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Evaluation of a decision support system for precision feeding of gestating sows

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Abstract

Precision feeding (**PF**) with the daily mixing of 2 diets with different lysine content (high (**H**) or low (**L**)) was previously reported for growing pigs to reduce protein intake and N excretion compared with a conventional feeding (**CF**) based on a single diet (**C**). Using a simulation approach based on farm data, the objective of the present paper was to describe and evaluate a decision support system for the PF of gestating sows allowing the daily distribution of a tailored ration to each sow. Two datasets, 1 of 2,511 gestations (farm A) and 1 of 2,528 gestations (farm B), reporting sows' characteristics at insemination and objectives at farrowing were used as inputs for a Python model. This model, mainly based on InraPorc, calculates the nutrient requirements of each sow over gestation and simulates the impact of PF in comparison to CF. Simulated diets L, H, and C contained 3.0, 6.5, and 4.8 g/kg of standardized ileal digestible lysine (**SID Lys**) and 2.0, 3.3, and 2.5 g/kg of standardized total tract digestible phosphorus (**STTD-P**), respectively. The influence of farm, parity, gestation week, and their interactions, on calculated SID Lys and STTD-P requirements was analyzed applying a mixed model. The calculated SID Lys and STTD-P requirements increased markedly in the last third of gestation ($P < 0.01$) and were higher for primiparous than for multiparous sows, unless after week 14 for STTD-P requirement. The calculated SID AA and mineral requirements were lower for farm B than farm A (respectively, 2.94 vs. 3.08 g/kg for SID Lys and 1.30 vs. 1.35 g/kg for STTD-P, $P < 0.01$). On average, feed L represented 86% and 92% of the feed projected to be delivered by the PF strategy in farms A and B, respectively. Compared to CF, average calculated dietary SID Lys content was lowered by 27% and 32% with PF, for farms A and B, respectively, while average calculated dietary phosphorus content was lowered by 13% and 16%. The simulated proportions of sows in excess and deficient in SID Lys were reduced with PF. Compared to CF, the PF strategy allowed for a 3.6% reduction in simulated feed cost per sow during gestation, and reduced nitrogen and phosphorus intake (by 11.0% and 13.8%, respectively) and excretion (by 16.7% and 15.4%, respectively). To conclude, these simulations indicate that PF of gestating sow appears to be relevant to meet the amino acid requirement while reducing feed cost, and supplies and excretion of nitrogen and phosphorus.

Key words: amino acid, environment, gestating sow, mineral, nutrition, precision feeding

Introduction

There is a high variability in nutritional requirements among gestating sows, especially at the end of gestation when the requirements of amino acids (**AA**) and minerals increase and are affected by prolificacy (Noblet et al., 1987; Jondreville and Dourmad, 2005; NRC, 2012). Nutritional requirements also vary regarding sow body condition at insemination (Dourmad et al.,

Abbreviations

AA	amino acid
AF	age at farrowing
BT	backfat thickness
BW	body weight
BWt	target body weight at farrowing
CF	conventional feeding
DSS	decision support system
LS	litter size
ME	metabolizable energy
PDS	postpartum dysgalactia syndrome
PF	precision feeding
SID Lys	standardized ileal digestible lysine
STTD-P	standardized total tract digestible phosphorus

2008; NRC, 2012; Gaillard et al., 2019) and parity (Noblet et al., 1993). In practice, all sows are generally fed the same standard gestation diet, and only the feeding level may be adjusted. Most often, nutritional supplies are limiting in AA and minerals, mainly at the end of gestation for young sows, while excesses are observed at earlier stages (Gaillard et al., 2019) and more frequently in older sows. New technologies have been developed to feed the group-housed sows, e.g., with automatic feeding stations that are sometimes designed to deliver several feeds. More generally, the development of precision feeding (**PF**) gives new opportunities to better take into account, in real time, the factors influencing nutritional needs (Brossard et al., 2016; Buis et al., 2016). In this context, models and decision support systems (**DSS**) have been developed to be integrated into automatic feeders for growing pigs (Hauschild et al., 2012; Cloutier et al., 2015; Brossard et al., 2017) and more recently for sows (Gaillard et al., 2019; Gauthier et al., 2019). These DSS are based on nutritional models that predict daily individual nutrient requirements, considering animals' characteristics, physiological stage, and housing conditions. In growing pigs, PF strategy, with the individual and daily mixing of 2 diets with high (**H**) or low (**L**) lysine content was previously reported to reduce protein intake and nitrogen excretion by 29% compared with a conventional feeding (**CF**) without any detrimental effect on average growth performance (Pomar et al., 2009). Using a simulation approach based on real farms data, the objective of the present paper was to describe and evaluate a DSS for the PF of gestating sows allowing the daily mixing of 2 diets formulated with different nutrient contents.

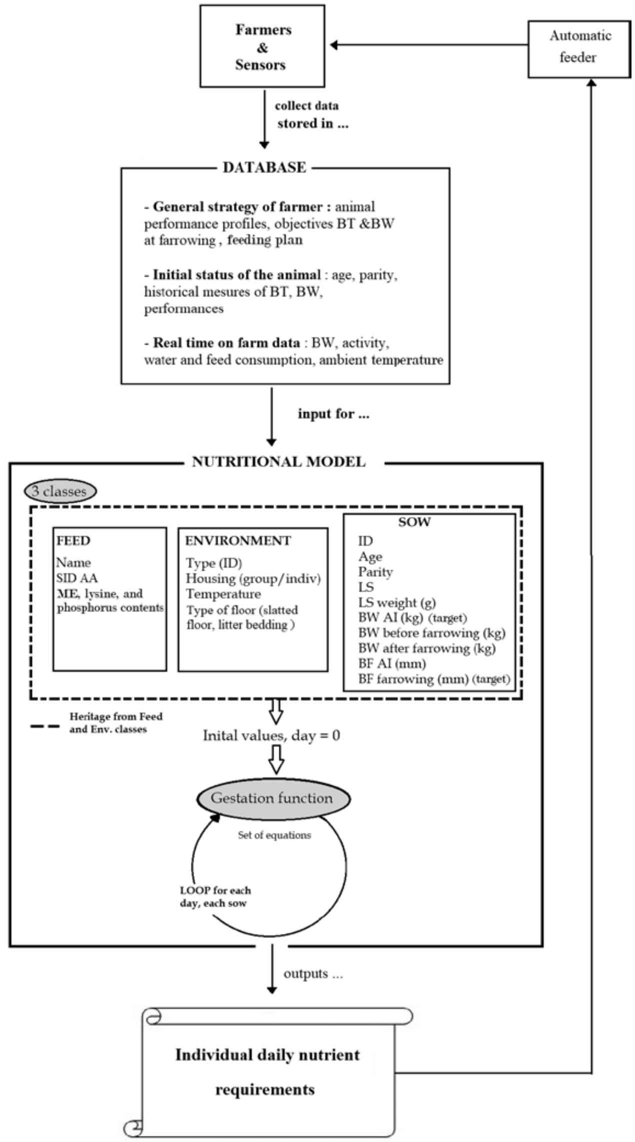

Figure 1. Overview of the DSS construction.

Material and Methods

Development of the DSS

General approach. In practice, the DSS will send daily instructions to the automatic feeder about the daily quantity of each diet to deliver to each sow to constitute their rations. Two diets will be available with different nutrient contents and mixed in the feeder based on the DSS instructions. Decisions will rely on a database containing rules about the on-farm general nutritional strategy, the initial status of the animals, i.e., age, parity, body weight (**BW**) and backfat thickness (**BT**) at insemination, and real-time data measured on farm (Figure 1). The farm strategy will be described using the profile of average characteristics of sows and their litters, per parity, calibrated with InraPorc (Dourmad et al., 2008), and the objectives of BW and BT after farrowing. The objective of BW depends on the age of the sow. Data collected in real time by sensors could also dynamically bring information about the sows (BW, physical activity, and feed consumption) and the environment (ambient temperature and relative humidity). However, the availability of this information could vary regarding the equipment available in the farm and the type of data collected. To build a decision based on these data, the nutritional model included in the DSS calculates the daily needs in metabolizable energy (**ME**), standardized ileal digestible (**SID**) AA, and minerals. Thereafter, the daily feed allowance is determined by the calculated energy requirement and the dietary ME content, while the quality of the feed mix to be delivered depends on the requirement in the most limiting AA (i.e., lysine).

