Dynamic modeling of nutrient use and individual requirements of lactating sows[1]

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ABSTRACT: Nutrient requirements of sows during lactation are related mainly to their milk yield and feed intake, and vary greatly among individuals. In practice, nutrient requirements are generally determined at the population level based on average performance. The objective of the present modeling approach was to explore the variability in nutrient requirements among sows by combining current knowledge about nutrient use with on-farm data available on sows at farrowing [parity, BW, backfat thickness (**BT**)] and their individual performance (litter size, litter average daily gain, daily sow feed intake) to estimate nutrient requirements. The approach was tested on a database of 1,450 lactations from 2 farms. The effects of farm (**A**, **B**), week of lactation (**W1**: week 1, **W2**: week 2, **W3+**: week 3 and beyond), and parity (**P1**: 1, **P2**: 2, **P3+**: 3 and beyond) on sow performance and their nutrient requirements were evaluated. The mean daily ME requirement was strongly correlated with litter growth (R^2 = 0.95; P < 0.001) and varied slightly according to sow BW, which influenced the maintenance cost. The mean daily standardized ileal digestible (**SID**) lysine requirement was influenced by farm, week of lactation, and parity. Variability in SID lysine requirement per kg feed was related mainly to feed intake (R^2 = 0.51; P < 0.001) and, to a smaller extent, litter growth (R^2 = 0.27; P < 0.001). It was lowest in W1 (7.0 g/kg), greatest in W2 (7.9 g/kg), and intermediate in W3+ (7.5 g/kg; P < 0.001) because milk production increased faster than feed intake capacity did. It was lower for P3+ (6.7 g/kg) and P2 sows (7.3 g/kg) than P1 sows (8.3 g/kg) due to the greater feed intake of multiparous sows. The SID lysine requirement per kg of feed was met for 80% of sows when supplies were 112 and 120% of the mean population requirement on farm A and B, respectively, indicating higher variability in requirements on farm B. Other amino acid and mineral requirements were influenced in the same way as SID lysine. The present modeling approach allows to capture individual variability in the performance of sows and litters according to farm, stage of lactation, and parity. It is an initial step in the development of new types of models able to process historical farm data (e.g., for *ex post* assessment of nutrient requirements) and real-time data (e.g., to control precision feeding).

Key words: amino acids, feed intake, milk production, mineral, model, sow

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INTRODUCTION

Nutrient requirements during lactation depend mainly on milk yield and feed intake, and vary greatly among individuals (NRC, 2012). In practice, however, the same standard lactation diet is generally delivered to all sows in the herd, and nutrient intake is often insufficient to meet nutrient requirements (Noblet et al., 1990), especially of primiparous sows. Sows experiencing negative energy balance can, to some extent, maintain their milk production by using their body energy reserves (Noblet and Etienne, 1986), while milk production appears more sensitive to protein or amino acid deficiency (Richert et al., 1997; NRC, 2012), which may influence the subsequent reproductive performance of sows (Trottier et al., 2015). Conversely, sows receiving more nutrients than required release large amounts of nitrogen and phosphorus in excreta, which results in increased environmental impacts and feeding costs. Although nutrient requirements seem to vary greatly due to variability in milk yield and feed intake, those during lactation are usually established at the population level, or for an average sow that represents the herd. Variability in the performance of sows within the herd is thus generally not considered or is considered only by using security margins (NRC, 2012). In recent years, development of innovative feeders and availability of technologies for high-throughput phenotyping of individual sows provide new opportunities to better adapt nutrient supplies to individual performance and requirements. Precision feeding has been successfully evaluated for growing pigs (Cloutier et al., 2015) and gestating sows (Dourmad et al., 2017) but not yet for lactating sows. Developing precision feeding during lactation first requires modeling evolution in nutrient use for each sow. The objective of the model developed is thus to explore the variability in energy, amino acids, and mineral requirements among sows, both per day and per kg of feed.

MATERIALS AND METHODS

The animal data used in this modeling approach were obtained from 2 studies which received approval from the University Laval and from the Sherbrooke Research and Development Centre of Agriculture and Agri-Food Canada animal use and care committees. They were carried out in accordance with the recommendations of the Canadian Council on Animal Care (CCAC, 2009).

General Approach

The originality of the approach developed (Fig. 1) is the combination of current knowledge about nutrient use of sows with the flow of data recorded on-farm during lactation. These data include 1) farrowing events [date of farrowing, parity, BW, and backfat thickness (**BT**) of sows, number and weight of piglets at birth and after litter homogenization], 2) events that occur during lactation (piglet cross-fostering and mortality, daily sow feed intake), and 3) weaning events (date of weaning, litter size, and litter weight). In practice, the farmer or sensors can record these types of data, which may provide a more accurate and dynamic prediction of nutrient requirements. A mechanistic module based mainly on the InraPorc model (Dourmad et al., 2008), was used on a daily basis to calculate nutrient requirements and predict changes in sow body reserves according to estimated milk production and measured feed intake. The module calculates daily maintenance costs and milk production costs for each sow, considering its daily performance. With this approach, nutrient requirements may change according to days in milk, performance, and individual farm situation.

Determining Nutrient Requirements

Nutrient use. Energy and amino acids are partitioned between maintenance costs and milk production costs. As Feyera and Theil (2017) described, the energy and amino acids that sows release during postpartum uterine involution also contribute to milk synthesis (Table 1, Eq. 1 and 6). Body reserves may also provide large amounts of lipids and protein in response to nutritional deficiencies. From Eq. 1 and 6, requirements were estimated without considering maternal energy supplies (**ER$_m$**) or amino acids (**AAR$_m$**), except those from the involuting uterus.

Milk production. In relation to the factorial approach, nutrient requirements of lactating sows are usually estimated from the quantity of milk

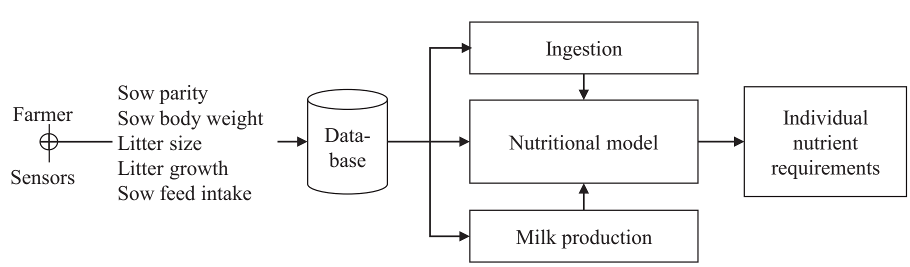

Figure 1. Estimate of individual nutrient requirements from data collected on-farm.

