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Energy and nutrient deposition and excretion in the reproducing sow: Model development and evaluation[1]

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ABSTRACT: Air and nutrient emissions from swine operations raise environmental concerns. During the reproduction phase, sows consume and excrete large quantities of nutrients. The objective of this study was to develop a mathematical model to describe energy and nutrient partitioning and predict manure excretion and composition and methane emissions on a daily basis. The model was structured to contain gestation and lactation modules, which can be run separately or sequentially, with outputs from the gestation module used as inputs to the lactation module. In the gestating module, energy and protein requirements for maintenance, and fetal and maternal growth were described. In the lactating module, a factorial approach was used to estimate requirements for maintenance, milk production, and maternal growth. The priority for nutrient partitioning was assumed to be in the order of maintenance, milk production, and maternal growth with body tissue losses constrained within biological limits. Global sensitivity analysis showed that nonlinearity in the parameters was small. The model outputs considered were the total protein and fat deposition, average urinary and fecal N excretion, average methane emission, manure carbon excretion, and manure production. The model was evaluated using independent data sets from the literature using root mean square prediction error (RMSPE) and concordance correlation coefficients. The gestation module predicted body fat gain better than body protein gain, which was related to predictions of body fat and protein loss from the lactation model. Nitrogen intake, urine N, fecal N, and milk N were predicted with RMSPE as percentage of observed mean of 9.7, 17.9, 10.0, and 7.7%, respectively. The model provided a framework, but more refinements and improvements in accuracy of prediction (particularly urine N) are required before the model can be used to assess environmental mitigation options from sow operations.

Key words: gestation, lactation, modeling, nutrient excretion, sow

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INTRODUCTION

The impact of swine production on the environment is of growing concern. On an animal basis, gestating and lactating sows consume a relatively greater amount of feed and excrete a greater amount of feces compared to growing and finishing pigs. Mathematical models can provide a better understanding on the nutrient utilization and excretion in a swine production system. Several models have been developed to predict nutrient deposition in mostly growing and finishing pigs (e.g., Van Milgen et al., 2008). However, there is less information on gestating and lactating sows, particularly on nutrient excretion (Rigolot et al., 2010). For assessment of mitigation options for a more sustainable swine production system, a sow model needs to predict composition and amount of nutrient excretion (Dourmad and Jondreville, 2007). Although Rigolot et al. (2010) developed a model to estimate the amount of manure and its composition, the model was static and only gave the total manure excretion for the whole gestation or lactation period. Because of scarcity of data (direct measurements), there are only a few models that were developed to predict methane emission from sows (e.g., Jørgensen, 2007).

Most extant sow simulation models need to be adapted or further developed to enable prediction of manure composition and mass. For example, previous models incorporated N, protein balance, or both into the

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model. However, because the AA composition of fetal tissue, maternal protein, and milk differs (Dourmad et al., 1999), model prediction would be improved by including the indispensable AA balance to account for limiting AA (Kim et al., 2009). NRC (2012) includes AA balances for calculating requirements of sows, but the model does not include manure composition and mass calculations. The InraPorc model (Dourmad et al., 2008) estimates the requirements of gestating and lactating sows, but does not estimate nutrient excretion and emission.

Outputs from animal models can potentially be used as inputs in manure and soil models to estimate farm-level emissions. The objectives of the current study were to develop and evaluate a dynamic model for the gestating and lactating sow describing 1) energy and nutrient partitioning, 2) manure excretion and composition, and 3) methane emissions on a daily basis.

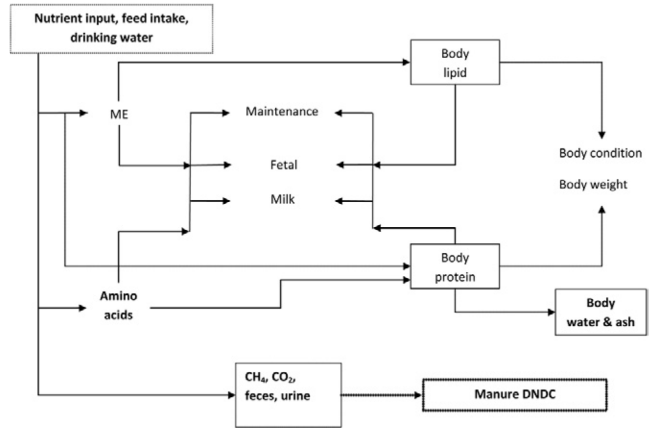

Figure 1. Overview of the model structure.

MATERIALS AND METHODS

Model Initialization

The general scheme of the model is given in Fig. 1. A factorial approach was used to estimate requirements for maintenance, deposition and mobilization of energy, and nutrients in milk, fetus, and maternal body tissues. Information on AA composition of fetuses, milk, and maternal protein was used to determine the partitioning of indispensable AA during gestation and lactation. Diet composition and feed intake was given as an input to the model to determine nutrient balances and deposition or mobilization of nutrients from maternal protein and lipid tissue. The sow is described in terms of BW (kg), backfat thickness (mm), and parity. Litter characteristics included size (number of piglets) and gain of nursing piglets (kg/d), which were inputs to the model. The model contained gestation and lactation modules, which can be run separately or sequentially.

Gestation Module

During gestation, the sow requires energy and nutrients for maintenance, fetal growth, and maternal growth. These individual components are described in detail in the following sections, and equations used in the gestation module are given in Table 1.

Energy for Maintenance. Metabolizable energy for maintenance (**MEm**) does not change throughout gestation. It was set to 440 kJ/kg BW$^{0.75}$ (Eq. [1]) for a sow with 240 min of standing activity per day (Dourmad et al., 2008).

Fetal Growth. Fetal growth changes throughout gestation. In the first third of gestation, the daily weight accumulation (g/d) is relatively slow compared with fetal growth during the last part of gestation. McPherson et al. (2004) reported that fetal BW increased cubically (Eq. [7]). However, the equation yields negative fetal BW until d 45 of gestation, which is not biologically feasible. Therefore, the cubic equation was used to describe fetal growth only from d 45 to 115 of gestation. A linear relationship, based on data by McPherson et al. (2004), was established to describe fetal growth from mating to d 45 (Eq. [6]). The equations by McPherson et al. (2004) were chosen over other equations from older studies to determine fetal growth, as piglet growth has increased dramatically over the last several decades. For example, Dourmad et al. (2008) used equations developed by Noblet et al. (1990) to describe fetal growth, and the NRC (2012) used Dourmad et al. (1999, 2008) as basis for their model. Energy retention in fetuses was calculated by adding the energy deposited as protein (as described in the following sections) and lipid (Eq. [5]). Fetal lipid gain changed around d 70 of gestation, with fetal lipid being deposited at 0.06 g/d before d 70 and 1.09 g/d after d 70 of gestation (Kim et al., 2009).