Nutritional model. The nutritional model included in the DSS is detailed in Gaillard et al. (2019). Three compartments are considered during gestation, i.e., body lipid, body protein, and conceptus. The status of these compartments is used to estimate sow's daily BW and BT. Requirements in energy and AA are calculated using a factorial approach. The ME requirement is the sum of the requirements for maintenance, conceptus development, and maternal growth. Maintenance requirements are calculated according to metabolic BW and can be modulated by the level of physical activity, the housing system (individually or group housed) and the ambient temperature. The amount of energy to be retained in body reserves over gestation is determined as the difference between maternal body energy at insemination and the target aimed at farrowing. This amount is calculated from BW and BT, based on equations proposed by Dourmad et al. (1997). The corresponding ME requirement is determined assuming a 0.77 average ME efficiency for maternal energy retention (Noblet et al., 1990). The ME requirement for conceptus growth is calculated regarding the quantity of energy retained in the fetuses and the corresponding ME efficiency (0.48, Noblet et al., 1990). Total nitrogen retention is calculated as the sum of N retention in conceptus and maternal tissues (Dourmad et al., 1999) Standardized ileal AA requirement is calculated based on the amount of each AA retained and their respective efficiency of retention, and the requirements for maintenance. Standardized total tract digestible phosphorus (**STTD-P**) requirements are calculated as the sum of requirements for maintenance (Bikker and Blok, 2017), conceptus (fetuses and placenta) growth and maternal body reserves (Jondreville and Dourmad, 2005). As proposed by Bikker and Blok (2017), a 0.98 STTD-P efficiency is assumed for phosphorus retention and maintenance.

Simulations

The Python (Python version 3.7.2, Python Software Foundation, Beaverton, Oregon) model used for the development of the DSS, and the present simulations are composed of 3 classes (*feed*, *environment*, and *sow*), and 1 gestation function. The gestation function calculates, for each day and each sow, the growth of the different body compartments and the nutrients requirements (Figure 1). The *sow* class inherits the attributes of the *feed* and *environment* classes. The inputs for the *feed* class corresponds to the dietary ME, SID AA, and STTD mineral contents. The inputs for the *environment* class are the housing system (e.g., in our case group-housed) and the room temperature (e.g., in our case 18 °C, thermoneutral condition). The inputs of the sow *class* are the identification number, age, parity, litter size (**LS**) of the studied gestation, average litter birth BW, individual sow's BW and BT at insemination, individual sow's estimated BW after farrowing, and average target BT after farrowing.

Two feeding strategies were simulated with the DSS with a constant feeding plan per sow all along the gestation. A CF strategy, performed with a control diet (**C**) containing 4.8 g SID Lys/kg and 2.5 g STTD-P/kg, was compared with a PF strategy, performed with 2 diets formulated for low (diet L: 3.0 g SID Lys/kg, 2.0 g STTD-P/kg) or high (diet H, 6.5 g SID Lys/kg and 3.3 g STTD-P/kg) AA and mineral contents. The 3 diets contained 13 MJ ME/kg. Diets L and H were formulated at least cost using average prices of feed ingredients observed in France over the first semester 2019 (IFIP, 2019). Diet C was obtained from a mixture of diets L (48.6%) and H (51.4%).

Simulations were run with the DSS to compare the 2 feeding strategies in terms of nutrient intake, excretion, efficiency of retention, and feed costs with 2 datasets collected in 2 experimental farms.

The database used for the evaluation of the DSS

Two datasets were obtained from crossbred Large White × Landrace sows from 2 different lines, in 2 experimental farms (2,511 gestations for farm A in Canada and 2,528 gestations for farm B in France). Each dataset contained the BW and BT of sows measured individually after insemination, as well as characteristics of litter (LS and litter birth BW). An individualized target of BW (**BWt**) after farrowing was determined for each sow regarding its age at farrowing (**AF**) using a specific equation calibrated for each farm:

Farm A (Weibull function, Dourmad et al., 2008): $BWt = 275 \times (1 - \exp(-3.824/1{,}000 \times AF^{0.9801}))$

Farm B (Brody model, Quiniou, 2019): $BWt = 331.4 \times (1 - 0.821 \times \exp(-2.121/1{,}000 \times AF))$

The objective of BT after farrowing was fixed for all sows at 18 mm in farm A and 20 mm in farm B in accordance with the actual practices of each farm.

In farm A, average (±SD) LS at birth was 14.1 (± 3.3) total born piglets with an average litter birth BW of 1.48 (± 0.24) kg per piglet, and a total litter weight of 20.5 (±4.4) kg (Table 1). The average sows' BW at insemination increased from 163 to 251 kg between the 1st and 8th (or more) gestation, while BT at insemination tended to be higher for the first and second parity sows than higher parities (16.9, 15.9, and 14.5 ± 0.4 mm, respectively, for parities 1, 2 and on average from parities 3 to 8+). In farm B, LS at birth was 16.0 (±3.7) total born piglets with an average BW of 1.41 (±0.25) kilogram per piglet, and a total litter weight of 22.0 (±4.5) kg (Table 1). The average sows' BW at insemination increased from 156 to 268 kg between the 1st and 8th (or more) gestation, while BT varied slightly with parity, being the lowest for the 2nd parity sows (13.8 mm) and the highest for the 8th (or more) parity sows (16.0 mm, Table 1). The average parity in Farms A and B was 3.9 and 3.5, respectively.

Calculation and statistical analyses

To consider the effect of the gestation stage, the daily data obtained from simulations were averaged into weekly data. The influence of farm (A and B), parity (primiparous and multiparous), and gestation week on calculated SID AA (Lys) and mineral requirements (STTD-P) was analyzed applying a linear mixed-effects model taking into account the random effect of the sows. The LME (linear mixed-effects) function from the NLM package (Pinheiro et al., 2018) in R software (version 3.4.2), was used to fit the linear mixed-effects models (Laird and Ware, 1982). The correlation over weeks for each sow was calculated with the temporal corAR1 function, representing an autocorrelation structure of order 1 (Pinheiro and Bates, 2000). The results were considered significant when the *P*-values were below 0.05.

Results

Determination of nutrient requirements

The average energy and nutrient requirements calculated over gestation are summarized in Table 2 for both farms, and for primiparous and multiparous sows. The triple interaction parity × farm × week was significant for all nutrients considered ($P < 0.01$). The average daily calculated ME requirement was higher for sows from farm B than from farm A (41.1 vs. 34.6 MJ/d on average, respectively). It increased with parity (33.1 and 38.9 MJ/d on average for primiparous and multiparous, respectively). The calculated SID Lys requirements (Figure 2), expressed in g per kg, increased from weeks 1 to 6, remained stable from weeks 7 to 10, and then increased again from week 11 until the end of gestation. The average calculated SID Lys requirements over the whole gestation decreased when parity increased (3.47 and 2.90 ± 0.02 g/kg for primiparous and multiparous, respectively) and was higher in farm A than in farm B (3.08 vs. 2.94 g/kg, respectively, Table 2). The daily calculated SID Lys requirement

Table 1. Description of the database used to test the DSS

Parity	Number of sows	Average BW at insemination, kg	Average BT at insemination, mm	Target BW after farrowing, kg	Target BT after farrowing, mm	Average LS	Average birth BW, g/piglet
Farm A							
1	392	163	16.9	203	18	13.3	1,405
2	389	192	15.9	227	18	13.5	1,557
3	413	211	15.0	243	18	14.1	1,523
4	384	227	14.4	255	18	14.9	1,480
5	335	234	14.1	260	18	15.0	1,472
6	253	241	14.1	263	18	14.8	1,438
7	187	246	14.6	265	18	13.9	1,445
8+	158	251	14.9	267	18	13.6	1,455
all	2,511	214	15.1	244	18	14.1	1,478
Farm B							
1	528	156	15.8	208	20	14.8	1,321
2	458	183	13.8	242	20	14.5	1,492
3	407	209	14.1	267	20	16.2	1,455
4	348	229	14.8	284	20	16.8	1,424
5	280	244	15.5	297	20	17.4	1,397
6	225	253	15.7	307	20	17.6	1,388
7	143	260	15.7	313	20	17.1	1,413
8+	139	268	16.0	320	20	16.1	1,398
all	2,528	210	15.0	265	20	16.0	1,412