Table 1. Main equations describing daily nutrient use of lactating sows[1]

Item	Equation	No.
Utilization of ME	$ME = ME_m + E_{milk}/k_{milk} ER_m/k_{rm} E_U \times k_{rm}/k_{milk}$	[1]
ME for maintenance[2], kJ/d	$ME_m(t) = 460 \times BW^{0.75}(t)$	[2]
Efficiency of ME for milk production[3]	$k_{milk} = 0.72$	
Efficiency of body reserves for milk production[3]	$k_{rm} = 0.88$	
Energy exported in milk[4,12], kJ/d	$E_{milk}(t) = (20.6 \times LADG\ 376 \times LS) \times \alpha(t)$	[3]
Energy content of the uterus wall[5], kJ	$\log(E_U) = 9.853\ \ 3.098 \times \exp(-0.006915 \times 115) + 0.06542 \times n$	[4]
Energy from uterine involution, kJ/d	$E_U(t) = \log(E_U) \times \exp[-\log(2)/\lambda \times (t-1)] - \log(E_U) \times \exp[-\log(2)/\lambda \times t]$	[5]
Utilization of AA	$AA = AA_m + (Prot_{milk} \times AA_{milk}/k_{AA}) - (AA_U + AAR_m) \times k_{AA}$	[6]
AA for maintenance, g/d	$AA_m(t) = [(AA_d + AA_{turn}) \times BW^{0.75}(t)] + AA_e \times DMI(t)$	[7]
Protein exported in milk[4,12], g/d	$Prot_{milk}(t) = (0.0257 \times LADG + 0.42 \times LS) \times 6.38 \times \alpha(t)$	[8]
Protein content of the uterus wall[5], g	$\log(Prot_U) = 7.653 - 4.207 \times \exp(-0.004477 \times 115) + 0.07239 \times n$	[9]
Protein from uterine involution, g/d	$Prot_U(t) = Prot_U \times \exp[-\log(2)/\lambda \times (t-1)]\ Prot_U \times \exp[-\log(2)/\lambda \times t]$	[10]
NR balance associated with Lys_{SID}[6], g/d	$NR_{lys}(t) = -14.2 + 1.335 \times Lys_{SID}(t) - 0.629 \times Prot_{milk}(t)/6.38 + Prot_U(t) \times 0.065$	[11]
Utilization of minerals (M)[7]	$M_{req}(t) = M_m(t) + M_{milk}(t)/0.98$	[12]
Phosphorus (P) for maintenance[8], g/d	$P_m(t) = 0.010 \times BW(t)$	[13]
P exported in milk[8,9], g/d	$P_{milk}(t) = Prot_{milk}(t) \times 1.55/50$	[14]
Calcium (Ca) for maintenance[7], g/d	$Ca_m(t) = 0.014 \times BW(t)$	[15]
Ca exported in milk[7], g/d	$Ca_{milk}(t) = P_{milk}(t) \times 1.37$	[16]
Half-life of postpartum uterine involution[10,11]**, d**	$\lambda = 6.2$	[17]
Milk production[12]**, kg/d**	$MP(t) = a \times t^b \times e^{(-c \times t)}$	[18]
	$a = \exp[1/3 \times (-ly_{20} \times \log(128/27) - 3 \times \log(20) \times ly_{30} + 5 \times \log(20) \times ly_{20} - 2 \times \log(20) \times ly_5 + 4 \times ly_5 \times \log(128/27) + 12 \times ly_{30} \times \log(5) - 20 \times \log(5) \times ly_{20} + 8 \times \log(5) \times ly_5)/\log(128/27)]$	
	$b = -(3 \times ly_{30} - 5 \times ly_{20} + 2 \times ly_5)/\log(128/27)$	
	$c = 1/15 \times [ly_5 \times \log(128/27) - ly_{20} \times \log(128/27) - 3 \times \log(20) \times ly_{30} + 5 \times \log(20) \times ly_{20} - 2 \times \log(20) \times ly_5 + 3 \times ly_{30} \times \log(5) - 5 \times \log(5) \times ly_{20} + 2 \times \log(5) \times ly_5]/\log(128/27)$	
	$ly_5 = 1.93 + 0.07 \times (LS - 9.5) + 0.04 \times (LADG - 2.05)$	
	$ly_{20} = 2.23 + 0.05 \times (LS - 9.5) + 0.23 \times (LADG - 2.05)$	
	$ly_{30} = 2.15 + 0.02 \times (LS - 9.5) + 0.31 \times (LADG - 2.05)$	
Milk production factor[12]	$\alpha(t) = MP(t)/MP_{average}$	[19]
Chemical composition of sows[6]	$Lipids(t),\ kg/d = -26.4 + 0.221 \times EBW(t) + 1.331 \times BT(t)$	[20]
	$Protein(t),\ kg/d = 2.28 + 0.178 \times EBW(t) + 0.333 \times BT(t)$	[21]
	$Energy(t),\ MJ/d = -1{,}074 + 13.65 \times EBW(t) + 45.94 \times BT(t)$	[22]

[1]ME = utilization of metabolizable energy, ME_m = ME for maintenance (kJ/d), t = days in milk during the lactation period (d), E_{milk} = energy in milk (kJ/d), k_{milk} = efficiency of ME for milk production, ER_m = energy from body reserves (kJ/d), k_{rm} = efficiency of energy from body reserves for milk production, E_U = energy from uterine involution (kJ/d), BW = body weight (kg), LADG = litter average daily gain (g), LS = litter size (number of piglets), α (t) = milk production factor per sow and per day, n = number of fetuses, AA = utilization of digestible AA (g/d), AA_m = AA for maintenance (g/d), $Prot_{milk}$ = protein exported in milk (g/d), AA_{milk} = AA composition of milk (g/d), k_{AA} = efficiency of AA for milk production, AA_U = AA from uterine involution (g/d), AAR_m = AA from body reserves (g/d), AA_d = AA losses due to desquamation (g/d), AA_{turn} = AA losses due to turnover (g/d), AA_e = AA endogenous losses (g/kg DMI), DMI = dry matter intake (kg), $Prot_U$ = protein from uterine involution (g/d), NR_{lys} = nitrogen retention balance associated with standardized ileal digestible lysine (g/d), Lys_{SID} = standardized ileal digestible lysine intake (g/d), M_{req} = mineral requirements (g/d), M_m = mineral for maintenance (g/d), M_{milk} = mineral exported in milk (g/d), P_m = phosphorus for maintenance (g/d), P_{milk} = phosphorus exported in milk (g/d), Ca_m = calcium for maintenance (g/d), Ca_{milk} = calcium exported in milk (g/d), λ = half-life of postpartum uterine involution (d), MP = milk production (kg), $MP_{average}$ = average milk production for the lactation period (kg/d). The parameters of the Wood equation, ly 5, ly 20 and ly 30 represent the natural logarithm of the milk yield at d 5, 20, and 30 of lactation, EBW = empty body weight (kg), BT = back fat thickness (mm).

[2]Noblet et al. (1990)

[3]Noblet and Etienne (1987)

[4]Noblet and Etienne (1989)

[5]Noblet (1990)

[6]Dourmad et al. (1998)

[7]Bikker and Blok (2017)

[8]Jondreville and Dourmad (2005)

[9]Guéguen and Perez (1981)

[10]Palmer et al. (1965)

[11]Graves et al. (1967)

[12]Hansen et al. (2012)

components produced (Noblet and Etienne, 1989; NRC, 2012). Determining the lactation curve is therefore essential to describe the amounts of nutrients required each day to produce milk. The Wood's nonlinear model, firstly developed for dairy cows (Wood, 1967), has been applied to other species including small ruminants, horses, and sows. The present model used the lactation curve of Hansen et al. (2012), who used meta-analysis to reparameterize the Wood lactation curve (Wood, 1967) as the natural logarithm of milk production at days 5, 20, and 30 (Eq. 18). The daily change in milk production is represented for each sow with a factor (α (t)) that integrates the effects of litter size and litter growth (Eq. 19).

