene expression and intracellular signalling pathways (Gorjão et al., 2009) future work in this area should consider separately the absolute and relative concentration of these omega-3 PUFAs. The availability and distribution of different PUFA sources to maternal and foetal tissue has also been shown to vary (Gázquez et al., 2017) and this is something that should be considered in future work.

Supplementation of omega-3 was also shown to have a negative effect on pre-weaning survival therefore the second hypothesis of this study must also be rejected. Supplementation of 1% salmon oil to the diet significantly increased pre-weaning mortality by *ca* 2.4% compared with a soya oil control in the first experimental period. This stands to directly influence the number of pigs weaned per sow per batch per farm per year, which is not only a critical performance metric for breeding units but a key influencer of a unit's financial viability. Interestingly, when sows were returned to a standard commercial diet pre-weaning survival increased significantly by *ca* 3.4% irrespective of diet. The effect was especially pronounced for those sows fed omega-3 in the previous reproductive period. The increased pre-weaning survival of piglets in Period 2 was observed across all sow parities which may suggest an un-controlled environmental or husbandry effect, or alternatively, the higher mortality in Period 1 may be a general effect of the carrier used to aid mixing of the oils into the diet. It is also possible that PUFA supplementation (irrespective of source) throughout gestation may have consequences for piglet survival.

Indeed, Shen et al. (2015) also showed a higher pre-weaning mortality when sows were fed omega-3 supplementation when compared to a control (additional corn starch), whereas olive oil supplementation reduced mortality. The authors also showed that fish oil increased susceptibility to oxidative stress in both sows and piglets compared to both olive oil and the control diet. Soya oil has also been shown to increase mortality compared to supplementation of medium chain triglycerides or coconut oil, thought to be due to lower glycogen stores (liver and muscle) in piglets from sows fed this treatment (Jean and Chiang, 1999). Replication, however, was low in both studies (n = 8 and n = 16 to 18 per treatment respectively). It is also of interest to consider whether the anti-inflammatory effects of PUFA are beneficial in a pathogen rich environment such as a commercial farm.

The effect of omega-3 supplementation on pre-weaning mortality did not reach significance when considering only those sows which farrowed across both experimental periods. Instead, there was a trend towards an interaction between diet and the experimental time period. The difference in the effect of omega-3 supplementation between the two sets of analysis is likely due to the removal of sows from both herds that were not followed through to the second experimental period when returned to commercial diets either because these sows were not in heat, returned or were culled from the breeding herds.

An interaction was observed during Period 2 between diet and parity for both pre-weaning mortality and average litter weight at birth whereby previous supplementation with omega-3 tended to be more detrimental for gilts and had a positive effect for sows that were supplemented during their second parity. No effect was seen for other sow parities. It must be taken into account that replication was low when considering each parity individually (57 gilts and 42 parity 2 sows continued through to Period 2) however, it would be of interest to explore the effect of omega-3 supplementation on gilts further.

Sows which received the omega-3 diets during the first trial parity tended to be fatter than sows receiving soya oil at weaning, and showed a better body condition score at both the first trial parity and the second trial parity where sows had been restored to the normal commercial diets fed on the unit. This suggests that the omega-3 supplementation may have changed sow metabolism and/or nutrient partitioning to allow more efficient use of nutrients and hence increased energy storage compared to the control sows. This effect continued even after omega-3 supplementation had been withdrawn with supplemented sows heavier at both weaning periods and at farrowing in Period 2 than those sows which had received the control diet. Omega-3 supplemented sows maintained significantly more body weight from farrowing to weaning. During lactation, sows mobilise body fat to meet the high associated energy demand. However, loss of body fat can have negative effects on subsequent reproductive performance (Thaker and Bilkei, 2005). In this case however the improved body condition and fatness of sows supplemented with omega-3 did not translate to improved piglet performance. It is likely that energy was partitioned from conceptus growth to maternal reserves during gestation hence resulting in lower litter weights at birth for sows supplemented with fish oil as observed in this experiment and as previously observed by other authors (Rooke et al., 2001, Eastwood et al., 2014).