Table 2. Effect of farm (Fa), parity (Pa), and week of gestation (W) on means of lysine and mineral requirements of sows calculated according to a factorial approach

	Farm (Fa)		Parity (Pa)		Farm × parity				P-values[4]				
Variable	A	B	Primi[1]	Multi[2]	A-Primi	A-Multi	B-Primi	B-Multi	RSD[3]	Fa	Pa	W	Fa × Pa[5]
Number of sows	2,511	2,528	920	4,119	392	2,119	528	2,000					
ME, MJ/d[6]	34.6	41.1	33.1	38.9	30.7[a]	35.3[b]	34.9[c]	42.7[d]	0.10	<0.01	<0.01	<0.01	<0.01
SID Lys, g/d[6]	8.25	9.24	8.90	8.71	8.66[a]	8.17[b]	9.07[c]	9.29[d]	0.32	<0.01	<0.01	<0.01	<0.01
SID Lys, g/kg[7]	3.08	2.94	3.47	2.90	3.62[a]	2.98[b]	3.36[c]	2.83[d]	0.31	<0.01	<0.01	<0.01	<0.01
STTD-P, g/d[6]	3.63	4.09	3.41	3.96	3.23[a]	3.70[b]	3.55[c]	4.24[d]	0.37	<0.01	<0.01	<0.01	<0.01
STTD-P, g/kg[7]	1.35	1.30	1.33	1.32	1.36	1.35	1.32	1.29	0.35	0.14	<0.01	<0.01	0.52

[1]Primi, primiparous sows; [2]Multi, multiparous sows; [3]RSD, relative standard deviation; [4]Triple interaction Fa × Pa × W was always significant ($P < 0.01$); [5]Different superscripts are used to compare the 4 means when they are significantly different with a P-value < 0.05; [6]Energy, AA and mineral requirements were calculated using a factorial approach on the basis of simulated protein and mineral retention, in the same way as performed in InraPorc (Dourmad et al., 2008) or NRC (2012); [7]With diets formulated at 13 MJ ME/kg.

expressed in gram per day was lower for multiparous sows than for primiparous sows in early gestation (from weeks 1 to 9), but higher for multiparous sows than for primiparous sows in late gestation (from week 14 to the end of gestation). The calculated STTD-P requirement per kilogram of feed increased markedly after week 9 for farm A and after week 10 for farm B (Figure 2). This requirement was lower for multiparous sows than for primiparous sows from weeks 1 to 9 and higher from week 14 until the end of gestation. Sows from farm A had higher calculated mineral requirements than those from farm B (1.35 vs. 1.30 g STTD-P/kg on average, respectively).

Composition of the ration

On average, diet L represented 86% and 92% of the ration projected to be delivered by the PF strategy in farms A and B, respectively. This proportion is estimated to vary with farm and to be lower in primiparous sows (72% and 88% in farms A and B, respectively) than in multiparous sows (85% and 92% in farms A and B, respectively, interaction farm × parity with $P < 0.01$). The estimated proportion of diet L in the ration of sows fed with the PF strategy decreased with gestation stage, especially for primiparous sows for which it averaged 50% and 55% of the ration during the last 3 wk of gestation in farms A and B, respectively, and dropped to 36% and 42% of the ration during the last week of gestation in farms A and B, respectively (Figure 3).

Evaluation of the SID Lys-based PF strategy

The average calculated SID Lys content of the ration distributed in the PF strategy was 3.50 and 3.28 g/kg for farms A and farm B, respectively, which is 27% and 32% lower than for the CF strategy (Table 3). This effect of PF strategy on calculated SID Lys content increased with parity. Indeed, 17% vs. 29% reduction for farm A, and 29% vs. 32% reduction for farm B, was calculated when comparing primiparous sows to multiparous sows (Table 3). With PF, the calculated SID Lys content of the ration increased with

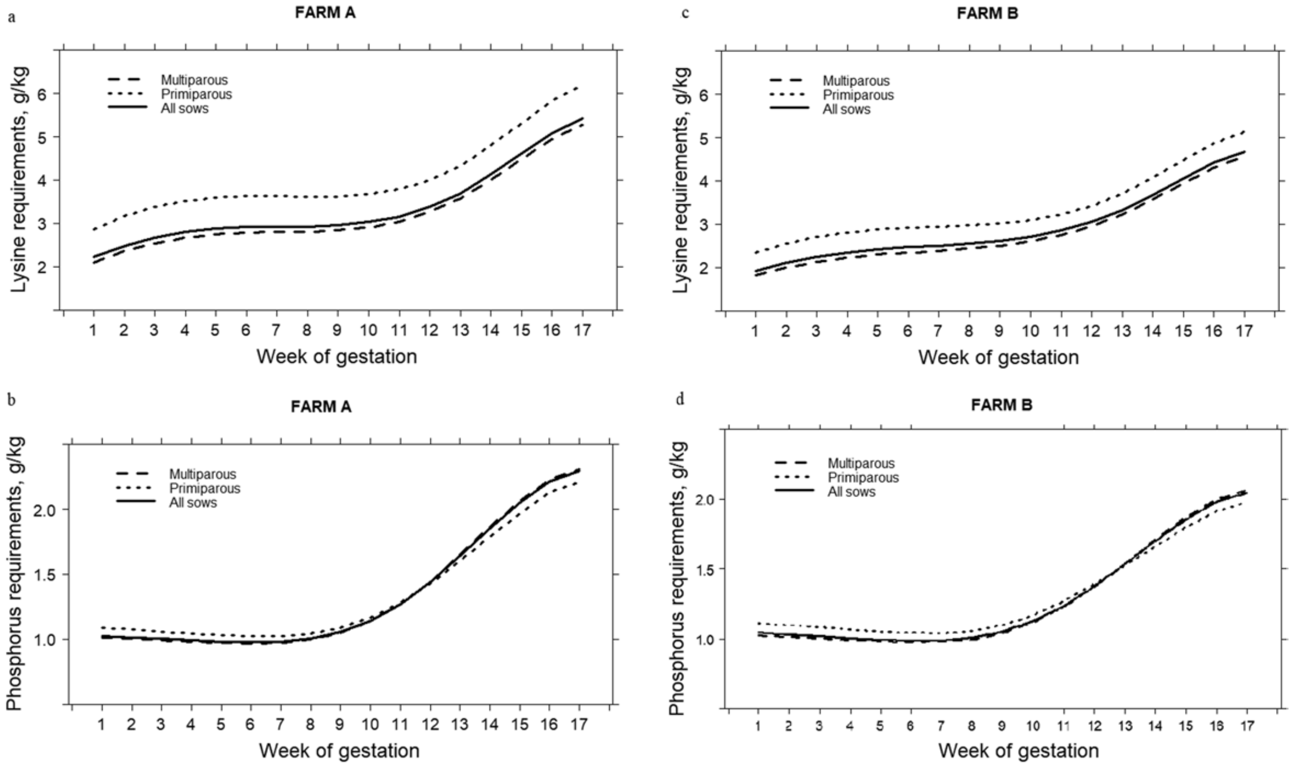

Figure 2. Evolution of the calculated average digestible lysine and phosphorus requirements over gestation (in g/kg) for all the sows, primiparous only and multiparous only, for farm A (a, b) and farm B (c, d).

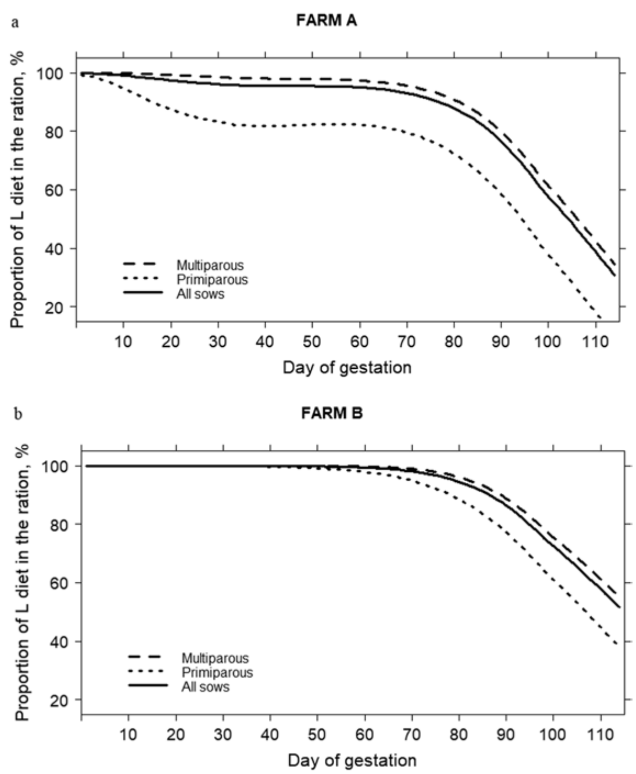

Figure 3. Estimated average proportions of the diet L (with low lysine content) in the ration to be delivered to the sows fed with the precision feeding strategy for farm A (a) and farm B (b). In this simulation, diet L (containing 3.0 g lysine per kilogram of feed and 2.0 g phosphorus per kilogram of feed) is mixed daily for each sow with diet H (containing 6.5 g lysine per kilogram of feed and 3.3 g phosphorus per kilogram of feed) to constitute the ration.