Metabolizable energy requirement. During lactation, the energy requirement for maintenance was estimated as 460 kJ ME/kg $BW^{0.75}$ (Noblet et al., 1990) (Eq. 2) and was assumed to be unaffected by thermoregulation and activity. According to Noblet and Etienne (1987), the efficiency of ME for milk production ($\mathbf{k_{milk}}$) of 72%, and that of energy mobilized from body reserves ($\mathbf{k_{rm}}$) of 88% were used. Energy in milk was calculated for each sow based on litter average daily gain and litter size (Noblet and Etienne, 1989; NRC, 2012) (Eq. 3). This equation was combined with the daily milk production factor (α (t)) to estimate the daily amount of energy exported in milk. In the present model, energy provided during postpartum uterine involution contributes to the total energy supply with the same efficiency as that from body reserves (k_{rm}). Energy content in the uterine wall at 115 d of gestation was estimated as a function of the number of fetuses (Eq. 4) (Noblet, 1990). The half-life of postpartum uterine involution was 6.2 d (Eq. 17), based on Graves et al. (1967) and Palmer et al. (1965). Daily energy release from the uterus was then calculated according to uterine energy content at parturition and its exponential rate of involution (Eq. 5).

Standardized ileal digestible amino acid requirements. Maintenance and milk production costs were calculated for all essential amino acids considering the contribution of uterine release (Table 1; Eq. 6). The maintenance requirement was estimated as the sum of desquamation, minimum protein turnover, and basal endogenous intestinal losses (NRC, 2012; Eq. 7). Integument losses (skin and hair) were estimated for each amino acid according to sow metabolic weight ($\mathbf{AA_d}$; Moughan, 1999). The requirement for minimum protein turnover ($\mathbf{AA_{turn}}$), also expressed per kg of metabolic weight (Table 2), reflects the minimum amino acid catabolism (NRC, 2012). Basal endogenous losses ($\mathbf{AA_e}$) are composed of protein secreted in the intestinal tract and not reabsorbed by the sow. They depend on feed dry matter intake (Eq. 7; Sauvant et al., 2004). The requirement for milk production was estimated for each amino acid, on a daily basis, from the amount of protein exported in the milk (Eq. 8), the amino acid content in sow milk (NRC, 2012), and a maximum marginal efficiency of utilization ($\mathbf{k_{AA}}$; Table 2). The maximum efficiency of standardized ileal digestible (**SID**) amino acid utilization was considered a constant value and was calculated from the ideal amino acid profile for lactation according to the approach developed by van Milgen et al. (2008) for fattening pigs and used by Strathe et al. (2015) for lactating sows. It was assumed that the ideal amino acid profile was obtained for an average sow weighing 180 kg, consuming 5.5 kg/d, with a litter growth of 2,200 g/d, and a litter size of 11 piglets. Using these data, the information in Table 2, and assuming that the maximum efficiency of lysine is 0.78 (Dourmad et al., 1998), the maximum efficiency of each amino acid was calculated. The result of this approach is that the maximum efficiencies of SID amino acids for milk are constant, while the ideal amino acid profile may vary according to the relative contribution of requirements for maintenance and milk production, which have different AA profiles, to total requirement. Protein content in the uterine wall at 115 d of gestation was estimated as a function of the number of fetuses (Eq. 9; Noblet, 1990). Daily protein release from the uterus was then calculated according to the uterine wall protein content at parturition and its exponential rate of involution (Eq. 10). Amino acids released during postpartum uterine involution are assumed to be used with the same k_{AA} efficiency as SID amino acids from feed (Table 2), assuming that they join the same blood pool of AA as the absorbed AA. Even if amino acid requirements are met, energy deficiency seems to lead to a minimum protein mobilization (Dourmad et al., 2008). The minimum ratio of catabolized protein to catabolized lipids was set at a default value of 1:20 (Pomar et al., 1991), given the relative lack of information on this topic in the literature. Each day, the balance between requirements and intake was calculated for each amino acid, and the most limiting amino acid was used to estimate body protein mobilization (Eq. 11).

Phosphorus and calcium requirements. Standardized total tract digestible phosphorus

Table 2. Maximum efficiency of using standardized ileal digestible protein and amino acids for milk protein deposition, calculated from the ideal amino acid profile, maintenance requirements and body composition

AA	Integument loss[1] (AA_d), mg/kg $BW^{0.75}$	Losses due to basal turnover[1] (AA_{turn}), mg/kg $BW^{0.75}$	Basal endogenous losses[2] (AA_e), g/kg DMI	Content in maternal body protein[3], g/16 g N	Ideal amino acid profile[4], % of Lysine	Milk composition[5], g/16 g N	Maximum efficiency (k_{AA})
Lysine	4.5	23.9	0.313	6.96	100	7.0	0.78[6]
Methionine	1.0	7.0	0.087	1.88	30	1.9	0.70
Cystine	4.7	4.7	0.140	1.03	30	1.6	0.61
Tryptophan	0.9	3.5	0.117	0.95	19	1.3	0.76
Threonine	3.3	13.8	0.330	3.70	66	4.3	0.74
Phenylalanine	3.0	13.7	0.273	3.78	60	4.1	0.77
Tyrosine	1.9	9.0	0.223	2.86	55	4.0	0.81
Leucine	5.3	27.1	0.427	7.17	115	8.4	0.82
Isoleucine	2.5	12.4	0.257	3.46	60	3.9	0.74
Valine	3.8	16.4	0.357	4.67	85	5.0	0.66
Histidine	1.3	10.2	0.130	2.79	42	3.0	0.80
Arginine	0.0	0.0	0.280	6.26	67	4.8	0.78
Methionine + Cystine	5.7	11.7	0.227	2.91	60	3.5	0.66
Phenylalanine + Tyrosine	4.9	22.7	0.496	6.64	115	8.1	0.79

[1]Moughan (1999)

[2]From Noblet et al. (2004)

[3]From Le Bellego and Noblet (2002)

[4]Dourmad et al. (2008)

[5]NRC (2012)

[6]The maximum marginal efficiencies were calculated based on the assumption that the amino acid profile is obtained for a sow weighing 180 kg, consuming 5.5 kg/d, with a litter growth of 2,200 g/d and a litter size of 11 piglets. The maximum efficiency of lysine was set at 0.78 (Dourmad et al., 1998) and the k_{AA} values of the other amino acids were estimated such as $k_{AA} = (Prot_{milk} \times AA_{milk}) / [(Lys_m + (Prot_{milk} \times Lys_{milk}) / 0.78) \times Id(AA:Lys) - AA_m]$, where k_{AA} is the marginal efficiency of amino acid "AA", $Prot_{milk}$ is the protein content of milk, AA_{milk} is the AA content of milk protein, Lys_{milk} is the lysine content of milk protein, Lys_m is the lysine maintenance requirement, AA_m is the AA maintenance requirement, 0.78 is the marginal efficiency of lysine for milk production, and Id(AA:Lys) is the AA:Lys ratio in the ideal protein for lactation.

(**STTD P**) and calcium (**STTD Ca**) requirements were estimated as the sum of requirements for maintenance and milk production (Eq. 12). The maintenance requirement was determined according to the literature review of Bikker and Blok (2017) and was 10 and 14 mg/kg BW for P and Ca, respectively (Eq. 13 and 15). The amounts of P and Ca in milk were estimated from milk protein content, assuming a milk P:protein ratio of 0.031 (Eq. 14; Jondreville and Dourmad, 2005; NRC 2012) and a milk Ca:P ratio in milk of 1.37 (Eq. 16; Bikker and Blok, 2017). As determined by Bikker and Blok (2017), an efficiency of 0.98 of STTD P and STTD Ca for milk was used. The total Ca requirement and Total Ca:STTD P ratio were estimated assuming 50% digestibility for STTD Ca (Bikker and Blok, 2017).

Sow body condition and chemical composition. Body weight and BT at farrowing were used to determine each sow's initial energy, protein, and fat contents (Eq. 20–22; Dourmad et al., 1998). Changes in BW and BT during lactation were then simulated based on the amounts of mobilized energy (**ER_m**), fat, and protein derived from the nitrogen balance (**NR**) and were used for factorial calculation of maintenance requirements.