Maternal Growth. The uterus increased in weight during gestation (Walker and Young, 1992). Growth of the mammary gland is limited until d 80 of gestation, but the growth accelerates afterward (Kim et al., 2009). Besides the growth associated with pregnancy, the sow will continue to grow toward mature weight. In this model, growth of the sow during gestation was not divided into maternal, uterine, and mammary gland growth. The efficiencies of ME for maternal body protein (**k$_p$**) and lipid (**k$_f$**) deposition were 0.60 and 0.80, respectively (Eq. [2] and [3]; Noblet et al., 1990; Strathe et al., 2010). Empty BW (**EBW**) and body composition were estimated using equations (Eq. [10], [11], and [12]) based on Dourmad et al. (1997). Fetal growth and maintenance were assumed to be a priority over maternal growth. Energy available for maternal growth was calculated as the difference between maternal ME intake and ME demands for fetal growth and maintenance. The model does not account for a negative energy balance during gestation.

Table 1. Equations and efficiencies used to describe energy and nutrient partitioning in the gestation module[1]

Item	Equation	No.
Energy (ME) for maintenance (MEm), kJ	$MEm = 440\ kJ/kg\ BW_{sow}^{0.75}$	[1]
Efficiency of dietary ME for deposition of body protein (k_p)	$k_p = 0.60$	[2]
Efficiency of dietary ME for deposition of body fat (k_f)	$k_f = 0.80$	[3]
Efficiency of dietary ME for deposition in conceptus (k_c)	$kc = 0.50$	[4]
ME deposition in fetuses (MEc), MJ/d	$MEc = [(PD_{fetus} \times 26.9)/1000 + (LD_{fetus} \times 39.7)/1000]/kc$	[5]
Fetal weight		
BW d 0 to d 45 post mating (BW_{fetus}), g	$BW_{fetus} = 0.474t$	[6]
BW d 45 to 115 post mating (BW_{fetus}), g	$BW_{fetus} = -62.922 + 0.00108t^3$	[7]
Fluids and membranes		
Weight of fluids and membranes (Wt_{fm}), g	$Wt_{fm} = BW_{fetus} \times 48.677e^{(-0.0415t)}$	[8]
Protein content of fluids and membranes (CP_{fm}), g	$CP_{fm} = Wt_{fm} \times 0.0087e^{(0.00146t)}$	[9]
Body composition		
Empty body weight (*EBW*), kg	$EBW = 0.96BW_{sow}$	[10]
Body protein content (CP_{body}), kg	$CP_{body} = 2.28 + 0.178EBW - 0.333P2$	[11]
Body fat content (CF_{body}), kg	$CF_{body} = -26.4 + 0.221EBW + 1.331P2$	[12]
AA absorption (AAD), g	AAD = Feed intake × DM (%) × AD	[13]
AA for maintenance (AAM), g	$AAM = AM \times BW^{0.75}$	[14]
AA for endogenous loss (AAE), g	AAE = AE × Feed intake (kg) × DM (%)	[15]
AA for fetal growth (AAF), g	$AAF = AF \times PD_{fetus}$	[16]
AA available for body deposition (AAB_i), g	$AAB_i = AAD_i – AAM_i – AAE_i - AAF_i$ i = {Lys, Met, sulfur AA, Thr, Trp, Ile, Leu, Val, Phe, Aromatic AA, N}	[17]
Efficiency of using dietary AA for maternal protein deposition (k_{pAA})	$k_{pAA} = 0.75$	[18]
Methane (CH_4) emission, % of DE	$CH_4 = 0.0838 + 0.00606 fDF$ (g/kg DM)	[19]
Methane (CH_4) emission, l/d	$CH_4 = 0.626 + 0.00894 fDF$ (g/d)	[20]
Water balance		
Water for digestion (*WD*), kg/d	$WD = 18/162DCHO + (18/110)DCP + (18/263)DL$	[21]
Carbohydrates for lipid retention (LR_{DCHO}), kg/d	$LR_{DCHO} = LR - LR_{DL}$	[22]
Water from synthesis of body protein and lipid (*WS*), kg/d	$WS = 0.16PR + 0.07LR_{DL} + 0.6LR_{DCHO}$	[23]
Water from nutrient oxidation (*WO*), kg/d	$WO = 0.42POX + 1.07LOX + 0.6DCHOOX$	[24]
Insensible heat loss (*IHL*), MJ/d	$IHL = 0.25HP$	[25]
Sensible heat loss (*SHL*), MJ/d	$SHL = 0.75HP$	[26]
Water evaporation (*WE*), kg/d	$WE = 0.4IHL$	[27]
Water gain of sow, g	$WG = 3.41 \times PD_{sow}$	[28]
C excretion		
C excretion in urine (*CU*), g/d	$CU = (NU/14.01) \times 0.5 \times 12.01$	[29]
C excretion in feces (*Cf*), g/d	$Cf = 12.01(43.3 \times UCP + 62.4 \times UCF + 37.0 \times UDF)$	[30]
Total N retention ($Total_{NR}$)	$Total_{NR} = N_{gain\_conceptus} - 0.4 + 45.9 \times \frac{t}{100} - 105.3 \times \left(\frac{t}{100}\right)^2 + 64.4 \times \left(\frac{t}{100}\right)^3 + A \times \left(\frac{ME_{in}}{1000} - \frac{MEmm}{1000}\right)$	[31]

[1] *t* = day of gestation, BW_{sow} = BW of the sow (kg), *P2* = back fat thickness (mm), PD_{fetus} = fetal protein deposition (g/d), LD_{fetus} = fetal lipid deposition (g/d), AD = dietary AA composition (g/kg DM intake), AM = AA composition for maintenance (mg/kg $BW^{0.75}$), AE = AA composition of endogenous loss (g/kg DM intake), AF = AA composition of fetal protein, AAD = dietary AA composition, AAM = AA for maintenance, AAE = endogenous AA loss (g/kg DM intake), AAF = AA composition of fetuses, *fDF* = fermentable dietary fiber (g/d or g/kg DM), *DCHO* = digested carbohydrate (kg/d), *DCP* = digested CP (kg/d), *DL* = digested lipid (kg/d), *LR* = retained lipid (kg/d), LR_{DL} = contribution of digested lipid to retained lipid (kg/d), *PR* = retained protein (kg/d), LR_{DCHO} = contribution of digested carbohydrate to retained lipid (kg/d), *POX* = oxidized protein = *DCP*– *PR*, *LOX* = oxidized lipid (kg/d) = *DL*– LR_{DL}, *DCHOOX* = oxidized carbohydrates (kg/d) = *DCHO*– carbohydrates used for lipid synthesis ($DCHO_{lipid}$), $DCHO_{lipid}$ = 2.60xLRDCHO (kg/d), *HP* = heat production (MJ/d), PDsow = protein deposition of the sow (g/d), *NU* = N in urine (g/d), *UCP* = undigested CP (g/d), *UCF* = undigested crude fat (g/d), *UDF* = undigested dietary fiber (g/d), $N_{gain\_conceptus}$ = daily N gain (g/d) of conceptus (fetuses, fluids and membranes), *A* = 0.571 at first parity and 0.366 at later parities, ME_{in} = ME intake (kJ), and *MEmm* = ME for maintenance at the day of mating (kJ).