Table 3. Effect of feeding strategy (St), farm (Fa), and parity (Pa) on calculated lysine and phosphorus supplies and on estimated efficiencies of retention, nitrogen, and phosphorus excretion and feed cost

	Strategy (St)		St × Fa				St × Pa				P-values					
	CF	PF	CF-A	CF-B	PF-A	PF-B	CF-P	CF-M	PF-P	PF-M	RSD	St	Fa	Pa	St×Fa	St×Pa
No. of sows	5,039	5,039	2,511	2,528	2,511	2,528	920	4,119	920	4,119						
% of L feed[4]	48.6	88.9	48.6	48.6	85.6	92.1	48.6[a]	48.6[a]	81.3[b]	90.5[c]	0.35	<0.01	<0.01	0.91	<0.01	<0.01
SID Lys[4]																
Intake, g/d	14.1	9.88	12.9[a]	15.2[b]	9.41[c]	10.4[d]	12.3[a]	14.5[b]	9.33[c]	10.0[d]	0.24	<0.01	<0.01	<0.01	<0.01	<0.01
Intake, g/kg[1]	4.80	3.39	4.80[a]	4.80[b]	3.50[c]	3.28[d]	4.80[a]	4.80[a]	3.65[b]	3.33[c]	0.21	<0.01	<0.01	0.91	<0.01	<0.01
Retention, %	33.3	45.7	33.9[a]	32.6[b]	44.7[c]	46.8[d]	42.5	31.2	55.2	43.6	0.35	<0.01	<0.01	<0.01	<0.01	0.47
STTD-P[4]																
Intake, g/d	7.32	6.27	6.73[a]	7.91[b]	5.88[c]	6.65[d]	6.41[a]	7.53[b]	5.74[c]	6.38[d]	0.16	<0.01	<0.01	<0.01	<0.01	<0.01
Intake, g/kg[1]	2.50	2.15	2.50[a]	2.50[b]	2.19[c]	2.10[d]	2.50[a]	2.50[a]	2.24[b]	2.12[c]	0.11	<0.01	<0.01	0.91	<0.01	<0.01
Retention, %	26.2	30.7	26.7[a]	25.6[a]	30.9[b]	30.5[c]	27.5[a]	25.9[b]	30.2[a]	30.8[c]	0.61	<0.01	<0.01	<0.01	0.04	<0.01
Crude protein[4]																
Intake, g/d	355	316	326[a]	384[b]	293[c]	338[d]	311[a]	365[b]	283[c]	323[d]	0.14	<0.01	<0.01	<0.01	<0.01	<0.01
Intake, g/kg[1]	121	108	121[a]	121[b]	109[c]	107[d]	121[a]	121[a]	110[b]	107[c]	0.07	<0.01	<0.01	0.91	<0.01	<0.01
Retention, %	20.0	21.9	20.4[a]	19.6[b]	22.0[c]	21.9[d]	25.3	18.8	27.2	20.8	0.40	<0.01	<0.01	<0.01	<0.01	0.21
Total P[4]																
Intake, g/d	14.5	12.5	13.3[a]	15.6[b]	11.7[c]	13.4[d]	12.7[a]	14.9[b]	11.3[c]	12.8[d]	0.15	<0.01	<0.01	<0.01	<0.01	<0.01
Intake, g/kg[1]	4.94	4.28	4.94	4.94	4.33	4.23	4.94	4.94	4.40	4.25	0.08	<0.01	<0.01	<0.01	0.14	0.44
Retention, %	13.5	15.3	13.5[a]	13.0[b]	15.5[c]	15.1[a]	13.9[a]	13.1[b]	15.3[c]	15.3[c]	0.60	<0.01	<0.01	<0.01	<0.01	<0.01
Excretion per gestation[4]																
N, kg/sow[2]	30.0	25.0	27.3[a]	32.7[b]	23.2[c]	26.9[d]	25.8[a]	30.9[b]	22.6[c]	25.6[a]	0.21	<0.01	<0.01	<0.01	<0.01	<0.01
P, kg/sow[3]	1.43	1.21	1.31[a]	1.56[b]	1.12[c]	1.30[d]	1.24[a]	1.48[b]	1.09[c]	1.24[d]	0.17	<0.01	<0.01	<0.01	<0.01	<0.01
Feed cost, €/sow/ gestation[5]	63.7	61.4	58.5[a]	68.8[b]	56.6[c]	66.2[d]	55.7[a]	65.4[b]	54.1[c]	63.0[d]	0.13	<0.01	<0.01	<0.01	<0.01	<0.01

[1]With diets formulated at 13 MJ ME/kg. [2]L and H diets contained 104 and 137 g of crude protein per kilogram, respectively. [3]L and H diets contained 4.10 and 5.73 g of total phosphorus per kilogram, respectively. [4]AA and mineral requirements were calculated using a factorial approach on the basis of simulated protein and mineral retention, in the same way as performed in InraPorc (Dourmad et al., 2008) or NRC (2012). This is also the case for the mineral and protein retention used for the determination of nutrient balance and excretion. Conversely, the data relative to the nutrient and feed supplies corresponds to the amounts that would have been supplied when applying the DSS in practice. [5]Estimated feed costs based on average prices of feed ingredients observed in France over the first semester 2019 (IFIP, 2019).

gestation stage to reach on average 5.23 and 4.55 g/kg during the last 2 wk of gestation in farms A and B, compared with 3.11 and 3.00 g/kg on average over the first 8 wk. The efficiency of simulated SID lysine retention was higher in PF compared with CF sows (45.7% vs. 33.3% respectively), the extent of the difference between the 2 strategies being greater in farm B than in farm A ($P < 0.01$). The efficiency of simulated SID Lys retention was on average greater in primiparous than in multiparous sows, but the extent of the improvement between CF and PF sows was not affected by parity. The simulated deposition of SID Lys increased with gestation stage from on average 3.48 (farm A) and 3.93 (farm B) g/kg over the first 8 wk of gestation, to on average 8.21 (farm A) and 8.80 (farm B) g/kg during the last 2 wk of gestation.

The simulated percentages of sows receiving adequate, excessive, or deficient amounts of SID Lys when fed with the CF or PF strategies are presented for all sows and for primiparous sows only for farm A (Figure 4a.) and for farm B (Figure 4b.). In both farms, the PF strategy was estimated to reduce the proportion of sows receiving lysine below their requirements (i.e., <95% of the calculated requirement) compared with CF, especially in the last 2 wk of gestation (1.05% and 43.6% in farm A, respectively, and 0.24% and 13.6% in farm B, respectively). For the primiparous sows, the difference between the 2 strategies was estimated to be more important, with 85% and 27% of the CF sows from farms A and B, respectively, that were fed a lysine-deficient ration in the last 2 wk of gestation compared to 3.4% and 0.05% of the PF sows. Moreover, in both farms, the proportion of sows fed in excess of lysine was estimated to be reduced with PF, the effect being more marked in primiparous sows.

Mineral supply associated with the Lys-based PF strategy

Calculated average STTD-P content of the ration distributed with the PF strategy was 2.19 and 2.10 g/kg for farms A and B, respectively, which is 13% and 16% lower than with the CF strategy (Table 3). This decrease was lower for primiparous (–5% and –14% for farm A and farm B, respectively), than for multiparous sows (–14% and –16% for farms A and B, respectively, Table 3). The estimated efficiencies of STTD-P and total phosphorus retention were higher in PF compared with CF sows (Table 3), the extent of this difference between the 2 strategies being greater in farm B than in farm A. These estimated efficiencies were on average greater in primiparous than in multiparous sows, but the extent of improvement between CF and PF sows was not affected by parity.