Description of the Database

A database from 2 experimental farms (Table 3) was used to represent the variability in sow and litter performances. The 2 datasets contained the same information on sows: parity, body condition at farrowing (i.e., BW, BT), and daily sow feed intake during lactation. Litter size was recorded at birth, after homogenization within 2 d of lactation, and at weaning. All events that influence litter size during lactation (e.g., piglet cross-fostering or death) were recorded, as were dates of farrowing and weaning. The first dataset (farm **A**), provided by the "Centre de Développement du Porc du Québec" (Québec City, Canada), contained data from 633 lactations, with an average parity of 3.9 (SD = 2.2) and an average BW of 241 (SD = 33.4) kg (Cloutier et al., unpublished data). The litter size averaged 11.6

Table 3. Description of lactating sows in the 2 databases used to estimate sow requirements

	No	Mean	SD	10th percentile	90th percentile
Farm A					
Sow parity	633	3.9	2.2	1.0	7.0
Sow body weight, kg	633	241.2	33.4	193.8	284.6
Sow backfat, mm	633	18.4	4.2	12.9	24.0
Sow feed intake, kg/d	633	6.5	1.2	5.0	8.2
Lactation duration, d	633	25.2	2.7	22.0	27.0
Sucking litter size	633	11.6	1.6	9.5	13.3
Litter weight gain, kg/d	633	2.56	0.34	2.14	2.99
Farm B					
Sow parity	817	1.9	0.8	1.0	3.0
Sow body weight, kg	817	218.3	24.7	186.5	250.5
Sow backfat, mm	817	14.5	4.0	9.2	20.3
Sow feed intake, kg/d	817	5.8	1.3	4.2	7.6
Lactation duration, d	817	18.6	2.6	15.0	22.0
Sucking litter size	817	11.9	1.2	10.3	13.3
Litter weight gain, kg/d	817	2.63	0.55	1.91	3.33

(SD = 1.6) suckling piglets, with an average daily weight gain of 2,569 (SD = 343) g. The duration of lactation was 25.2 (SD = 2.7) days. The second dataset (farm **B**), provided by Laval University (Québec City, Canada), contained data from 817 lactations, with an average parity of 1.9 (SD = 0.8) and an average BW of 218 (SD = 24.7) kg (Lemay and Guay, 2017). Parity was relatively low, mainly because this farm was used for selection purposes. Litter size averaged 11.9 (SD = 1.2) suckling piglets per sow, with an average daily weight gain of 2,633 (SD = 554) g. Lactation was shorter, with an average duration of 18.6 (SD = 2.6) days. In both datasets, sows were fed close to ad libitum using an automated feeder (Gestal, JYGA Technologies, Québec, Canada) that recorded daily feed intake and feeding behavior.

Calculations and Statistical Methods

The computational model was implemented using Python 3 (Python Software Foundation, Beaverton, OR). It simulated daily performance of each sow using the information available in the database and the calculated energy, amino acid, and mineral requirements. All statistical analyses of inputs and simulated data were calculated using the appropriate GLM procedure (SAS v9.4, SAS Inst., Cary, NC), considering statistical significance when $P < 0.05$, with fixed effects of farm (**A**, **B**), week of lactation (**W1**: week 1, **W2**: week 2, **W3+**: week 3 and beyond), parity (**P1**: 1, **P2**: 2, **P3+**: 3 and beyond), interaction between farm and week of lactation, interaction between farm and parity, and a random sow effect to consider repeated measurements within a lactation period. Standardized ileal digestibility amino acid and STTD mineral requirements per kg of feed were estimated for each week based on the mean daily requirements and mean daily feed intake of the studied stage.

RESULTS

Performance

Mean sow feed intake, milk energy, and protein outputs differed between farms and among weeks of lactation and parities ($P < 0.001$; Table 4). Sow feed intake was higher on farm A than farm B (6.54 and 5.84 kg/d, respectively). Feed intake was lower in W1 (4.48 kg/d) than in W2 and W3+ (6.59 and 7.42 kg/d, respectively). Feed intake also increased with parity, from 5.19 to 6.75 kg/d for P1 and P3+ sows, respectively. The mean milk energy output was higher on farm B than farm A (49.8 and 48.6 MJ/d, respectively; $P = 0.001$). Milk energy output was lowest in W1 (34.8 MJ/d), intermediate in W2 (56.0 MJ/d), and highest thereafter (58.1 MJ/d). Among parities, P2 sows had the highest milk energy output, while P1 sows had the lowest. The mean milk protein output was also higher on farm B than farm A (463 and 452 g/d, respectively) (Fig. 2). Milk protein output increased with week of lactation, from 326 to 539 g/d for W1 and W3+, respectively. Like for energy output, protein output was highest for P2 sows and lowest for P1 sows. The interaction between farm and week was significant for feed intake, with lower intake in early lactation on farm B (Fig. 3), and for milk energy and protein, with a more pronounced increase in output with

Table 4. Influence of farm, week of lactation, and sow parity on performance and calculated ME, standardized ileal digestible (SID) lysine and standardized total tract digestible (STTD) phosphorus and calcium requirements[1]

	Farm		Week of lactation			Parity				*P*-value				
Item	A	B	1	2	3+	1	2	3+	RSD[2]	Fm	P	W	Fm × W	Fm × P
No. of sows	633	817	1,450	1,450	1,397	454	379	617						
Performance														
Feed intake, kg/d	6.54	5.84	4.48[c]	6.59[b]	7.42[a]	5.19[c]	6.30[b]	6.75[a]	0.98	<0.001	<0.001	<0.001	<0.001	0.27
Milk energy, MJ/d	48.6	49.8	34.8[c]	56.0[b]	58.1[a]	47.5[c]	51.1[a]	49.4[b]	4.8	0.001	<0.001	<0.001	<0.001	0.07
Milk protein, g/d	452	463	326[c]	521[b]	539[a]	446[c]	474[a]	459[b]	42.5	<0.001	<0.001	<0.001	<0.001	0.11
ME														
Requirement, MJ/d	94.6	94.1	74.0[c]	103.7[b]	106.7[a]	89.2[b]	96.6[a]	96.7[a]	6.6	0.01	<0.001	<0.001	<0.001	<0.001
Balance, MJ/d	−9.6	−18.1	−15.9[b]	−18.0[c]	−10.3[a]	−21.7[c]	−14.7[b]	−9.0[a]	13.6	<0.001	<0.001	<0.001	<0.001	0.005
SID lysine requirement														
Mean, g/d	43.1	43.6	30.2[c]	49.3[b]	51.7[a]	41.8[c]	44.8[a]	43.7[b]	3.8	0.01	<0.001	<0.001	<0.001	0.08
Mean, g/kg	6.8	7.8	7.0[c]	7.9[a]	7.5[b]	8.3[a]	7.3[b]	6.7[c]	1.6	<0.001	<0.001	<0.001	<0.001	0.004
STTD P requirement														
Mean, g/d	16.7	16.8	12.6[c]	18.7[b]	19.3[a]	16.0[b]	17.2[a]	17.0[a]	1.3	0.003	<0.001	<0.001	<0.001	0.01
Mean, g/kg	2.6	3.0	2.9[b]	3.0[a]	2.8[c]	3.2[a]	2.8[b]	2.6[c]	0.6	<0.001	<0.001	<0.001	<0.001	0.001
STTD Ca requirement														
Mean, g/d	22.9	23.1	17.3[c]	25.7[b]	26.5[a]	22.0[b]	23.6[a]	23.3[a]	1.8	0.003	<0.001	<0.001	<0.001	0.01
Mean, g/kg	3.6	4.1	4.0[b]	4.1[a]	3.9[c]	4.4[a]	3.9[b]	3.6[c]	0.9	<0.001	<0.001	<0.001	<0.001	0.001

[a–c]Means within a row with different superscripts significantly differ ($P < 0.05$)

[1]Data were analyzed using a generalized linear model that included the effect of farm (Fm), week of lactation (W), sow parity (P), interaction between farm and week of lactation (Fm × W), interactions between farm and parity (Fm × P), and a random sow effect to consider repeated measurements within a lactation period

[2]RSD = residual standard deviation.