Table 2. Daily AA requirement (standardized ileal digestible AA) for maintenance, endogenous loss, and AA composition of maternal, fetal, and milk protein

	Maintenance requirement[1]		Endogenous loss of AA	Composition of					
				Maternal protein[2]		Fetuses		Milk[2]	
AA	mg/kg $BW^{0.75}$	% of Lys	g/kg DM intake	g/16 g N	% of Lys	g/16 g N	% of Lys	g/16 g N	% of Lys
Lys	36	100	0.292	7.0	100	5.9	100	7.5	100
Met	9	25	0.080	1.8	26	1.4	24	1.7	23
Total sulfur AA	49	139	0.254	3.4	49	2.7	46	3.2	43
Thr	53	147	0.454	4.0	57	3.5	59	3.9	52
Trp	11	31	0.130	1.0	14			1.4	19
Ile	16	44	0.252	3.5	50	3.0	51	3.8	51
Leu	23	64	0.446	7.0	100	6.2	105	8.8	117
Val	20	55	0.340	4.7	67	4.6	78	4.7	63
Phe	18	50	0.268	4.4	63	3.4	58	3.9	52
Total aromatic AA	37	103	0.482	6.7	96	5.8	98	8.1	108

[1]Dourmad et al. (1999).
[2]Darragh and Moughan (1998).

Amino Acid and Nitrogen Balance. The CP intake, indispensable AA intake, and the apparent digestibility of protein were given as inputs to the model, from which the protein and N excreted in feces can be calculated. Urinary N was calculated by subtracting fecal N and retained N from N intake. Fetal protein gain changed around d 70 of gestation, with fetal protein being deposited at 0.25 g/d before d 70 and 4.63 g/d after d 70 of gestation (Kim et al., 2009). This approach was simpler than the equations used by Dourmad et al. (2008) and NRC (2012) to avoid further complexity in the model development. The data used for determining fetal protein gain were collected on several days (d 45, 60, 75, 90, 102, and 112) during gestation on 33 sows (McPherson et al., 2004) and provided an appropriate fit for the current model development. The AA composition of protein deposited in fetuses (Eq. [16]) was calculated from the AA composition of fetal body protein (Table 2). The efficiency of using dietary AA for deposition of protein in the conceptus was set to 0.50 (Table 1; Eq. [4]; Dourmad et al., 2008). The AA requirement for maintenance (standardized ileal digestible AA), endogenous loss of AA, and AA composition of fetal and maternal protein are given in Table 2. Amino acids available for maternal deposition were calculated by subtracting AA for maintenance, endogenous loss, and fetal growth from the AA intake (Eq. [13]–[17]). Protein and N deposition were calculated using the concept of the first limiting AA. The efficiency of using dietary AA for deposition of maternal protein was set to 0.75 (Eq. [18]). In each time step, AA balances were calculated based on the law of conservation of mass. The energy-dependent phase of protein deposition was based on an empirical relationship derived by Dourmad et al. (1999). The model derived the limiting factor by taking minimum achievable protein deposition and setting that as the protein deposition for the current time step. Once the protein deposition has been set, urinary N excretion is computed by means of mass balance. Lipid deposition was derived in a similar fashion, factoring in the associated partial efficiency of utilizing ME above maintenance for lipid deposition.

The protein contents of fluids and membranes were calculated using Eq. [9] (Walker and Young, 1992), where the protein content depended on the weight of fluids and membranes and day of gestation (Eq. [8]). Protein was assumed to contain 16% N. The total N retained in the sow at each day of gestation was calculated from the equation (Eq. [31]) by Dourmad et al. (1999), where the N retention depended on ME intake, MEm at mating, parity (first or multiple), and day of gestation. The N retained in maternal tissues was then calculated by subtracting N retained in the conceptus (fetuses, fluids, and membranes) from the total N retention. Nitrogen for maintenance was set to 0.440 g/kg $BW^{0.75}$ (Everts, 1998).

Methane Emission. Methane emission is related to the amount and type of fiber ingested. Several studies reported a linear relationship between fermentable dietary fiber (**fDF**) intake (g/kg DM) and methane production (e.g., Le Goff et al., 2002; Jørgensen, 2007; Jørgensen et al., 2007, 2011). The equations proposed by Jørgensen et al. (2011) were used in the model (Eq. [19] and [20]). The fDF was calculated by subtracting starch, sugar, digestible CP, and digestible crude fat from digestible OM (g/kg DM). Starch and sugars were assumed to be 100% digestible.

Water Balance. The water balance must be established to estimate the manure weight. Water is obtained by the sow through drinking, water in feed, and metabolic water. The intake of drinking water was closely related to feed intake (Kruse et al., 2011a), but only limited studies have measured water intake in gestating sows. Kruse et al. (2011a) found that multiparous sows had a greater, although not statistically significant, water-to-feed ratio than primiparous and biparous sows (7.5 vs. 5.9 L/kg feed daily). The water intake related to feed intake can be calculated from the feed intake (an input to the model) and the DM content of the feed. The water-to-feed value was set as the default value, but the water intake can be adjusted by the user.

The digestion of polysaccharides, protein, and triacylglycerol requires water, which can be estimated by Eq. [21] when the intake of digestible protein (**DCP**), lipid (**DL**), and carbohydrate (**DCHO**) is calculated (Schiavon and Emmans, 2000). The metabolic water comes from oxidation of nutrients (AA, lipid, and carbohydrates) and from the synthesis of protein and lipid (Schiavon and Emmans, 2000). Water from synthesis (**WS**) of macromolecules is proportional to the retained protein and lipid and the source used in the synthesis. To predict WS, Schiavon and Emmans (2000) made the following assumptions on the metabolic fate of the nutrients: 1) digested protein that is not retained is completely oxidized, and 2) DL is retained with an efficiency of 0.90. The contribution of lipid (**LR_{DL}**) and carbohydrates (**LR_{DCHO}**) for lipid retention (**LR**) was calculated by Eq. [22]. The calculation of WS assumed that 0.16, 0.07, and 0.60 g water were released for each gram of protein retained (**PR**), LR_{DL}, and LR_{DCHO}, respectively (Eq. [23]). Oxidation of 1 kg carbohydrate, protein, and lipid produces 0.60, 0.42, and 1.07 kg water, respectively. The water arising from oxidation (**WO**) was calculated from Eq. [24]. Heat production (**HP**) was calculated by subtracting retained ME from ME intake. Insensible heat loss (**IHL**) and sensible heat loss (**SHL**) at thermoneutrality was calculated by Eq. [25] and [26], respectively. Water evaporation (**WE**; kg/d) was obtained by assuming 0.4 kg water was lost for each MJ heat dissipated as vapor (Eq. [27]).