Over the first 80 d of gestation, all PF and CF sows were projected to be fed above their calculated STTD-P requirement. Most of the STTD-P deficiency were estimated to occur during the last 3 wk of gestation with 2.9% and 1.6% STTD-P deficient sows with PF (farms A and B, respectively) against 10% and 6.2% with CF (farms A and B, respectively). Over the last 3 wk of gestation, there were no estimated STTD-P deficient primiparous sows with PF in both farms against 6.5% and 2.1% with CF in farms A and B, respectively.

Economic and environmental impacts of the PF strategy

The estimated feed cost was projected to be different between farms and was affected by the feeding strategy. Gestation feed cost was estimated to be 17% higher in farm B than in farm A (67.5 vs. 57.6 €/sow, respectively), the extent of this farm difference being greater with CF than with PF feeding strategy (+10.3 and +9.6 €/sow, respectively, $P < 0.01$). Compared to CF, PF strategy was estimated to reduce feed cost by 3.6% (61.4 vs. 63.7 €/sow, $P < 0.01$), the extent of this reduction being lower in farm A than in farm B (–1.6 vs. –2.4 €/sow, respectively, $P < 0.01$). Estimated feed cost was greater for multiparous sows than for primiparous sows (64.2 vs. 54.9 €/sow, respectively, $P < 0.01$), the extent of this parity difference being slightly greater with CF (+9.7 €/sow) than with PF strategy (+8.9 €/sow).

Calculated nitrogen (**N**) and phosphorus (**P**) excretion varied according to farm, parity, and feeding strategy (Table 3). Calculated total N excretion per sow per gestation was 17% higher in farm B than in farm A (29.8 vs. 25.2 kg N/sow, respectively), the extent of this between farm difference being greater with CF than with PF feeding strategy (+5.4 and +3.7 kg N/sow, respectively, $P < 0.01$). Sows fed with the PF strategy had on average 16.7% lower total N excretion over gestation than CF sows (25.3 and 29.8 kg N/sow, respectively, $P < 0.01$), the extent of this feeding strategy difference being greater in farm B than in farm A (5.8 and 4.1 kg N/sow, respectively, $P < 0.01$). Multiparous sows had on average 17% greater N excretion over gestation than primiparous sows (28.2 vs. 24.2 kg N/sow, respectively, $P < 0.01$), the extent of this parity difference being higher with CF than with PF strategy (5.1 vs. 3.0 kg N/sow, $P < 0.01$). Total P excretion was calculated to be 17.2% higher in farm B than in farm A (1.43 vs. 1.22 kg P/sow, respectively), the extent of this farm difference being greater in CF compared with PF strategy (0.25 and 0.18 kg P/sow, respectively, $P < 0.01$). Sows fed the PF strategy had on average 14.6% lower total P excretion over gestation than CF sows A (1.17 vs. 1.37 kg P/sow, respectively), the difference between feeding strategies being greater in farm A than in farm B (0.24 vs. 0.15 kg P/sow, $P < 0.01$). Multiparous sows had on average 16.7% greater P excretion over gestation than primiparous sows (1.36 vs. 1.16 kg P/sow, respectively, $P < 0.01$), the extent of this difference being greater in CF than in PF sows (0.24 vs. 0.15 kg P/sow, $P < 0.01$).

Discussion

Variation in energy and nutrient requirements

Calculated average ME requirement was 16% lower in farm A than in farm B. This is mainly related to phenotypic differences and BW targets at farrowing between the 2 farms. Indeed, according to the equations describing the evolution with age of BW after farrowing, mature BW reaches 275 kg in farm A compared with 320 kg in farm B. This results in increased energy requirements for maintenance and maternal gain in farm B. Moreover, the lower target of BT at farrowing (18 vs. 20 mm) and the lower prolificacy in farm A also contribute to explain the difference in ME requirement.

The slight increase in calculated SID Lys requirements from weeks 1 to 6 is related to maternal growth, mainly in primiparous sows, and/or recovery of body protein reserves in multiparous sows, as requirement for embryos is very limited at that time. The strong increase in calculated SID Lys requirements that occurs in late gestation is in accordance with previous studies (Kim et al., 2009; Levesque et al., 2011) and is due to a switch of nutrient demand from maternal lean tissue growth to fetal and mammary growth (McPherson et al., 2004). Based on this important variation, an adjustment of the dietary AA content during gestation is of interest, with for instance the use of a different diet during the last third of the gestation. Indeed, with a single diet of constant and average AA content, the sows are overfed in AA in early gestation which increases feed costs and

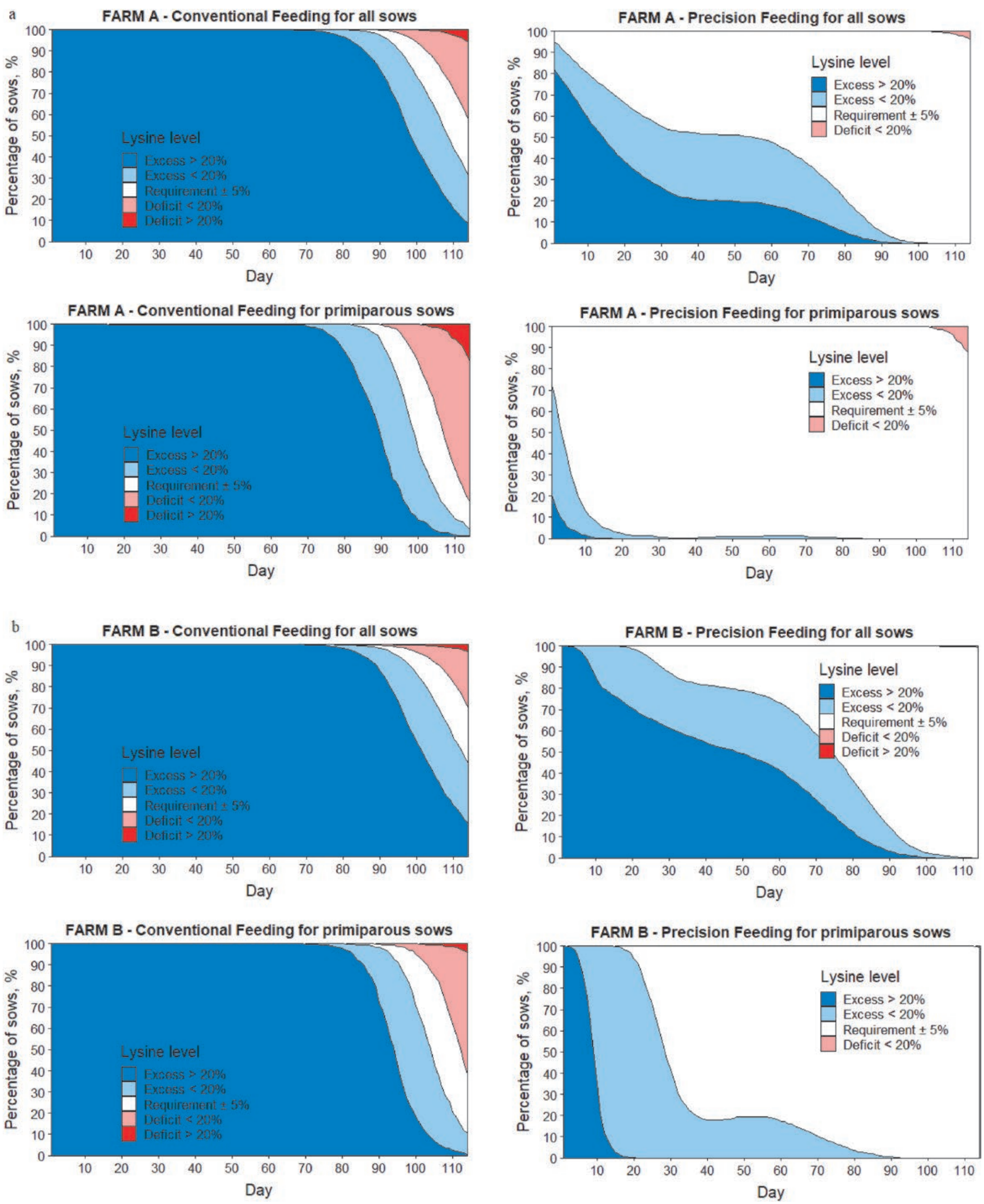

Figure 4. Estimation of the influence of feeding strategy (CF vs. precision feeding) during gestation on the proportion of sows (all sows vs. primiparous) receiving adequate (white), deficient (pink and red), or excess (blue) amounts of lysine, in farm A (a) or farm B (b).

environmental impacts through the excretion of nitrogen due to AA supplied in excess (Adeola, 1999). At the same time, with this strategy, sows, mainly young ones, are underfed in AA in late gestation leading to a mobilization of maternal proteins to support fetal growth (Clowes et al., 2003) and possibly to a reduction of piglets birth weight.