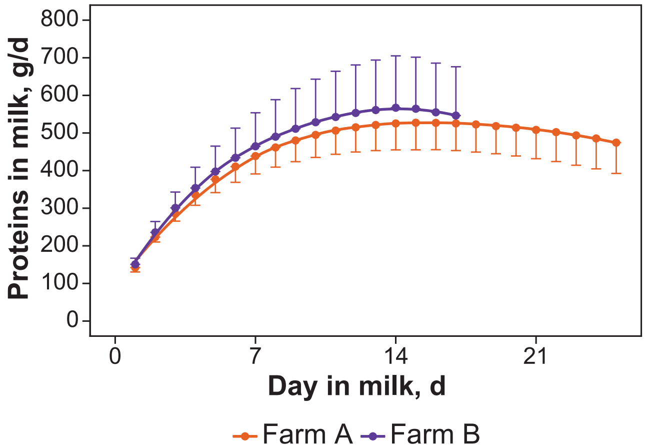

Figure 2. Mean milk protein output and variability on farm A (Cloutier et al., 2019, unpublished data) and B (Lemay and Guay, 2017) during lactation. Error bars represent 1 standard deviation.

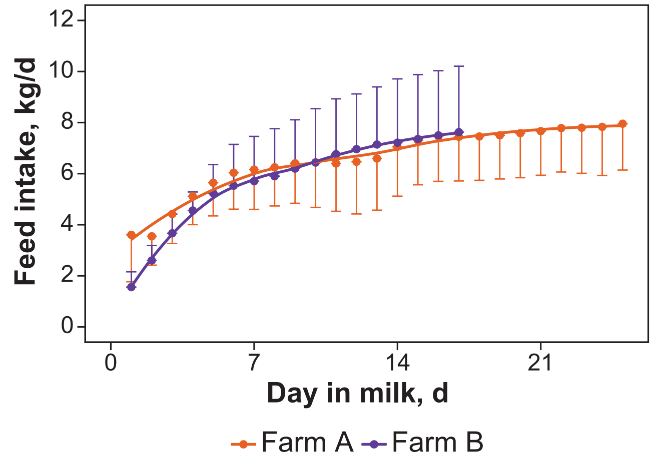

Figure 3. Mean feed intake and variability on farm A (Cloutier et al., 2019, unpublished data) and B (Lemay and Guay, 2017) during lactation. Error bars represent 1 standard deviation.

day in milk (Fig. 2) on farm B. No interaction was found between farm and parity.

Energy Requirements and Energy Balance

The mean daily energy requirement was strongly correlated with litter growth (Fig. 4), with an R^2 of 0.95 ($P < 0.001$), but varied slightly according to sow BW, which influenced maintenance cost. Although milk energy output was higher on farm B, the total ME requirement was slightly lower (94.1 MJ/d) than that on farm A (94.6 MJ/d; $P < 0.01$) because farm A had the heaviest sow BW. Week and parity had a large influence on the energy requirement ($P < 0.001$). The ME requirement increased with week of lactation, from 74.0 MJ/d (W1) to more than 100 MJ/d (W2 and W3+, respectively; $P < 0.001$). The ME requirement was higher for P2 and P3+ sows (96.6 and 96.7 MJ/d, respectively) than for P1 sows (89.2 MJ/d; $P < 0.001$), due to higher maintenance requirements in older sows.

The mean energy balance, calculated for a diet containing 13.0 MJ ME/kg, was negative for both farms and all weeks and parities. The energy balance varied greatly among sows and was negative for sows consuming less than 7.51 kg/d ($P < 0.001$; Fig. 5). It was also negative when litter growth exceeded 1,960 g/d ($P < 0.001$). The energy balance was lower on farm B than farm A (−18.1 and −9.6 MJ ME/d, respectively). The largest deficit occurred in W2 (−18.0 MJ ME/d; $P < 0.001$). The energy deficit was larger for P1 than P2 and P3+ sows (−21.7, −14.7 and −9.0 MJ ME/d, respectively; $P < 0.001$).

The total amount of energy released during postpartum uterine involution averaged 11.3 (SD = 2.6) MJ per sow and was larger on farm A (12.0 MJ) than farm B (10.7 MJ; $P < 0.001$). It was also larger for P3+ (12.2 MJ) than P1 (10.5 MJ) and P2 (10.8 MJ) sows ($P < 0.001$). Approximately 60% of the energy from postpartum uterine involution was released in W1, 27% in W2, and 13% in W3+.

Standardized Ileal Digestible Lysine Requirement

The daily SID lysine requirement was strongly correlated with milk protein output, with an R^2 of 0.99 ($P < 0.001$). The SID lysine requirement differed between farms A and B (43.1 and 43.6 g/d, respectively; $P < 0.01$). The mean SID requirement per kg of feed was strongly correlated with feed intake ($R^2 = 0.51$, $P < 0.001$), and correlated to a smaller extent with litter growth ($R^2 = 0.27$, $P < 0.001$; Fig. 6).

Week and parity had strong effects on the daily SID lysine requirement ($P < 0.001$). The SID lysine requirement increased with week of lactation, from 30.2 (W1) to 49.3 (W2) and 51.7 g/d (W3+). It was lower for P1 (41.8 g/d) than P2 and P3+ sows (44.8 and 43.7 g/d, respectively). The mean SID lysine requirement per kg of feed was lower on farm A than farm B (6.8 and 7.8 g/kg, respectively; $P < 0.001$). The dietary SID lysine content needed to meet the requirement of 80% of the sows was 7.6 and 9.4 g/kg on farm A and B, respectively (Fig. 7), which is 11.8 and 20.5% higher than the mean requirement, respectively. The mean requirement per kg of feed was lowest in W1 (7.0 g/kg), highest in W2 (7.9), and intermediate (7.5 g/kg) in W3+. On average for the 2 farms, the SID lysine concentration needed to meet the requirement of 80% of the sows was 8.3, 9.4, and 8.8 g/kg in W1, W2, and W3+, respectively (Fig. 8). Parity also influenced

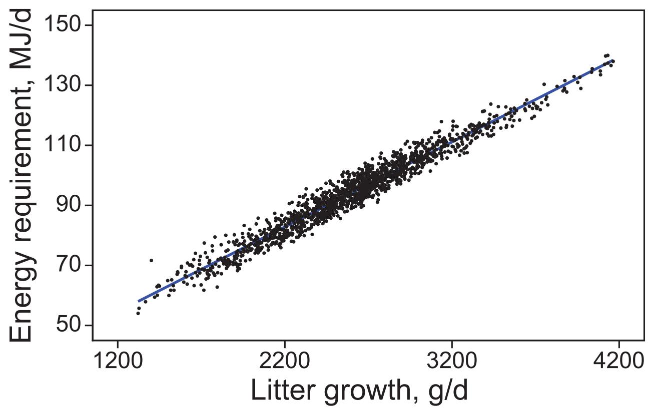

Figure 4. Mean daily metabolizable energy requirement per lactating sow as a function of litter growth ($R^2 = 0.95$; blue line). Each point represents the mean requirement of a lactating sow for the lactation period.