Water retention in maternal tissue is related to protein deposition, which was assumed that 3.41 kg water was retained per kilogram protein retained (Eq. [28]; derived from Dourmad et al., 1997). Water excretion in manure (**WM**; kg/d) was calculated by subtracting daily water evaporation and body water deposition from water intake, metabolic water, and water from synthesis.

Fecal and Urinary Carbon Excretion and Manure Production. The fecal and urinary carbon excretion was calculated from the undigested fractions of dietary protein, fat, and fiber (Le Goff and Noblet, 2001) using Eq. [29] and [30]. Urinary C excretion is proportional to urinary N excretion based on the assumption that the C in urine originated solely from urea. Measurements and predictions of manure (feces + urine) weight and composition have mostly been available for finisher pigs, but a few studies have also investigated predictions for sows (Robert et al., 2000; Masse et al., 2003). The excretion of carbon in manure was calculated from N balance and urinary and fecal carbon excretion.

Lactation Module

During lactation, the sow requires energy and nutrients for maintenance and milk production. Sows might become catabolic during lactation and mobilize protein and lipid from body reserves to support milk production. An ad libitum feed intake curve was given as default value in the model (Eq. [35]; Table 3), but the daily feed intake can be adjusted by the user.

Energy for Maintenance and Changes in Body Composition. Metabolizable energy for maintenance is assumed not to change throughout lactation and was set to 460 kJ/kg $BW^{0.75}$ (Eq. [32]; Dourmad et al., 2008). Empty body weight, protein, and lipid composition at d 1 postpartum were calculated by Eq. [10], [11], and [12], respectively (Table 1; Dourmad et al., 1997). The model reflects the ability of the sow to mobilize body protein and lipid when the total requirements of energy and AA exceed the intake. Relevant literature (Dourmad et al., 1997; Dourmad et al., 1998; Sauber et al., 1998; Jones and Stahly, 1999; McNamara and Pettigrew, 2002; Clowes et al., 2003a; Gill, 2006) was summarized to quantify the relationship between the mobilization of body protein and lipid and how the ratio between mobilized lipid and protein changes with the body condition of the sow. During negative energy and protein balances, the sow mobilizes both protein and lipid with different ratios between mobilized lipid and protein, and at farrowing, the ratio between body lipid and protein was on average about 2.0, which was adopted in the model. An equation (Eq. [41]; Table 3) was developed to describe the proportion of mobilized protein out of the total mobilization (lipid + protein). The sow has an ability to mobilize body tissues, but limitations were imposed. In the model, the limit for protein mobilization was set to 1% of the body protein pool per day. No limit was set for body lipid mobilization.

Milk Production. The milk production was calculated using a set of equations derived by Hansen et al. (2012). Based on these equations protein, lipid, lactose, and energy contents were calculated (Eq. [36]–[39]). Dourmad et al. (2008) used a curve proposed by Whittemore and Morgan (1990) to estimate milk production throughout lactation and provided equations to estimate the average daily amounts of energy and N excreted in milk. The curve proposed by Whittemore and Morgan (1990) was based on milk yield data obtained by the weigh-suckle-weigh (**WSW**) technique, which is known to underestimate milk production (Hansen et al., 2012). Using similar input to the lactation curve developed by Hansen et al. (2012) and NRC (2012), the NRC model predicted a lower milk production. The lactation curve used by NRC

Table 3. Equations and efficiencies used to describe energy and nutrient partitioning in the lactation module[1]

Item	Equation	No.
Energy (ME) for maintenance (MEm), kJ	MEm = 460 kJ/kg $BW^{0.75}$	[32]
Efficiency of dietary ME for milk (k_l)	$k_l = 0.72$	[33]
Efficiency of body energy for milk (k_t)	$k_t = 0.88$	[34]
Feed intake (FI), kg	$FI = \phi1 + (\phi2 - \phi1) \times \exp(-\exp(\phi3) \times t)$	[35]
Milk yield (*MY*), kg/d	$ly_5 = 1.93 + 0.07(LS - 9.5) + 0.04(LG - 2.05)$	[36]
	$ly_{20} = 2.23 + 0.05(LS - 9.5) + 0.23(LG - 2.05)$	
	$ly_{30} = 2.15 + 0.02(LS - 9.5) + 0.31(LG - 2.05)$	
	$a = \exp(1/3 \times (-ly_{20} \times \log(128/27) - 3 \times \ln(20) \times ly_{30} + 5 \times$	
	$\log(20) \times ly_{20} - 2 \times \log(20) \times ly_5 + 4 \times ly5 \times \log(128/27) + 12 \times$	
	$ly_{30} \times \log(5) - 20 \times \log(5) \times ly_{20} + 8 \times \log(5) \times ly_5) / \log(128/27)$	
	$b = -(3 \times ly_{30} - 5 \times ly_{20} + 2 \times ly_5)\log(128/27)$	
	$c = (1/15 \times (ly_5 \times \log(128/27) - ly_{20} \times \log(128/27) - 3 \times \log(20)$	
	$\times ly_{30} + 5 \times \log(20) \times ly_{20} - 2 \times \log(20) \times ly_5 + 3 \times ly_{30} \times \log(5) - 5 \times$	
	$\log(5) \times ly_{20} + 2 \times \log(5) \times ly_5) / \log(128/27))$	
	$MY = a \times t^b \times e^{(-c \times t)}$	
Milk composition, %		
Milk CP (*MCP*), %	$MCP = 5.18 + 4.43 \times (t^{-1} - 0.17) + 0.07 \times (CP_{diet} - 15.9)$	[37]
Milk lactose (*ML*), %	$ML = 5.38 + 0.01 \times (t - 15.8)$	
Milk fat (*MF*), %	$MF = 7.30 - 0.065 \times (t - 13.3)$	
Net energy (NE_L) in milk, kJ	$NE_L = Fat_{milk} \times 38.9 + CP_{milk} \times 23.9 + Lactose_{milk} \times 16.5$	[38]
ME for milk (ME_L), kJ	$ME_L = NE_L / k_l$	[39]
Energy balance (EB)	EB = k_l × [MEI– MEm]- NE_L	[40]
Proportion of mobilized protein out of total mobilization (X)	X = 0.15- 0.05 × ((L/P)-2)	[41]
Efficiency of dietary AA for milk AA (klAA)	$k_{lAA} = 0.75$	[42]
Efficiency of body AA for milk AA (ktAA)	$k_{tAA} = 0.88$	[43]
AA absorption (AAD), g	AAD = FI × DM (%) × AD	[44]
AA for maintenance (AAM), g	AAM = AM × $BW^{0.75}$	[45]
AA for endogenous loss (AAE), g	AAE = AE × FI × DM (%)	[46]
AA acids for milk (AAL), g	AAL = AL × MCP × 10 × MY	[47]
AA available for body deposition/mobilization (AAB_i)	AAB_i = klAA × (AAD_i– AAM_i– AAE_i)- AAL_i i = {Lys, Met, sulfur AA, Thr, Trp, Ile, Leu, Val, Phe, Aromatic AA, N}	[48]