Litter weight at weaning was not significantly different between treatments in this study, in contrast to that of Eastwood et al. (2014) but in agreement with Rooke et al. (2001) again highlighting that the improved body reserves of the sows at farrowing did not result in improved piglet performance. The lack of difference in weaning weight may be attributable to the treatments used. Both fish oil and soybean oil have been shown previously to increase weaning weight of piglets compared to an isoenergetic control diet that contained no oil (Jin et al., 2017). Therefore, the two treatments may both act on the same, currently unknown, mechanisms associated with piglet growth. Fish oil and soybean oil fed in combination (3% and 1% respectively) tended to increase piglet average daily gain in the first 7 days of life but were found to have no effect on gene expression in the liver or blood suggesting that feeding PUFA to gestating sows had no effect on metabolic programming of piglets (de Greeff et al., 2015) which may explain the lack of difference in litter weight at weaning observed in this experiment.

Arachidonic acid (ARA) is a precursor to the 2 series prostaglandins (PG) and has been shown to have a much higher concentration in foetal than maternal blood due to preferential selection between PUFAs for placental transfer (Haggarty, 2002, Tanghe and De Smet, 2013). Both EPA and DHA can decrease the synthesis of 2 series PG through competition for the same enzyme (prostaglandin H synthase) and/or by selective incorporation into the phospholipid membrane (Allen and Harris, 2001). It has been suggested that omega-3 supplementation may increase gestation length by reducing prostaglandins required for the induction of labour. Supplementation of omega-3 PUFA during pregnancy in humans has been definitively shown to reduce the incidence of pre-term labour through inhibition of PG synthesis (Middleton et al., 2018). However, in this study, there was no difference in gestation length between sows fed salmon oil and those fed soya oil although somewhat surprisingly gestation length increased by 0.3d in both treatment groups in the second experimental period when all sows were receiving commercial diets. This increase in gestation length in the second time period cannot be attributed to the cessation of omega-3 supplementation.

Interestingly, although the evidence is conflicting in the literature, the predicted reduction in ARA associated with omega-3 supplementation may reduce birthweight of piglets (reviewed by Tanghe and De Smet (2013)). Litter weight at birth was significantly lower for sows supplemented with omega-3 in Period 1 and significantly increased during the second observed period (for both omega-3 and soya oil supplemented sows) when sows were returned to a commercial diet. ARA concentration alongside the concentration of PGE_2 and $PGF_2\alpha$ may be something to be explored in future studies investigating the influence of omega-3 PUFA on sow reproductive performance, to determine the effect on prostaglandin synthesis and piglet birthweight as PGE_2 has previously been suggested to have a key role during the early stages of pregnancy on embryo development, reduced levels of which may impact both litter size and birth weight (Giguère et al., 2000). Supplementation of PUFA in the first half of gestation has been shown previously to increase the incidence of low birth weight piglets whereas supplementation of monounsaturated fatty acids (MUFA) has been shown to do the opposite (Laws et al., 2009) thought to be due to the partitioning of nutrients to placental development. Rooke et al. (2001) found that although supplementing salmon oil at 1.65% throughout gestation and lactation resulted in reduced individual pig birthweights it increased neonatal vitality resulting in a reduction in pre-weaning mortality (98 sows per treatment). In contrast, in the current experiment reduced litter weight was accompanied by a 2.4% increase in pre-weaning mortality in sows which had received omega-3 during gestation compared with sows which had received soya oil.

7. Conclusion

Feeding omega-3 fatty acids to sows during gestation negatively affected piglet survival and did not increase subsequent litter size but improved the body weight, condition and fatness of sows at weaning compared to controls.

Ethics approval and consent to participate

Ethical approval for the protocol was granted by the Animal Welfare and Ethical Review Body at both sites (University of Leeds and Harper Adams University).