During the first two-thirds of the gestation, the calculated STTD-P requirements were low and corresponded to the requirements for maintenance and maternal growth, while during the last third of gestation the calculated STTD-P requirements increased, due to the rapid growth and bone mineralization of the fetuses (Jondreville and Dourmad, 2005; NRC, 2012). This outlines the possibility of a reduction in phosphorus and calcium supplies in early gestation, but this has to be done carefully as the model does not consider any requirement for the restoration of body minerals that may have been mobilized during the previous lactation yet.

As proposed by Gaillard et al. (2019), feeding the sows by parity group (primiparous and multiparous) and period (early vs. late gestation), with specific nutrient contents for each farm, might be the first step toward a better adjustment of AA supplies to requirements. In practice, this would require to group the sows according to their parity (primiparous and multiparous) and gestation stage (early and late) and use a specific diet for each group. As shown by Ball and Moehn (2013) and Dourmad et al. (2009), this would be the 1st step to reduce feed cost, as well as nutrient excretion. Nevertheless, this kind of phase feeding strategy does not deal with the individual variability of requirements, and additional adaptations are expected toward PF. Moreover, as shown by the comparison of the 2 farms in the present study, calculated nutrient requirements also vary between farms. This is partly due to the different sows' BW at insemination, different objectives of BW and BT at farrowing, and differences in prolificacy. This reinforces the interest for tailored diets based on farm specific data and individual requirements (Gaillard et al., 2019), supported by the development of automatic feeders able to identify and feed each animal differently, each day.

Precision feeding

The individual and daily nutrient adjustment were estimated to allow for a 3.6% reduction in feed cost compared with the CF strategy. This is in accordance with Pomar et al. (2009) who reported that in growing pigs, feed cost was lowered by 4.0% with a precision feeding strategy, compared with conventional phase feeding. Pomar et al. (2009) and Brossard et al. (2019) also reported a reduction in nitrogen and phosphorus intake and excretion for growing pigs fed with a precision feeding strategy. For gestating sows, the simulations indicate that precision feeding is also expected to reduce nitrogen and phosphorus intake (by 11.0% and 13.8%, respectively) and excretion (by 16.7% and 15.4%, respectively). From these simulations, precision feeding strategy seemed more efficient for reducing N and P excretion in farm B than in farm A. This is partly because sows in farm B had lower nutrient requirements per kilogram of feed on average than sows in farm A, resulting in a higher frequency of overfed animals in farm B. This outlines the importance of adjusting the nutrient content of the "low-nutrient" diet according to the farm. Indeed, according to the evolution of calculated SID Lys requirement with the stage of gestation, it appears that SID Lys content of the L diet could be reduced in both farms.

The important remaining excess in phosphorus supply estimated with precision feeding strategy is partly due to the implemented PF strategy only based on lysine requirement. Hence, in such condition, it was not possible to deal with the different dynamics of lysine and phosphorus requirements over gestation (NRC, 2012; Gaillard et al., 2019). To modulate lysine and phosphorus supplies independently, this would require to use simultaneously 3 diets differing in their SID Lys and STTD-P contents, or a minerals supplement. The excess of STTD-P supplies to most sows over the first half of gestation results also from the STTD-P content of L diet (2.0 g/g) which is higher than the average requirement (about 1.1 g/kg; Figure 2). But in practice it might be difficult to achieve lower dietary STTD-P content since the L diet already contained no mineral phosphate and the only way to decrease STTD-P would be to reduce phytase addition, with no effect on P excretion.

Besides the interest of reducing nitrogen and phosphorus intake and excretion, it is important to meet precisely daily energy and nutrient requirements during the gestation as it may also have short- or long-term consequences, i.e., on the future phases of the reproductive cycle. On a short-term basis, the gestating sow is able to mobilize her body reserves of protein, energy, and minerals to prioritize pregnancy over growth, but the further effects of under- or oversupplying nutrients are not always easy to discern (Huber, 2019). Concerning primiparous sows, precision feeding is specifically interesting as, although they have a greater body protein and weight gain during gestation, they are able to satisfy their requirements for maternal and fetal growth without digging into their own reserves (Buis, 2016). In that study, group-housed gilts fed with a PF strategy during gestation had a similar LS and litter growth than gilts fed with a CF strategy, but PF gilts ate more (+9%) and tended to loose less weight during the subsequent 21 d lactation period, which may benefit long-term reproductive performance.

Consequences of gestation feeding programs on sow longevity are not well known but some studies found that failing to meet the individual nutrient requirements might affect not only the following reproductive cycles but also performance at longer term (Dourmad et al., 1994; Trottier et al., 2015). Moreover, some recent studies indicate that nutrition of the sow during gestation may also affect the digestive capacity, the immune system robustness of the offspring (Chen et al., 2017) and piglets' survival at birth. Maternal body reserves should not be excessive at the end of pregnancy to avoid farrowing problems, especially an increase of stillbirth (Quiniou, 2016), and postpartum dysgalactia syndrome (**PDS**), which are typical for fat sows (Micquet et al., 1990; Göransson, 1989), and may impair feed intake after farrowing (Dourmad, 1991) and reduce longevity (Niemi et al., 2017). Conversely, too thin sows at farrowing have lighter piglets at birth and at weaning (Quiniou, 2016), with an increased risk of mortality. This suggests that there should be an optimal range for sow's body condition at farrowing, in relation with energy supply, resulting from a compromise between limiting the risk of occurrence of sow's health disorders and decreasing piglets' birth weight and their survival. By allowing to better consider the different factors affecting the nutrient requirements, precision feeding should allow to reduce the inter-individual variability of sows' characteristics at farrowing, resulting in an easier management of the farrowing period with improved piglets' survival and sows' lactation performance (Quiniou, 2016).

Model and DSS adjustment in practice

In this study, the objective of BW at farrowing depended on the age of the sow at insemination, and on a relationship between AF and BW previously characterized in each farm. To better deal with inter-individual variability, it would be interesting to consider the change of BW with age of each animal during its lifespan to better specify the objective of BW at the next farrowing. This implies to develop a system allowing the DSS to adapt progressively to individual trajectory of BW. New analytic software has being developed to estimate automatically and on real-time individual BW via video recording (Kashiha, 2014;

Pezzuolo, 2018). This would be a practical solution to collect daily individual BW on farm, replacing the scales that are difficult to calibrate or even not available in practice.

Ambient temperature of the gestating room could also be recorded daily and considered in the requirements calculations. The DSS is already designed to take temperature into account. When temperature drops below the low critical temperature, ME requirement for maintenance increases by 10 kJ/kg BW$^{-0.75}$/d/°C for group-housed sows. Therefore, it only needs daily data to run, easily collected with a simple thermometer in the sows' room.

Similarly, the physical activity of each sow could be recorded daily and integrated in the model to adjust daily nutrient requirements. Accelerometers are being developed and can be fixed on the ear on the sow (Marcon et al., 2017; Scheel et al., 2017). They are able to assess the number of movements per hour but also the postures (standing, lying, and walking). The DSS is already designed to take into account sow's physical activity, but due to a lack of data, it was not considered in the present study.