[1]t = days in milk, φ1= maximum feed intake during lactation (kg, the asymptote of the curve), φ2 = intake at d 1 postpartum (kg), φ3 = curvature coefficient (default = -2.5), *ly5* = milk yield (kg) at d 5 postpartum, *ly20* = milk yield (kg) at d 20 postpartum, *ly30* = milk yield (kg) at d 30 postpartum, *LS* = litter size (number of piglets), *LG* = litter gain (kg/d), *t* = days postpartum, CP_{diet} = protein content of diet (%), Fat_{milk} = fat output in milk (g/d), CP_{milk} = protein output in milk (g/d), $Lactose_{milk}$ = lactose output in milk (g/d), MEI = ME intake (MJ), L = body lipid pool, (kg), *P* = body protein pool (kg), AD = dietary AA composition (g/kg DM intake), AM = AA composition of AA for maintenance (mg/kg $BW^{0.75}$), AE = AA composition of endogenous loss (g/kg DM intake), AL = AA composition of milk protein (Table 2), AAD = dietary AA composition, AAM = AA for maintenance, AAE = endogenous AA loss (g/kg DM intake), and AAL = AA excretion in milk. Some equations are the same as for the gestating sow and are not repeated.

(2012) was based on Dourmad et al. (1999, 2008) and estimated the daily milk production from the calculated N excreted in milk, which used litter gain and the number of pigs per litter as inputs. Milk production represented the majority of the nutrient and energy requirement during lactation. Thus, use of a model that accurately described changes in milk production during lactation is critical for accuracy of the model. Milk production has a priority over body tissue deposition, so energy intake was used for maintenance and milk production first. If the energy intake was not sufficient to meet the demands for maintenance and milk production, the model allows the sow to mobilize energy from body reserves. The efficiency of using dietary ME and body energy for milk was set to 0.72 and 0.88, respectively (Eq. [33] and [34]). If the requirements of the first limiting AA for maintenance and milk production exceed the limits of AA intake and AA mobilized from body protein, the model reflected a reduction in milk production. The sow must have a large negative AA balance before reducing milk production, as the sow has an ability to mobilize body tissues and a priority for milk production before body tissue deposition. Furthermore, King et al. (1993) showed that the dietary protein concentration had to be low (6 to 9%) before milk production decreased.

Nitrogen and Amino Acid Balance. During lactation, the sow requires AA for maintenance and milk production. The AA requirement for maintenance is shown in Tables 2 and 3 (Eq. [45]). The net AA excreted in milk was calculated from the milk yield curve and the protein content of the milk (Eq. [47]; Table 3). The AA for milk production can come from dietary protein or mobilization from body protein. The efficiency of using dietary AA and body protein for milk AA are 0.75 and 0.88, respectively (Eq. [42] and [43]). In each time step, the AA and N balances were established using the AA and N composition of dietary protein (Eq. [44]), milk protein (Eq. [47]), body protein, and AA requirement for maintenance. Energy balance was computed to determine the body energy tissue loss (Eq. [48]). Under periods of negative body protein accretion, the model derived the protein-mobilizing factor (both energy and AA) by calculating the maximum protein realized loss and then checked if the loss exceeded the physiological constraint imposed by 1% of the body protein pool. If so, protein loss was set at maximum rate, and milk production was computed under these conditions. Fecal N was calculated from dietary N intake and digestibility. Urinary N was calculated by subtracting N in feces, milk, and N deposition in body protein from N intake.

Water Balance, Carbon Excretion, Manure Production, and Methane Emission. The water balance for the lactating sow was calculated using the same equations as those used for the gestating sow (Table 1; Eq. [21]–[28]), but during lactation, water excretion in milk was also included. The amount of water in milk was calculated from the DM content of the milk and milk yield. Water-to-feed ratio for first, second, and third parity sows was 4.7, 5.2, and 4.9, respectively (Kruse et al., 2011b). These ratios were set as default values, but water intake can be adjusted by the user. Water retention in maternal tissue was related to protein deposition (negative when the sow is catabolic). The assumption that 3.41 kg water retained per kilogram protein retained was derived from Dourmad et al. (1997). Methane emission, fecal and urinary C excretion, and manure mass and composition were estimated using the same equations as those used for the gestating sow (Eq. [19], [20], [29], and [30]).

Model Implementation and Simulation

The gestation and lactation modules were implemented in R (R Development Core Team, 2007) using the Flexible Modeling Environment (**FME**) version 1.2 package (Soetaert and Petzoldt, 2010). The FME package is a modeling tool designed to confront a mathematical model with data. The package includes algorithms for sensitivity and Monte Carlo analyses, parameter identifiability, model fitting, and provides a Markov-chain-based method to estimate parameter confidence intervals. The gestation and lactation modules can be run separately or for the entire reproductive cycle. When simulating the entire reproductive cycle, body composition, BW, and backfat thickness for d 115 of gestation were used as an input to the lactation module.

Sensitivity Analysis

Global sensitivity analysis is the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty. Most sensitivity analysis in animal science literature are local, i.e., 1-parameter-at-a-time type of analysis. Global sensitivity analysis was conducted using the method described by Saltelli et al. (2008). All parameters were included in the analysis, and a parameter (P) matrix (x_{ij}; $i = 1,..,10{,}000$ and $j = 1,\ldots,P$) was constructed with each column representing a parameter and each row representing a draw from normal distributions. The values for each parameter were drawn from P normal distributions, one for each parameter, with a coefficient of variation of 2.5% of the original value. Hence, 10,000 simulations were performed, with the parameter inputs for each simulation being given by a row from the parameter matrix. The outputs were saved from each run and stored in a model output matrix (y_{ik}; $i = 1,..,10{,}000$ and $k = 1, 2,.., N$), with the rows being simulations and the columns the outputs from the model. The x and y matrices were normalized column-wise, with the use of the following equations:

$$X_{ij} = \frac{x_{ij} - \overline{x}_{.j}}{\sigma_{x.j}}$$

$$Y_{ik} = \frac{x_{ij} - \overline{x}_{.j}}{\sigma_{y.k}}$$

The column-wise mean values of parameter and model outputs were denoted by $\overline{x}_{.j}$ and $\overline{y}_{.j}$, respectively, $\sigma_{x_{.j}}$ and $\sigma_{y_{.k}}$ were the column-wise standard deviations, and X_{ij} and Y_{ik} were the normalized parameter and output values, respectively. The k^{th} set of model outputs ($Yi^{(k)}$) were regressed on the X_{ij}, where the upper subscript k was used to indicate the k^{th} ($k = 1, 2,.., N$) regression model and fitted using an ordinary least square:

$$Y_i^{(k)} = \sum_{j=1}^{24} \beta_j^{(k)} \cdot X_{ij} + e_i^{(k)}$$

The error term in the k^{th} regression model was denoted by $e_i^{(k)}$. The betas, $\beta_j^{(k)}$, represent the change in model output standard deviation per 1 unit change in parameter standard deviation, which was estimated for the k^{th} model output. In the standardized regression setting,