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

KMcD contributed to analysing the data, interpreting the results and co-wrote the manuscript, SI provided the experimental data and specific management information from site 2, SJ formulated the experimental diets and contributed to study design, LJB contributed to the study design, development of the 2 oil products and contributed to writing of the manuscript, DC contributed to the study design, CE contributed to the study design and HMM led study design, data analysis, interpretation of the data and co-writing the manuscript. All authors read and approved the final manuscript

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Table 1 The composition and nutrient specifications of both the gestation and lactation diets for the control and omega 3 diets (% as-fed basis)

Treatment	B	A	B	A
	Dry sow Control	Dry sow Omega 3	Lactating sow Control	Lactating sow Omega 3
Raw Material	%	%	%	%
Barley	15.00	15.00	.	.
Wheat	35.52	35.52	53.43	53.43
Wheatfeed	36.86	36.86	4.42	4.42
Maize Germ	.	.	10.00	10.00
Bakery Meal	3.01	3.01	2.61	2.61
Soya Hipro GM	.	.	7.10	7.10
Sunflower meal	.	.	10.00	10.00
Phytase	0.25	0.25	0.25	0.25
Optomega 50 Salmon Oil [a]	.	2.00	.	2.00
Soy50 Fat Premix [a]	2.00	.	2.00	.
L-Lysine	0.13	0.13	0.66	0.66
DL-Methionine	.	.	0.02	0.02
Threonine	.	.	0.14	0.14
L-Tryptophan	.	.	0.01	0.01
Choline Chloride Sol 75%	0.03	0.03	0.03	0.03
Vitamin E 100	0.15	0.15	0.08	0.08
Sow premix [b]	.	.	0.10	0.10
Limestone Coarse	1.24	1.24	1.02	1.02
DCP	.	.	0.72	0.72
Salt	0.35	0.35	0.34	0.34
Sodium Bicarbonate	0.22	0.22	0.04	0.04
Soya Oil GM	0.25	0.25	2.03	2.03
Rouxminate	5.00	5.00	5.00	5.00
	------------	------------	------------	------------
	100.00	100.00	100.00	100.00
Nutrient Composition				
Oil B	4.62	4.62	6.46	6.46
Protein	11.50	11.50	15.21	15.21
Fibre	4.43	4.43	4.06	4.06
Ash	5.73	5.73	6.19	6.19
Salt	0.52	0.52	0.50	0.50
Calcium	0.83	0.83	0.96	0.96
Phosphorous	0.44	0.44	0.55	0.55
Sodium	0.25	0.25	0.20	0.20
Digestible energy	12.28	12.28	13.48	13.48
Vit A	10000.0	10000.0	10000.0	10000.0
Vit D3	1875.0	1875.0	1875.0	1875.0
Vit E	200.0	200.0	200.0	200.0
Lysine	0.45	0.45	0.89	0.89

[a] Salmon and soya oil supplements contained 50% oil and 50% carrier matrix so that each oil was supplemented as 1% of the diet.

[b] Vitamin and mineral premix included the following (per kg of diet): 10,000 IU Vitamin A (retinly acetate), 1875 IU Vitamin D_3 (cholecalciferol), 200 IU Vitamin E (alpha tocopherol acetate), 4mg Vitamin K (Hetrazeen), 1.5mg Vitamin B1 (Thiamine), 4mg Vitamin B2 (Riboflavin), 3.5mg Vitamin B6 (Pyridoxine hydrochloride), 15ug Pantothenic acid (calcium pantothenate), 20mg Nicotinic acid, 200ug Biotin, 2mg Folic acid, 15 mg Copper (sulphate), 1mg Iodine, 80mg Iron (sulphate monohydrate), 50mg Manganese (sulphate monohydrate), 0.25mg selenium (selenite), 100mg Zinc (sulphate monohydrate) and 100mg OXY-NIL® BPC Dry (BHT, propyl gallate, citric acid)

Table 2 Sow reproductive performance across the first experimental period where sows received a diet containing either salmon oil (omega-3, n = 199) or soya oil (control, n = 192) from service through to the subsequent service. Values presented are estimated marginal means. Significant values (p < 0.05) and trends (p < 0.1) are highlighted in bold.