In a long-term perspective, individual behaviors could also be identified and integrated in the calculation of daily nutrient requirements. Indeed, there is an apparent link between productivity and behavior or more generally welfare (Dourmad, 2019). For example, Cariolet et al. (1997) reported that the frequency of stereotypies (i.e., considered as abnormal behavior) and the time spent standing after the meal decreased when body score increased. Very active sows standing and walking for a long-time spend more energy for activity resulting in a decrease of body condition. At the same time, the occurrence of body lesions is also increasing in sows with poor body condition indicating an impaired welfare (Cariolet et al., 1997). Another way to reduce gestating sows stereotypies could be the inclusion of more fiber in the diet, inducing satiety without excessive energy intake (Meunier-Salaün and Bolhuis, 2015), which as well highlights the relationship between sow nutrition and welfare. Increasing the amount of fiber in the ration of gestating sows should reduce standing time, feeding rate, and nonfeeding behaviors, but it should also increase feeding time (including mastication) and weight gain compared with sows fed a diet containing less fiber. Reducing apparent feeding motivation of gestating sows should therefore improve their welfare. In order to include components of behavior in the DSS, software analyzing video recordings have been developed and should be able to detect automatically abnormal behaviors like aggressive interactions (Oczak et al., 2013; Viazzi et al., 2014) or sows' posture (Nasirahmadi et al., 2015; Leonard, 2019). Moreover, diet formulation options should be added in the model and available "in real time".

All these adjustments will require the farms to be equipped with automated feeding equipment, devices including the full DSS and sensors (weighing scales, cameras, accelerometers, hydro-thermometers, etc.) that will continuously collect information to increment real-time databases. These changes will also allow to improve the management of sows across their successive physiological stages and over their whole lifetime.

Conclusion

Like for growing pigs, the results of the DSS simulation indicate that precision feeding for gestating sows is a potential relevant strategy to better meet their AA requirement while reducing feed cost, and nitrogen and phosphorus supplies and excretion. Performing precision feeding by mixing 2 diets, which formulation was primarily adapted to improve AA supplies, appears efficient to meet sows' calculated AA requirements but less efficient regarding their calculated phosphorus requirements, because of different dynamics of requirements. The DSS developed in the present study allows the adaptation of the quantity and the quality of the ration distributed daily to each sow all along the gestation with rather simple criteria (BW at insemination, expected litter characteristics, and body condition). In practice, this DSS has the potential to integrate several types of in real-time data collected by different sensors installed in the farms to characterize housing conditions (i.e., temperature and relative humidity) and animal behavior (i.e., activity and interactions), to fit better nutrients supplies and requirements. Precision feeding might result as well into an improved compromise between animal productivity and welfare, and subsequently a better social acceptance of pig production systems. Furthermore, the return on investment in precision feeding equipment can be considered based on the reduction of feed cost simulated in the present study.

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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

Literature Cited

Adeola, O. 1999. Nutrient management procedures to enhance environmental conditions: an introduction. *J. Anim. Sci.* **77**:427–429. doi:10.2527/1999.772427x

Ball, R. O., and S. Moehn. 2013. Feeding pregnant sows for optimum productivity: past, present, and future perspectives. In: J. R. Pluske and J. M. Pluske, editors, *Manipulating pig production XIV*. Proceedings of the Fourteenth Biennial Conference of the Australasian Pig Science Association; Corowa, Australia; p. 151–169.

Bikker, P., and M. C. Blok. 2017. *Phosphorus and calcium requirements of growing pigs and sows*. Wageningen Livestock Research, Wageningen; p. 74. CVB Documentation Report 59. doi:10.18174/424780

Brossard, L., J. Y. Dourmad, F. Garcia-Launay, and J. Van Milgen. 2017. Chapter 10 – Modelling nutrient requierments for pigs to optimize feed efficiency. In: J. Wiseman, editor, *Volume 2: animal breeding and nutrition*. University of Nottingham Achieving sustainable production of pig meat, Burleigh Dodds Science Publishing, Cambridge, UK; p. 185–208.

Brossard, L., J. Y. Dourmad, J. Van Milgen, M. Marcon, and N. Quiniou. 2016. *Chapitre 10 – Elevage de précision en filière porcine: état des lieux et enjeux*. Elevage de précision, Editions France Agricole, Paris, France; p. 145–165.

Brossard, L., M. Marcon, J. Y. Dourmad, J. van Milgen, J. Pomar, V. Lopez, and N. Quiniou. 2019. Application of a precision feeding program in growing pigs: effect on performance and nutrient use. In: *Book of abstracts of the 70th annual meeting of the European federation of animal science*. The Netherlands: Wageningen Academic Publishers; *p*. 469.

Buis, R. Q. 2016. *Development and application of a precision feeding program using electronic sow feeders and effect on gestating* *primiparous sow performance* [M.Sc. thesis]. Guelph, Canada: Department of Animal Biosciences. University of Guelph; p. 101. http://hdl.handle.net/10214/9866

Buis, R. Q., D. Wey, and C. F. M. de Lange. 2016. Development of precision gestation feeding program using electronic sow feeders and effects on gilt performance. *J. Anim. Sci.* **94**:125–126. (Meeting Abstract). doi: 10.2527/msasas2016-266

Cariolet, R., C. Vieuille, P. Morvan, F. Madec, M. C. Meunier-Salaün, J. C. Vaudelet, V. Courboulay, J. P. Signoret. 1997. Evaluation du bien être chez la truie gestante bloquée. Relation entre le bien être et la productivité numérique. *J. Rech. Porcine*. **29**:149–160. http://www.journees-recherche-porcine.com/texte/1997.php

Chen, Y., D. Mou, L. Hu, J. Zhen, L. Che, Z. Fang, S. Xu, Y. Lin, B. Feng, J. Li, *et al*. 2017. Effects of maternal low-energy diet during gestation on intestinal morphology, disaccharidase activity, and immune response to lipopolysaccharide challenge in pig offspring. *Nutrients*. **9**:1115–1133. doi: 10.3390/nu9101115

Cloutier, L., C. Pomar, M. P. Létourneau Montminy, J. F. Bernier, and J. Pomar. 2015. Evaluation of a method estimating real-time individual lysine requirements in two lines of growing-finishing pigs. *Animal* **9**:561–568. doi:10.1017/S1751731114003073

Clowes, E. J., F. X. Aherne, A. L. Schaefer, G. R. Foxcroft, and V. E. Baracos. 2003. Parturition body size and body protein loss during lactation influence performance during lactation and ovarian function at weaning in first-parity sows. *J. Anim. Sci.* **81**:1517–1528. doi:10.2527/2003.8161517x

Dourmad, J. Y. 1991. Effect of feeding level in the gilt during pregnancy on voluntary feed intake during lactation and changes in body composition during gestation and lactation. *Livest. Prod. Sci.* **27**:309–319. doi: https://doi.org/10.1016/0301-6226(91)90126-B

Dourmad, J. Y. 2019. Chapter 5: evolution of the feeding approach in sows during the last decades. In. *Novus book: nutrition of hyperprolific sows*. Ed. Missouri, USA: Novus International; p. 107–132. [accessed August 24, 2020] https://www.novusint.com/pages/nutritionofhyperprolificsows

Dourmad, J. Y., L. Brossard, and J. Van Milgen. 2009. Nutrition-environment interaction in the sow: interest of modelling approach. Proceeding of the 30th Western Nutrition Conference, Winnipeg, Manitoba; p. 182–192.