Table 4. Model input to simulate the reproductive cycle of a sow

Stage of reproductive cycle	Input
Gestation	
BW at mating, kg	160
Parity of sow	1
Backfat thickness at mating, mm	15
Litter size (No. of fetuses)	12
Feed intake 1,[1] kg/d	2.5
Feed intake 2,[1] kg/d	3.0
Day of feed change	70
Feed composition, % as-fed basis	
Corn	81.7
Soybean meal	14.3
Dicalcium phosphate	2.5
Calcium carbonate	0.5
Salt	0.5
Vitamin-mineral premix	0.5
Calculated content, %	
DM	89.3
CP	14.6
N	2.34
Lys	0.58
Fermentable dietary fiber	6.60
Lactation	
Litter size (No. of suckling piglets)	12
Average litter gain, kg/d	2.5
Lactation length, d	28
Feed intake at d 1 postpartum, kg	2.5
Maximum feed level, kg	7
Feed composition, % as-fed basis	
Corn	61.7
Soybean meal	29.5
Fat	5.0
Dicalcium phosphate	2.3
Calcium carbonate	0.5
Salt	0.5
Vitamin-mineral premix	0.5
Calculated content, %	
DM	89.8
CP	20.2
N	3.22
Lys	0.97
Fermentable dietary fiber	9.95

[1]Feed intake was increased at d 70 of gestation.

the model output variance for the k^{th} model output was given by linear relationships in the parameters and was calculated as

$$\sum_{j=1}^{P}\beta_j^2 .$$

This is equal to R^2; hence, the quantity $1 - R^2$ is the fraction of the model variance for the k^{th} model output, which is not explained by linear relationships in the parameters. This fraction was interpreted as the degree of nonlinearity in model output caused by interactions between model parameters. If $R^2 > 0.8$, then β_j^2 approximated the first-order sensitivity indices obtained with variance decomposition methods (Saltelli et al., 2008). The model was deemed sensitive to a parameter if the square of the estimated regression parameter, β_j^2, was greater than 0.01 for any model output. Hence, model sensitivity coefficients that explained more than 1% of the total model variance were reported. The global analysis was conducted separately for the gestation and lactation modules. The model outputs considered in the sensitivity analysis were the total protein and fat deposition, average urinary and fecal N excretion, average methane emission, manure C excretion, and manure production. Model behavior analysis was conducted on average responses because of data limitations. The available data for evaluation contained only treatment means.

Model Evaluation

The model was evaluated using data from the literature (King et al., 1993; Dourmad et al., 1996, 1998; Sauber et al., 1998; Jones and Stahly, 1999; McNamara and Pettigrew, 2002; Gill, 2006). Studies containing all the necessary inputs to the model were used in the evaluation. The results were generated for the entire gestation and lactation period, and predicted and observed values were given. Because of the scarcity of data to evaluate the dynamic aspect of the model, average values per day or total values for the entire gestation or lactation were used in the evaluation. The root mean square prediction error (**RMSPE**) was used as a measure of the differences between the values predicted by the model and the observed values. The concordance correlation coefficient (**CCC**) was also used to evaluate the agreement between observed and predicted values by measuring variation from the line of unity.

RESULTS AND DISCUSSION

Model Simulation

The gestation and lactation modules were used to simulate the reproductive cycle of a sow with input values given in Table 4. The changes in body composition and N balance were evaluated by comparisons with literature data. The dynamic model gave daily output throughout gestation and lactation, but no data sets on sows were available that included all of the information collected. Therefore, only results of the simulation, where literature data were available, were mentioned and discussed in this section. Selected outputs from the simulation were provided in Table 5. The sow gained weight and backfat during gestation, but lost weight and

Table 5. Selected outputs from simulation of reproductive cycle[1]

Output	Gestation	Lactation
BW, kg		
Initial	160	219
Final	238	196
Gain	78.0	−23.0
Backfat thickness, mm		
Initial	15.0	23.2
Final	23.2	19.9
Gain	8.20	−3.30
Protein deposition, g/d	63.7	−97.7
Fat deposition, g/d	204	−329
N balance, g/d		
N intake	56.4	154
N retention	14.1	−15.8
Fecal N	5.48	15.4
Urinary N	36.7	67.4
Milk N	–	86.8
C excretion,[2] g/d	143	310
Methane emission, L/d	2.05	4.87
Manure production, kg/d	13.5	17.1

[1]Results for protein and fat deposition, N balance, C excretion, methane emission, and manure production are average numbers for gestation and lactation, respectively.

[2]Carbon excretion in urine and feces.

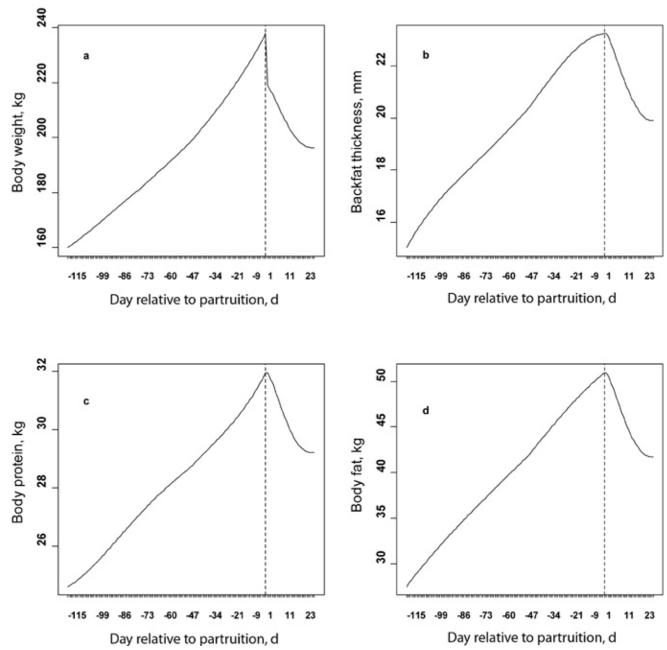

Figure 2. Simulation of (A) BW (kg), (B) backfat thickness (mm), (C) body protein (kg), and (D) body fat during a reproductive cycle. The vertical dashed line indicates the day of parturition.

backfat during lactation (Fig. 2). The weight loss was partly attributed to parturition (fetuses, membranes, and water) and partly to mobilization of body protein and fat. The same pattern of changes in BW and backfat thickness was observed by Clowes et al. (2003a).

In the simulation, the sow gained 78 kg of BW and 8.2 mm of backfat during gestation, which was in the upper range reported in the literature (e.g., Robert et al., 2000; Ji et al., 2005; Gill, 2006). Thus, the model or equations used to predict BW and body composition might overestimate maternal weight and fat gain during gestation. Another explanation could be that the greater daily intake used in the simulation (2.5 to 3 kg/d), compared to intakes in studies by Gill (2006; 2.25 kg/d) and Ji et al. (2005; 2 kg/d), increased the amount of nutrients available for retention. During lactation, the sow lost 23 kg of BW and 3.3 mm of backfat, which was normal for a lactating sow (e.g., McNamara and Pettigrew, 2002; Clowes et al., 2003a; Gill, 2006).