	Diet			P value		
	Omega 3	Control	*SEM*	Diet	Parity	Diet*Parity
Farrowing live weight[a] (kg)	258.9	261.1	*3.26*	0.123	**0.068**	0.294
Farrowing back fat[a] (mm)	20.5	20.1	*1.17*	0.365	**0.070**	0.930
Farrowing condition score[a]	3.1	3.0	*0.16*	0.743	**0.002**	0.243
Weaning live weight[a] (kg)	234.8	230.9	*2.04*	**0.010**	**< 0.001**	0.238
Weaning P2 fat[a] (mm)	16.2	15.7	*0.83*	0.252	**< 0.001**	0.416
Weaning condition score[a]	2.9	2.8	*0.11*	0.426	**< 0.001**	0.179
Change in live weight (kg)	-23.7	-27.8	*2.28*	**0.008**	**0.046**	0.469
Change in back fat (mm)	-3.8	-4.6	*0.96*	0.152	**0.005**	0.330
Change in condition score	-0.22	-0.27	*0.14*	0.473	**< 0.001**	0.110
Gestation length (d)	115.5	115.2	*0.12*	0.324	0.488	0.451
Total born	14.9	14.9	*0.28*	0.895	**< 0.001**	0.940
Born alive[b]	13.4	13.4	*0.15*	0.803	**0.044**	0.817
Total litter wt[b] (kg)	19.3	19.9	*0.36*	**0.047**	**< 0.001**	0.258
Number weaned	11.1	11.2	*0.18*	0.342	**0.003**	0.458
Weaning age (d)	26.6	26.6	*0.13*	0.956	**0.002**	0.742
Litter wean wt[c] (kg)	85.1	86.0	*2.88*	0.517	**< 0.001**	0.317
Litter gain[d] (kg)	66.2	65.9	*2.15*	0.811	**< 0.001**	0.916
Mortality[e] (%)	16.6	14.2	*1.00*	**0.046**	0.332	0.695
Wean to service (d)	5.9	6.3	*0.43*	0.503	0.503	0.619

[a] Controlled for weight, condition or fat at the start of the experiment, [b] Controlled for total born, [c] Controlled for weaning age, [d] Controlled for total born and total weaned [e] Controlled for total born and the change in sows body condition

Table 3 Sow reproductive performance across the second experimental period where sows returned to an un-supplemented commercial diet that had previously received salmon oil (omega-3, n = 139) or a soya oil control (n = 138) throughout the prior parity. Values presented are estimated marginal means. Significant values (p < 0.05) and trends (p < 0.1) are highlighted in bold.

	Diet			P value		
	Omega 3	Control	*SEM*	Diet	Parity	Diet*Parity
Farrowing live weight[a] (kg)	290.0	282.3	*3.13*	**0.006**	**< 0.001**	0.497
Farrowing back fat[a] (mm)	19.1	18.2	*1.28*	0.100	**< 0.001**	0.260
Farrowing condition score[a]	3.5	3.3	*0.11*	**< 0.001**	**< 0.001**	0.398
Weaning live weight[b] (kg)	247.2	243.7	*2.03*	**0.043**	**< 0.001**	0.719
Weaning P2 fat[b] (mm)	18.0	17.5	*0.46*	0.188	**< 0.001**	0.692
Weaning condition score[b]	3.3	3.1	*0.07*	**0.063**	**< 0.001**	0.101
Change in live weight (kg)	-36.0	-38.0	*1.90*	0.264	**0.047**	0.573
Change in back fat (mm)	-1.14	-1.31	*0.73*	0.693	0.263	0.991
Change in condition score	-0.18	-0.20	*0.10*	0.752	**< 0.001**	0.060
Gestation length (d)	115.4	115.5	*0.13*	0.629	0.671	0.835
Total born	14.7	14.7	*0.36*	0.955	0.210	0.852
Born alive[c]	13.4	13.3	*0.10*	0.562	**0.009**	0.364
Total litter wt[c] (kg)	20.4	20.3	*0.26*	0.718	**0.049**	**0.045**
Number weaned	11.4	11.3	*0.26*	0.393	**< 0.001**	0.157
Weaning age (d)	26.4	26.4	*0.15*	0.716	**0.087**	0.827
Litter wean wt[d] (kg)	88.1	87.7	*1.46*	0.749	**0.001**	0.733
Litter gain[e] (kg)	68.4	67.9	*1.33*	0.700	**< 0.001**	0.470
Mortality[f] (%)	10.8	12.5	*1.12*	0.201	**0.020**	**0.019**
Wean to service (d)	5.2	5.2	*0.20*	0.882	0.760	0.437