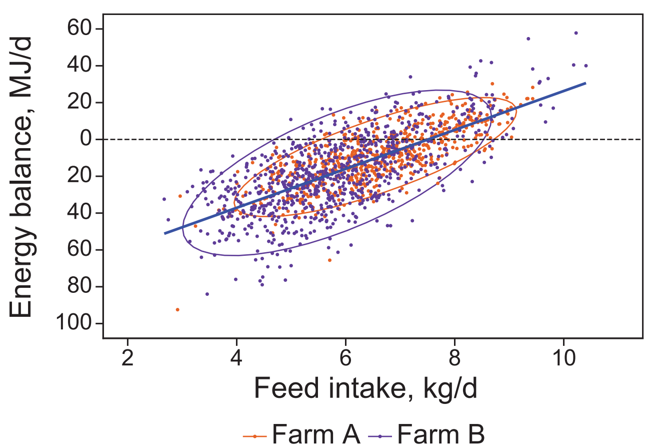

Figure 5. Mean metabolizable energy balance per lactating sow as a function of feed intake ($R^2 = 0.52$; blue line). Each point represents the mean balance of a lactating sow for the lactation period.

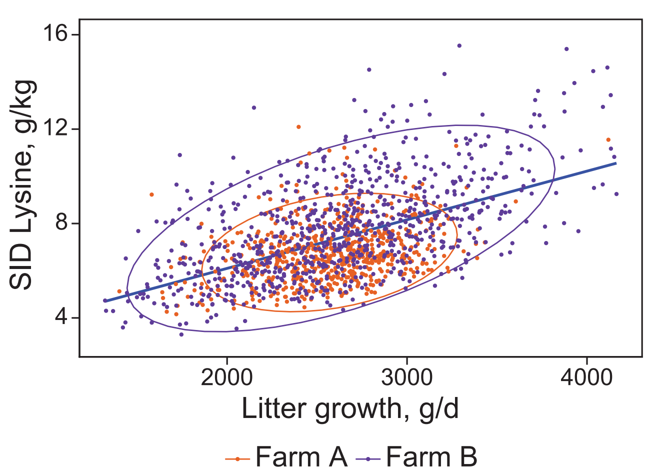

Figure 6. Mean standardized ileal digestible lysine requirement per lactating sow as a function of litter growth ($R^2 = 0.99$; blue line). Each point represents the mean requirement of a lactating sow for the lactation period.

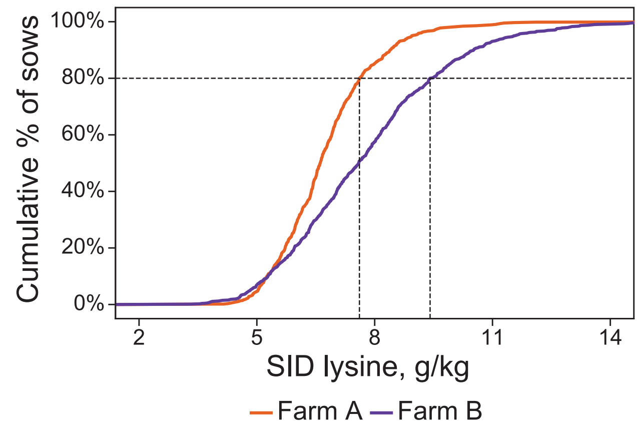

Figure 7. Cumulative distribution of the standardized ileal digestible (SID) lysine requirement per kg of feed according to farm. Vertical dashed lines represent the dietary concentration of SID lysine needed to meet the requirement for 80% of the sows on each farm.

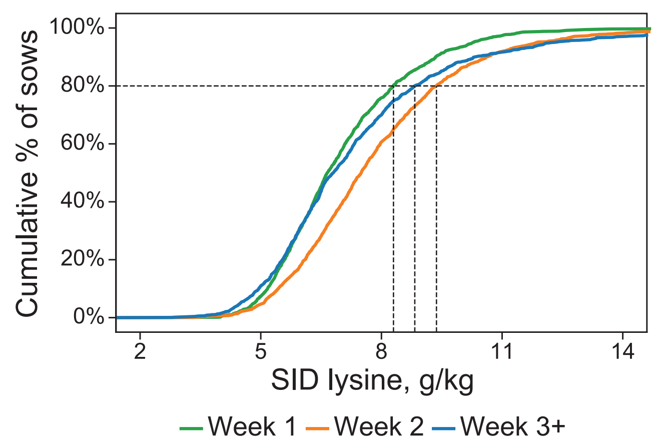

Figure 8. Cumulative distribution of the standardized ileal digestible (SID) lysine requirement per kg of feed according to week of lactation. Vertical dashed lines represent the dietary concentration of SID lysine needed to meet the requirement for 80% of the sows during each week of lactation.

the SID lysine requirement, with mean values of 8.3, 7.3, and 6.7 g/kg for P1, P2, and P3+ sows, respectively. The SID lysine concentration needed to meet the requirement of 80% of sows was 9.8, 8.6, and 7.6 g/kg for P1, P2, and P3+ sows, respectively (Fig. 9).

The total amount of lysine released by the involuting uterus averaged 29.7 (SD = 7.5) g per sow, over an average lactation of 21.9 d. This amount was larger on farm A (31.7 g) than farm B (28.2 g; $P < 0.001$) and was also influenced by parity, with a larger contribution for P3+ (32.3 g) than P1 (27.4 g) and P2 sows (28.4 g). Approximately 60% of lysine from postpartum uterine involution was released in W1, 27% in W2, and 13% in W3+.

Changes in other amino acid requirements per day and per kg of feed according to farm, week of lactation, and parity were similar to those observed for SID lysine, due to the low variation in the profile of amino acid requirements. The ratio of SID AA requirement per 100 g SID lysine requirement (mean ± SD) was 30.2 ± 0.5 g/100 g for methionine, 60.6 ± 0.3 g/100 g for methionine and cysteine, 19.1 ± 0.2 g/100 g for tryptophan, 66.4 ± 0.4 g/100 g

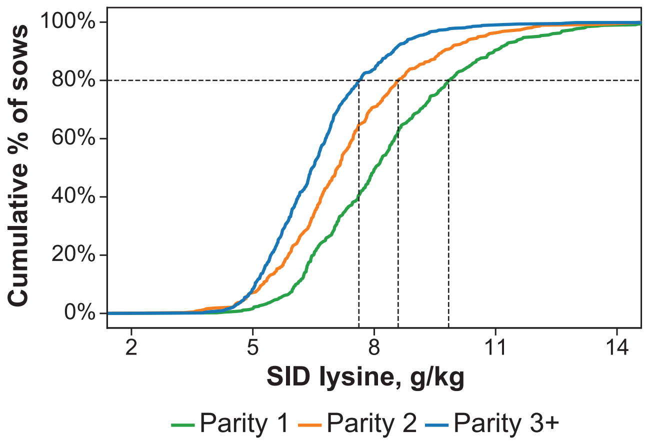

Figure 9. Cumulative distribution of the standardized ileal digestible (SID) lysine requirement per kg of feed according to sow parity. Vertical dashed lines represent the dietary concentration of SID lysine needed to meet the requirement for 80% of the sows in each parity population.

for threonine, 60.1 ± 0.3 g/100 g for phenylalanine, 115.4 ± 0.4 g/100 g for phenylalanine and tyrosine, 115.1 ± 0.2 g/100 g for leucine, 60.3 ± 0.2 g/100 g for isoleucine, 85.7 ± 0.3 g/100 g for valine, 42.0 ± 0.0 g/100 g for histidine, and 66.3 ± 0.6 g/100 g for arginine.