In the gestating sow, 25, 10, and 65% of the total N intake was retained and excreted in feces and urine, respectively. In 3 studies (Theil et al., 2002; Clowes et al., 2003b; Renteria-Flores et al., 2008), using the same BW for sows as in the simulation, the N retention was 22 to 52% of the total N intake; thus, the simulated retention was in the lower end of this range. The fecal excretion was greater (13 to 20%) and the urinary excretion (34 to 55%) was reduced compared to studies by Clowes et al. (2003b) and Renteria-Flores et al. (2008). In the simulation, the average N intake during gestation was 56.4 g/d, which was greater than the average N intake of 1 group in the study of Theil et al. (2002; 43.4 g/d), Clowes et al. (2003b; 48 to 53 g/d), and Renteria-Flores et al. (2008; 40 g/d). The other group in the study of Theil et al. (2002) had an average N intake of 57.7 g/d, which approximated N intake in the simulation, but N excretion was only 62.5% of N intake compared to 75% of N intake in the simulation. These observations indicate that the digestibility of protein may be overestimated in the model. In the lactating sow, N intake increased during lactation, which resulted in increased N excretion in urine and feces. The same pattern was reported in the study of Theil et al. (2004), where N balances were obtained 2, 3, and 4 wk postpartum. In the simulation, the average N intake and N excreted in milk was 154 and 86.8 g/d, respectively, which was similar to wk 4 in the study of Theil et al. (2004; 157.9 and 82.8 g/d).In the simulation, urine excretion was greater (67.4 vs. 44 g/d) and fecal N excretion was reduced (15.4 vs. 28 g/d) compared to values reported by Theil et al. (2004).

During gestation and lactation, the average daily methane emission was predicted to be 2.05 and 4.87 L/d, respectively, which was less than the values reported by Le Goff et al. (2002) and some studies included in Jørgensen et al. (2011; Fig. 3). This was mainly due to a reduction in the fermentable fiber content of diets used in the simulation compared to the other studies. Methane emission depends on the amount of fermentable fiber consumed (function of feed intake), resulting in a greater

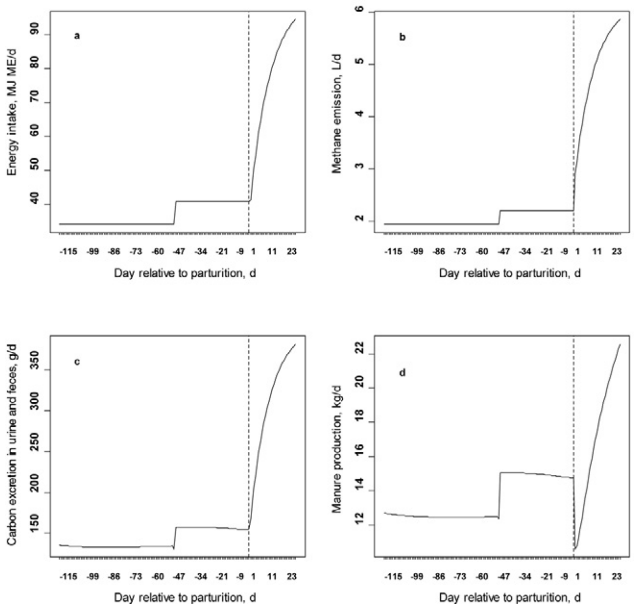

Figure 3. Simulation of (A) energy intake (MJ ME/d), (B) methane emission (L/d), (C) carbon excreted in urine and feces (g/d), and (D) manure production (kg/d) during a reproductive cycle. The vertical dashed line indicates the day of parturition.

emission from lactating sows compared to gestating sows because of the increased feed intake during lactation.

The daily manure production during gestation and lactation was estimated to be 13.5 and 17.1 kg/d, respectively (Table 5; Fig. 3). In a study by Robert et al. (2000), gestating sows fed a concentrate diet produced 18.6 kg manure/d, but the fecal excretion was overestimated because of a short collection period and excessive water intake, resulting in a greater urine excretion. Masse et al. (2003) reported that gestating sows fed a concentrate diet produced 12.4 ± 8 kg manure/d, which is in agreement with our prediction, although the between sow variation in the study was large. The accuracy of the model can be improved by generating new data on gestating and lactating sows. In some areas, such as body composition, information on modern sows is scarce and new data could be used to calibrate the model. Simulations of N transactions for the gestating and lactating phases are given in Fig. 4.

Sensitivity Analysis

Gestation. The results of the sensitivity analysis are given in Table 6. The degree of linearity (R^2) was close to 1 for all tested outputs. The protein deposition was affected by BW at mating (**BW-0**), Lys content of body protein, efficiency of utilization of dietary AA, and the parameter used to determine maternal protein deposition. The fat deposition was affected by BW-0 and parameter, but also by the efficiency coefficients (k_p, k_f, and efficiency of energy deposition in conceptus). Urinary N and C excretions were affected by the number of pigs per litter, fetal protein deposition after d 70, BW-0, Lys content of body protein, efficiency of dietary utilization of AA ($\mathbf{k_{lAA}}$) for body AA, and a parameter used to calculate maternal N deposition. Manure production during gestation depended on the water-to-feed ratio, which was used to calculate the water intake. The water intake was used to determine the urinary excretion, which accounts for part of the manure.

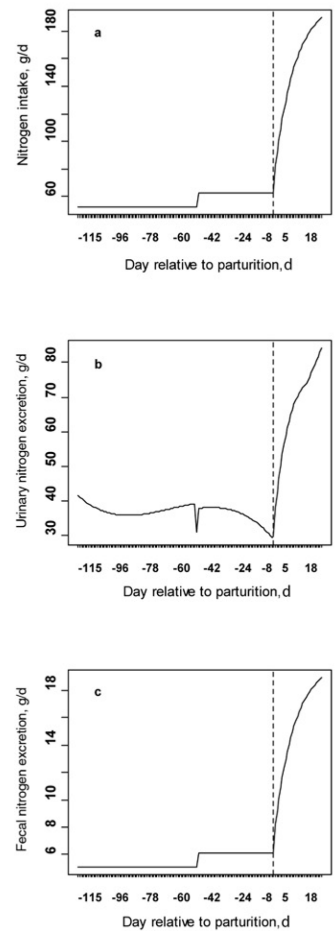

Figure. 4. Simulation of (A) N intake (g/d), (B) urinary N excretion (g/d), and (C) fecal N excretion (g/d) during a reproductive cycle. The vertical dashed line indicates the day of parturition.