[a] Not controlled for weight, condition or fat at service as this was not recorded for site 2 [b] Controlled for weight, condition or fat at farrowing, [c] Controlled for total born, [d] Controlled for number weaned and weaning age, [e] Controlled for total born and total weaned [f] Controlled for total born

Table 4 Sow reproductive performance across two experimental periods when provided with a diet supplemented with salmon oil (omega-3, n = 139) or soya oil (control, n = 138) throughout the first time period (Period 1). Values presented are estimated marginal means. Significant values ($p < 0.05$) and trends ($p < 0.1$) are shown in bold.

	Period 1			Period 2			P value		
	Omega 3	Control	*SEM*	Omega 3	Control	*SEM*	Diet	Period	Diet * Period
Farrowing live weight[a] (kg)	258.1	258.1	*2.07*	290.9	283.1	*2.10*	0.130	**< 0.001**	**0.003**
Farrowing back fat[a] (mm)	20.3	19.7	*0.54*	19.4	18.9	*0.54*	0.460	**0.016**	0.240
Farrowing condition score[a]	3.1	3.0	*0.06*	3.6	3.3	*0.06*	**0.036**	**< 0.001**	**0.011**
Weaning live weight[b] (kg)	241.0	236.9	*1.25*	237.7	233.5	*1.38*	**0.008**	**0.012**	0.945
Weaning back fat[b] (mm)	16.0	15.3	*0.32*	18.4	17.7	*0.31*	**0.073**	**< 0.001**	0.791
Weaning condition score[b]	2.9	2.8	*0.05*	3.2	3.0	*0.05*	**0.024**	**< 0.001**	0.750
Change in live weight (kg)	-23.9	-27.1	*1.23*	-34.8	-38.1	*1.25*	**0.031**	**< 0.001**	0.401
Change in back fat (mm)	-4.11	- 4.58	*0.38*	-1.27	-1.75	*0.37*	0.277	**< 0.001**	0.621
Change in condition score	-0.27	-0.33	*0.06*	-0.21	-0.27	*0.06*	0.382	0.297	0.695
Gestation length (d)	115.2	115.1	*0.12*	115.5	115.4	*0.11*	0.814	**0.010**	0.334
Total born	15.1	14.8	*0.29*	14.9	14.6	*0.29*	0.502	0.456	0.610
Born alive[c]	13.6	13.5	*0.10*	13.5	13.4	*0.10*	0.418	0.573	0.962
Total litter weight[c] (kg)	19.1	19.8	*0.25*	20.5	20.5	*0.25*	0.250	**< 0.001**	**0.066**
Number weaned[c]	11.3	11.3	*0.12*	11.4	11.4	*0.12*	0.762	0.421	0.256
Weaning age (d)	26.6	26.5	*0.13*	26.5	26.4	*0.13*	0.490	**0.099**	0.502
Litter wean weight[d] (kg)	88.1	87.7	*1.02*	88.6	88.3	*1.02*	0.777	0.508	0.835
Litter gain[e] (kg)	69.3	68.3	*0.96*	68.5	67.5	*0.96*	0.405	0.319	0.649
Mortality[f] (%)	15.5	13.9	*0.88*	10.7	11.9	*0.93*	0.838	**< 0.001**	**0.089**
Wean to service (d)	5.8	6.1	*0.28*	5.1	5.4	*0.28*	0.481	**0.031**	0.397

[a] Not controlled for starting weight, condition or fat as this data was not recorded for period 2 at Site 2, [b] Controlled for farrowing weight, condition or fat [c] Controlled for total born [d] Controlled for wean age and number weaned [e] Controlled for total born and total weaned, [f] Controlled for total born and the change in condition score