Dourmad, J. Y., M. Etienne, J. Noblet, and D. Causeur. 1997. Prédiction de la composition chimique des truies reproductrices à partir du poids vif et de l'épaisseur de lard dorsal. Application à la définition des besoins énergétiques. *J. Rech. Porcine* **29**:255–262. [accessed August 24, 2020] http://www.journees-recherche-porcine.com/texte/1997.php

Dourmad, J. Y., M. Etienne, A. Prunier, and J. Noblet. 1994. The effect of energy and protein intake of sows on their longevity. *Livest. Prod. Sci.*, **40**:87–97. doi:10.1016/0301-6226(94)90039-6

Dourmad, J. Y., M. Etienne, A. Valancogne, S. Dubois, J. van Milgen, and J. Noblet. 2008. InraPorc: a model and decision support tool for the nutrition of sows. *Anim. Feed Sci. Tech.* **143**:372–386. doi: 10.1016/j.anifeedsci.2007.05.019

Dourmad, J. Y., J. Noblet, M. C. Père, and M. Etienne. 1999. Mating, pregnancy and pre-natal growth. In: Kyriazakis, I. editor, A Quantitative Biology of the Pig, CAB; pp. 129-153

Gaillard, C., R. Gauthier, L. Cloutier, and J. Y. Dourmad. 2019. Exploration of individual variability to better predict the nutrient requirements of gestating sows1. *J. Anim. Sci.* **97**:4934–4945. doi:10.1093/jas/skz320

Gauthier, R., C. Largouët, C. Gaillard, L. Cloutier, F. Guay, and J. Y. Dourmad. 2019. Dynamic modeling of nutrient use and individual requirements of lactating sows1. *J. Anim. Sci.* **97**:2822–2836. doi:10.1093/jas/skz167

Göransson, L. 1989. The effect of feed allowance in late pregnancy on the occurrence of agalactia post-partum in the sow. *J. Vet. Med*. **36**:505–513. doi: 10.1111/j.1439-0442.1989.tb00760.x

Hauschild, L., P. A. Lovatto, J. Pomar, and C. Pomar. 2012. Development of sustainable precision farming systems for swine: estimating real-time individual amino acid requirements in growing-finishing pigs. *J. Anim. Sci.* **90**:2255–2263. doi:10.2527/jas.2011-4252

Huber, L. A. 2019. Sow feeding strategies: gestating sows. Proceedings of London Swine Conference, Canada; p. 51–55. https://www.londonswineconference.ca/resources

IFIP. 2029. BAROPORC de l'IPIF - Aliment IFIP, prix mensuel. [accessed August 24, 2020] www.ifip.asso.fr/fr/indicateur-aliment-ifip.com

Jondreville, C., and J. Y. Dourmad. 2005. Le phosphore dans la nutrition des porcs. *INRA Prod. Anim.* **18**:183–192. http://www.evapig.com/IMG/pdf/Jondreville_Dourmad2006-Prod_Anim-2.pdf

Kashiha, M., C. Bahr, S. Ott, C. P. H. Moons, T. A. Niewold, F. O. Ödberg, and D. Berckmans. 2014. Automatic weight estimation of individual pigs using image analysis. *Comput. Electron. Agric.* **107**:38–44. doi: 10.1016/j.compag.2014.06.003

Kim, S. W., W. L. Hurley, G. Wu, and F. Ji. 2009. Ideal amino acid balance for sows during gestation and lactation. *J. Anim. Sci.* **87**(14 Suppl.):E123–E132. doi:10.2527/jas.2008-1452

Laird, N. M., and J. H. Ware. 1982. Random-effects models for longitudinal data. *Biometrics*. **38**:963–974.

Leonard, S. M., H. Xin, T. M. Brown-Brandl, and B. C. Ramirez. 2019. Development and application of an image acquisition system for characterizing sow behaviors in farrowing stalls. *Comput. Electron. Agric.* **163**:104866. doi: 10486610.1016/j.compag.2019.104866

Levesque, C. L., S. Moehn, P. B. Pencharz, and R. O. Ball. 2011. The threonine requirement of sows increases in late gestation. *J. Anim. Sci.* **89**:93–102. doi:10.2527/jas.2010-2823

Marcon, M., G. Melot, V. Courboulay, S. Boulot, and Y. Rousselière. 2017. Monitoring du niveau d'activité des truies par un accéléromètre communiquant placé sur la boucle d'identification. *Journées Rech. Porcine*. **49**:171–172. http://www.journees-recherche-porcine.com/texte/2017/bienetre/B08.pdf

McPherson, R. L., F. Ji, G. Wu, J. R. Blanton, Jr, and S. W. Kim. 2004. Growth and compositional changes of fetal tissues in pigs. *J. Anim. Sci.* **82**:2534–2540. doi:10.2527/2004.8292534x

Meunier-Salaün, M. C., and J. E. Bolhuis. 2015. High-fibre feeding in gestation. In: C. Farmer, editor, *The gestating and lactating sow*. The Netherlands: Wageningen Academic Publishers; p. 95–116. doi: 10.3920/978-90-8686-803-2

Micquet, J. M., F. Madec, and F. Paboeuf. 1990. Epidémiologie des troubles de la mise bas chez la truie. *J. Rech. Porcine France*. **22**:325–332.

Nasirahmadi, A., U. Richter, O. Hensel, S. Edwards, and B. Sturm. 2015. Using machine vision for investigation of changes in pig group lying patterns. *Comput. Electron. Agric.* **119**:184–190. doi: 10.1016/j.compag.2015.10.023

Niemi, J. K., P. Bergman, S. Ovaska, M. L. Sevón-Aimonen, and M. Heinonen. 2017. Modeling the costs of postpartum dysgalactia syndrome and locomotory disorders on sow productivity and replacement. *Front. Vet. Sci.* **4**:181. doi:10.3389/fvets.2017.00181

Noblet, J., J. Y. Dourmad, and M. Etienne. 1990. Energy utilization in pregnant and lactating sows: modeling of energy requirements. *J. Anim. Sci.* **68**:562–572. doi:10.2527/1990.682562x

Noblet, J., Y. Henry, and S. Dubois. 1987. Effect of protein and lysine levels in the diet on body gain composition and energy utilization in growing pigs. *J. Anim. Sci.* **65**:717–726. doi:10.2527/jas1987.653717x

Noblet, J., X. S. Shi, and S. Dubois. 1993. Metabolic utilization of dietary energy and nutrients for maintenance energy-requirements in sows – basis for a net energy system. *Br. J. Nutr.* **70**:407–419. doi: 10.1079/bjn19930135

NRC. 2012. *Nutrient requirements of swine: eleventh revised edition*. Washington, DC: National Academies Press. doi: 10.17226/13298

Oczak, M., G. Ismayilova, A. Costa, S. Viazzi, L. Thays Sonoda, M. Fels, C. Bahr, J. Hartung, M. Guarino, D. Berckmans, *et al.* 2013. Analysis of aggressive behaviours of pigs by automatic video recordings. *Comput. Electron. Agric.* **99**:209–217. doi: 10.1016/j.compag.2013.09.015

Pezzuolo, A., M. Guarino, L. Sartori, L. A. González, and F. Marinello. 2018. On-barn pig weight estimation based on body measurements by a Kinect v1 depth camera. *Comput. Electron. Agric.* **148**:29–36. doi: 10.1016/j.compag.2018.03.003

Pinheiro, J. C., and D. M. Bates. 2000. *Mixed-effects models in S and S-PLUS*. USA: Springer, esp; p. 235, 397.

Pinheiro, J., D. Bates, S. DebRoy, D. Sarkar, and R. C. Team. 2018. NLME: linear and nonlinear mixed effects models. USA: R package version 3.1-137. https://CRAN.R-project.org/package=nlme

Pomar, C., L. Hauschild, G. H. Zhang, J. Pomar, and P. A. Lovatto. 2009. Applying precision feeding techniques in growing-finishing pig operations. *Rev. Bras. Zootecn.* **38**:226–237. doi:10.1590/S1516-35982009001300023

Quiniou, N. 2016. Conséquences de l'hétérogénéité des réserves corporelles de la truie à la fin de la gestation sur le déroulement de la mise bas et les performances de lactation. *J. Rech. Porcine.* **48**:207–2012. http://www.journees-recherche-porcine.com/texte/2016.php

Quiniou, N. 2019. Modélisation de l'évolution moyenne du poids vif après la mise bas selon l'âge chez des truies croisées Large White x Landrace. *Journées Rech Porcine.* **51**:123. http://www.journees-recherche-porcine.com/texte/2019.php

Scheel, C., I. Traulsen, W. Auer, K. Müller, E. Stamer, and J. Krieter. 2017. Detecting lameness in sows from ear tag-sampled acceleration data using wavelets. *Animal* **11**:2076–2083. doi:10.1017/S1751731117000726

Trottier, N. L., L. J. Johnston, and C. F. M. de Lange. 2015. Applied amino acid and energy feeding of sows. Chapter 6. In: C. Farmer, editor, *The gestating and lactating sow*. Wageningen, the Netherlands: Wageningen Academic Publishers; p. 117–145. doi: 10.3920/978-90-8686-803-2

Viazzi, S., G. Ismayilova, M. Oczak, L. T. Sonoda, M. Fels, M. Guarino, E. Vranken, J. Hartung, C. Bahr, and D. Berckmans. 2014. Image feature extraction for classification of aggressive interactions among pigs. *Comput. Electron. Agric.* **104**:57–62. doi: 10.1016/j.compag.2014.03.010