Digestible Phosphorus Requirement

The mean STTD P requirement was higher on farm B than farm A (16.8 and 16.7 g/d, respectively; $P < 0.01$). The requirement increased during the lactation period, from 12.6 g/d in W1 to 18.7 g/d in W2 and 19.3 g/d thereafter. At the same time, the mean STTD P requirement was higher for P2 and P3+ sows (17.2 and 17.0 g/d, respectively) than for P1 sows (16.0 g/d). The mean STTD P requirement per kg of feed was lower on farm A than farm B (2.6 and 3.0 g/kg, respectively; $P < 0.001$). The dietary concentration of STTD P needed to meet the requirement of 80% of sows was 2.9 and 3.6 g/kg on farm A and B, respectively, which is 11.5 and 20% more concentrated than the mean requirement, respectively. The mean STTD P requirement per kg of feed was intermediate in W1 (2.9 g/kg), highest in W2 (3.0 g/kg), and lowest in W3+ (2.8 g/kg). The mean requirement was greater for P1 (3.2 g/kg) than for P2 and P3+ sows (2.8 and 2.6 g/kg, respectively).

Digestible and Total Calcium Requirements

The mean STTD Ca requirement was slightly higher on farm B than farm A (23.1 and 22.9 g/d, respectively; $P < 0.003$). The requirement increased during the lactation period, from 17.3 g/d in W1 to 25.7 g/d in W2 and 26.5 g/d thereafter. At the same time, the mean STTD Ca requirement was greater for P2 and P3+ sows (23.6 and 23.3 g/d, respectively) than for P1 sows (22.0 g/d). The mean STTD Ca requirement per kg of feed was lower on farm A than farm B (3.6 and 4.1 g/kg, respectively; $P < 0.001$). The dietary concentration of STTD Ca needed to meet the requirement of 80% of sows was 4.0 and 5.0 g/kg on farm A and B, respectively, which is 11.1 and 22.0% more concentrated than the mean requirement, respectively. The mean STTD Ca requirement per kg of feed was intermediate in W1 (4.0 g/kg), highest in W2 (4.1 g/kg), and lowest in W3+ (3.9 g/kg). The mean requirement was greater for P1 (4.4 g/kg) than for P2 and P3+ sows (3.9 and 3.6 g/kg, respectively). The total Ca requirement was calculated assuming 50% digestibility for Ca, resulting in a Total Ca:STTD P ratio of 2.75. This ratio was not influenced by farm, parity, or week of lactation.

DISCUSSION

General Structure of the Model

The modeling approach is based on combining current knowledge about nutrient use of lactating sows with the flow of data produced on-farm. The approach allows to capture individual variability in the performance of sows and litters according to farm, week of lactation, and parity. Daily records of sow feed intake and litter size and an estimate of daily milk production were used to build a dynamic model representing individual changes in nutrient requirements during the lactation period. To our knowledge, this model is the first to include individual performances to determine nutrient requirements of lactating sows; however, similar approaches have explored this for gestating sows (Dourmad et al., 2017) and fattening pigs (Hauschild et al., 2012).

Milk Nutrient Output

Milk energy and protein outputs increased with parity and differed most between primiparous and second parity sows. This result is consistent with changes in milk production among parities observed by other authors (Salmon-Legagneur, 1958; Beyer et al. 2007; Dourmad et al., 2012).

Daily nutrient requirements increased during lactation, as previously described by Strathe et al. (2015). Milk production was the main reason for this increase, explaining more than 90% of the variability in daily nutrient requirements. The shape of the lactation curve used in the present model came from the review of Hansen et al. (2012) and resulted in predictions of peak milk production during the third week of lactation, which is consistent with results of other authors (Salmon-Legagneur, 1958; Etienne et al., 1998; Theil et al., 2012). Thus, weaning on farm A occurred mainly during the plateau phase of milk production described by Quesnel et al. (2015), while weaning on farm B occurred mainly near peak lactation. Compared to the lactation curve used in the InraPorc model (Dourmad et al., 2008), which was derived from Whittemore and Morgan (1990), the curve used in the present model predicted lower milk nutrient output during the first days of lactation, followed by a faster increase. Choosing the right shape for the lactation curve has a large effect on predicted milk production and consequently on the dynamics of nutrient requirements. Since the literature provides few observations of sow milk production during the first days of lactation, predictions remain relatively uncertain for this period, although the use of meta-analysis has improved it (Hansen et al., 2012).

Influence of Postpartum Uterine Involution on the Nutrient Supply

The nutrients supplied by the involuting uterus during early lactation were considered in the factorial approach of Feyera and Theil (2017), but until now had not been considered when estimating nutrient requirements (NRC, 2012). From data available in the literature, we estimated the half-life of the weight of the involuting uterus as 6.2 d. This short half-life explains why the uterus supplied nutrients mainly in early lactation. The uterine contribution to the SID lysine requirement during the first week of lactation was 6.2%, which is slightly lower than the 9% found by Feyera and Theil (2014). The uterine contribution to the ME requirement during the first week of lactation was lower (1.6%) than that to amino acid requirements, while that to the P requirement was not considered due to lack of information on the P content of uterine tissues.

Energy Requirement

The total ME requirement of lactating sows is highly variable, and is composed on average in our dataset, of milk production costs (72%), and maintenance costs (28%). Milk production thus had the largest influence on variability in the ME requirement of lactating sows, as described by Feyera and Theil (2017). The amount of energy exported in milk was slightly larger on farm B than farm A. However, maintenance costs were higher on farm A due to a heavier BW, and the total ME requirement was higher on farm A. Among sows within farms, milk production costs explain 95% of variability in the ME requirement (Fig. 4), while maintenance costs explain only small variations in the ME requirement.

Approximately 78% of the sows experienced negative energy balance during lactation (median deficit: −19.3 MJ ME /d). Conversely, the other 22% of sows consumed more than necessary and experienced a positive energy balance (median excess: 8.9 MJ ME/d). In practice, it may be of interest to identify the sows with a positive energy balance, which may result from low milk production or a large appetite, and then restrict their energy supply. The huge variability in the energy balance is related to litter growth (i.e., milk production) and sow feed intake. The energy balance was more negative on farm B than farm A, and more negative for primiparous sows than for multiparous sows, since primiparous sows had lower mean feed intake. During the lactation period, energy balance was lowest during the second week because the energy requirement was at its highest, while feed intake was still increasing. As suggested by Strathe et al. (2015), this was likely because milk production increased more rapidly than feed intake capacity did.

Amino Acid Requirement

The SID lysine requirement varied greatly among sows. Milk protein output had the largest influence on this increase, explaining 99% of the variability in the daily SID lysine requirement (Fig. 6). The SID lysine requirement differed by farm, with a higher mean daily requirement on farm B than farm A due to higher litter performance. Similarly, the variation observed in milk protein output as a function of parity showed a higher daily SID lysine requirement for multiparous sows, which is consistent with the NRC (2012) requirement estimated for the same performance. The change in milk protein outputs influenced the SID lysine requirement among the weeks of lactation. As observed for milk protein output, the SID lysine requirement increased with the week of lactation, which is consistent with Strathe et al. (2015).

The variability in the SID lysine requirement per kg of feed was higher than that in the daily SID lysine requirement. Feed intake and litter growth explained 51 and 27% of this variability, respectively. Differences in mean feed intake and litter growth between farms, and variability in them, resulted in a larger mean and higher variability in the SID lysine requirement per kg of feed on farm B than farm A (Fig. 10). On both farms, the SID lysine requirement per kg of feed decreased with parity (Fig. 10), as feed intake capacity increased. The SID lysine requirement per kg of feed peaked during the second week of lactation, probably because milk production increased more rapidly than feed intake capacity did (Strathe et al., 2015).

We also compared the requirements per kg of feed obtained in the present study to those from other recommendations (Fig. 10). The NRC (2012) SID lysine requirement per kg of feed meets the requirements of the 66th, 75th, and 78th percentile for P1, P2, and P3+ parity populations on farm A, respectively. Nevertheless, due to a greater variability in farm B than in farm A, the NRC (2012) recommendations only meet the requirements of the 41st, 54th, and 57th percentile for P1, P2, and P3+ parity populations on farm B, respectively. The InraPorc (Dourmad et al., 2008) SID lysine requirement per kg of feed meets the requirements of the 65th, 59th, and 58th percentile on farm A, and the 46th, 50th, and 48th percentile on farm B for P1, P2, and P3+ parity populations, respectively. Thus, the InraPorc recommendations are likely to overestimate the median requirement by 10% on farm A but lie near the median requirement on farm B. Because InraPorc ignores individual variability, however, it underestimates the requirement at the population level. The

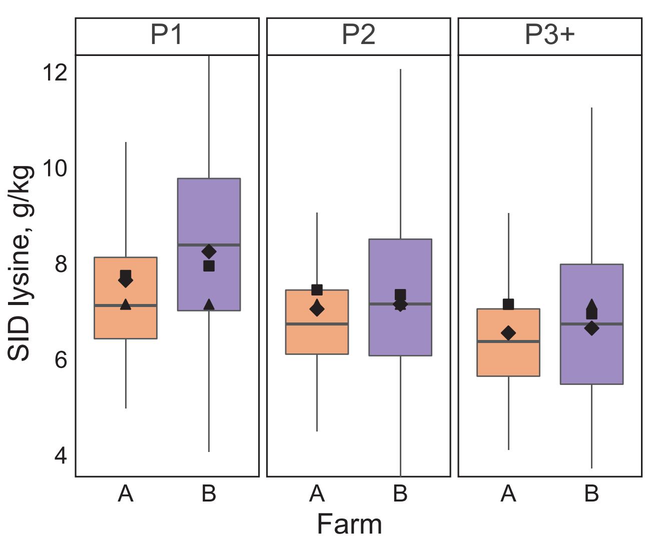

Figure 10. Boxplots of the standardized ileal digestible lysine requirement per kg of feed of lactating sows according to parity and farm. Estimated requirements are compared to recommendations of Dourmad et al., 2008 (♦), NRC, 2012 (■), and Tybirk, 2015 (▲). Whiskers represent 1.5 times the interquartile range.

Danish recommendations (Tybirk, 2015), which do not differ by parity, meet the SID requirements of a lower percentage of primiparous sows, especially on farm B (27th, 50th, and 61st percentile on farm B, and 51st, 62nd, and 78th percentile on farm A, for P1, P2, and P3+ parity populations, respectively).

Meeting sows' SID requirements appears to vary greatly between farms and among parities (Fig. 10). Thus, the use of farm-specific data, which are increasingly available in practice, provides new opportunities to consider between- and within-farm variability and better adapt recommendations to meet the requirements. This also raises the question of the efficiency of utilization to be used for determining amino acid requirements. When estimating a population requirement, the efficiency of utilization has to be reduced to account for between animal variability. For instance, in NRC (2012), the milk SID lysine efficiency is 0.67, representing an adjustment to the reference value of 0.75 to account for between animal variation. This 0.67 value is consistent with the values recently measured on group of sows by Huber et al. (2015, 2016). The apparent efficiency of lysine estimated in the present study when the requirement of 80% of the sows is met (i.e., 0.69 and 0.65 for farm A and B, respectively) is also consistent with the efficiency value used by NRC (2012). Conversely, when estimating individual requirements, the efficiency of utilization should correspond to a maximal efficiency measured slightly below the requirement. The efficiency value of 0.78 used for SID lysine in the present model was calculated for a nil N balance from the equation obtained by Dourmad et al. (1998) relating N balance, SID lysine intake and lysine in milk. This value is slightly higher than the reference value of 0.75 given by NRC (2012) and slightly lower than the 0.80 value used by Strathe et al (2015).

In the present study, the SID lysine requirement per kg of feed was met for 80% of sows when the supply amounts to 112 and 120% of the mean population requirement on farm A and B, respectively. In comparison, Brossard et al. (2009) and Pomar et al. (2009) showed that average daily gain in growing pigs is close to maximum when the SID lysine supply is 110% of the mean population requirement. This indicates that variability in amino acid requirements of lactating sow populations may be greater than that in growing pig populations. This may be because variability in requirements originates from that in both appetite and milk production, which are high and weakly correlated.

Formulating diets to consider between-sow variability could increase SID amino acid concentrations to meet the requirements of a larger percentage of sows in the herd (e.g., 80% of sows; Figs 7–9). However, this is likely to increase the mean excess in sows receiving more nutrients than required and consequently to increase feeding costs. An alternative would be to develop precision feeding strategies to adapt nutrient supplies to individual requirements. This could be done by feeding a tailored ration obtained by mixing different diets, as already developed for fattening pigs (Pomar et al., 2009).

Mineral Requirements

Daily STTD mineral requirements varied greatly among sows. Like for SID amino acid requirements, litter performance and milk nutrient outputs had the largest influence on STTD mineral requirements. Like for amino acids, daily STTD P and STTD Ca requirements increased with the week of lactation and were higher on farm B than farm A due to the higher litter performance on farm B. Changes in milk nutrient output according to parity led to greater STTD P and Ca requirements in multiparous sows, which is consistent with NRC (2012) requirements estimated for the same performance. Standardized total tract digestible mineral requirements per kg of feed were influenced mainly by feed intake, which resulted in large differences according to the week of lactation, parity, and the farm. The STTD P requirement was met for 80% of sows when the STTD P content was 112 and 120% of the mean population requirement on farm A and B, respectively. The total Ca:STTD P ratio in the present study (2.75) is close to the values of 2.8 to 2.9 calculated by Bikker et al. (2017) but higher than the fixed ratio of 2.0 used by the NRC (2012) for lactating sows and lower than the 3.2 ratio suggested by Jongbloed et al. (1999).

Modeling Requirements from the Perspective of Precision Feeding

The present model highlights the influence of sow milk production and appetite on the amount and composition of the optimal ration to be fed each day to lactating sows. Due to the variability between and within sows and litter performances, lactating sow populations seem to have greater variability in nutrient requirements per kg of feed than growing pig populations. Thus, precision feeding appears to be a promising strategy to better adapt the nutrient supply to individual requirements during lactation. However, further research is required to accurately predict both real-time milk production and feed intake, and develop a full decision support system, based on the present model, that could be embedded in automated feeding equipment. In the meantime, sow characteristics (parity, daily feed intake, mean protein intake, and body weight) and litter characteristics (number and weight of piglets) are likely correlated with milk production and can be used to predict individual milk production (Dourmad et al., 2012; Vadmand et al. 2015). Predicting feed intake is a great challenge due to the large variations among lactating sows and also for individual sows during the lactation period. Recent access to real-time data collected by on-farm sensors is another opportunity to develop more accurate predictions.

The model approach developed in the present study is thus an initial contribution to the development of a new paradigm of models that would be "data ready" and "precision-feeding ready", and able to process both historical farm data (e.g., for *ex post* assessment of nutrient requirements) and real-time data (e.g., to control precision feeding).

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