The efficiency coefficients k_p and k_f determined by Noblet et al. (1990) and Strathe et al. (2010) for growing pigs are parameters that have an influence on prediction of fat deposition. The BW and composition of sows has changed during the last 20 to 30 yr, which may have caused changes in protein and fat metabolism and efficiencies of dietary ME utilization. These values should be evaluated on modern sows. Information on the efficiency of using single AA for body AA (k_{lAA}) is scarce. The efficiency of AA use impacts body protein deposition and urinary N excretion. Future research should focus on investigating individual AA, as the current focus is to optimize feed use to minimize the environmental impact. Additionally, more synthetic AA are used in the feed to meet exact requirements of the sow.

Table 6. Sensitivity coefficients for the sow model, which accounts for more than 1% of the total model variance[1]

Output/ parameters[2]	Protein deposition	Fat deposition	Fecal N	Urinary N	C excretion	Urinary C	Methane emission	Manure production
Gestation								
R^2	0.998	0.999	–	0.998	–	0.998	–	1.000
A	0.476	0.043	–	0.423	–	0.423	–	–
k_{lAA}	0.046	–	–	0.042	–	0.042	–	–
k_p	–	0.049	–	–	–	–	–	–
k_f	–	0.357	–	–	–	–	–	–
k_c	–	0.012	–	–	–	–	–	–
k2	–	–	0.046	0.046	–	–	–	–
LS	–	–	0.058	0.058	–	–	–	–
BW-0	0.418	0.533	–	0.373	–	0.373	–	–
LysB	0.045	–	–	0.042	–	0.042	–	–
WFR	–	–	–	–	–	–	–	0.999
Lactation								
R^2	0.983	0.996	0.999	0.952	0.998	–	0.999	0.999
a	0.163	0.134	–	–	–	–	–	0.025
b	0.403	0.367	–	0.013	–	–	–	0.071
c	0.038	0.039	–	–	–	–	–	–
LysL	0.127	0.022	–	0.401	0.013	–	–	–
k_{lAA}	0.102	0.018	–	0.324	0.011	–	–	–
Asym	0.079	0.134	0.622	0.112	0.608	–	0.622	0.620
lrc	0.049	0.075	0.357	0.057	0.346	–	0.357	0.149
k_l	–	0.171	–	–	–	–	–	–
R0	–	–	0.029	–	0.028	–	0.029	0.012
k_t	–	–	–	0.014	–	–	–	–
LysB	–	–	–	0.013	–	–	–	–
WFR	–	–	–	–	–	–	–	0.458

[1]The values for each parameter were drawn from normal distributions, 1 for each parameter, with a CV of 2.5% of the original value. The variables tested in the analysis were total protein and fat deposition, average fecal and urinary N and C, average methane emission, and average manure production.

[2]*A* = parameter in the equation to determine maternal N retention, *klAA* = efficiency of dietary AA for deposition in body AA and milk during gestation and lactation, respectively, *kp* = efficiency of utilizing dietary ME for protein deposition in maternal tissue, *kf* = efficiency of utilizing dietary ME for fat deposition in maternal tissue, *kc* = efficiency of utilizing ME for deposition in conceptus, *k2* = protein deposition in fetuses after d 70 of gestation, *LS* = litter size, *BW-0* = BW of the sow at mating, *LysB* = Lys content of body protein; *WFR* = water-to-feed ratio; *a*, *b,* and *c* = parameters in the Wood function; *LysL* = Lys content of milk, *Asym* = maximum feed intake during lactation, *lrc* = slope of lactation feed intake curve, *kl* = efficiency of utilizing dietary energy for milk energy, *R0* = start feed intake during lactation, and *kt* = efficiency of utilizing body stores for milk.

Lactation. The protein and fat deposition was affected by 3 parameters (***a***, ***b***, and ***c***) of the equation used to predict milk production (the Wood function as parameterized by Hansen et al., 2012). The parameters in the feed intake curve and fat deposition were also affected by the efficiency of utilization of dietary energy for milk energy as large quantities of protein and fat are excreted in milk. Milk production was prioritized over the maternal fat and protein deposition, so the remains of the dietary intake were deposited on the body, or a dietary deficit was mobilized from body fat or protein.

Fecal N excretion was affected by parameters, maximum feed intake during lactation (**Asym**), slope of lactation feed intake curve (**lrc**), and start of feed intake during lactation (**R0**) of the feed intake curve. Urinary N excretion was affected by parameters Asym and lrc, of the feed intake curve, but also by the *b* parameter of the Wood function, Lys content of the milk, efficiency of dietary utilization of AA for milk (k_{lAA}), efficiency of utilization of body stores for milk, and Lys content of body protein. The urinary N was calculated from the difference of digestible intake and deposition in milk and body tissues. The C excretion was affected by parameters Asym, lrc, and R0 for the feed intake curve, Lys content of milk, and k_{lAA}.

Methane emission depended on parameters of the feed intake curve because it was calculated from the fermentable fraction of dietary fiber. Manure production during lactation was influenced by water-to-feed ratio, but also by parameters R0, Asym, and lrc associated with the feed intake curve and the *a* and *b* parameters of the Wood function. Feed intake determines fecal excretion, which is part of the manure. A large amount of water was excreted in milk, which affected water balance and, therefore, the amount of water excreted in urine and feces.

The parameters used to determine milk production influence body composition. Hansen et al. (2012) developed a model to more precisely describe lactation in

Table 7. Summary of references used in the evaluation of changes in body fat and protein during gestation

				At mating			At farrowing		
Reference	Group	No. of sows	Parity	BW	Body lipid	Body protein	BW	Body lipid	Body protein
				kg					
Gill (2006)	1	10	1	134	29	21	177	24	22
	2	10	1	118	31	16	170	40	42
Dourmad et al. (1996)	1	7	4.9	207	28	24	252	29	25
	2	7	4.9	201	28	24	266	37	27
	3	7	4.9	206	28	24	286	45	28

sows than that described by older equations. The Hansen et al. (2012) model minimized errors caused by inaccurate estimation of milk yield. Another parameter that should be evaluated for the lactating sow is k_{lAA}, which impacts body protein deposition and urinary N excretion. Currently, k_{lAA} is assumed to be the same for all indispensable AA, which may not be true.

Model Evaluation

Changes in Body Composition. The ability of the model to predict changes in body lipid and protein during gestation was evaluated using data from the literature (Dourmad et al., 1996; Gill, 2006). Only 2 studies were used in the evaluation, as only these studies contained the information needed as inputs to the model and reported measured variables that can be used for evaluation. The body pool of protein and fat at d 1 and 115 of gestation and the change in body protein and fat from d 1 to 115 of gestation were evaluated. Gill (2006) investigated changes in body composition as responses to different levels of Lys (0.75 and 0.50%) during gestation in gilts. The gilts were fed either a high or low Lys to energy ratio during rearing to evaluate the effect of different body conditions at mating (Table 7). Dourmad et al. (1996) tested the effect of different energy intakes by feeding a diet at 3 levels (2.3, 2.7, and 3.1 kg/d) during gestation on changes in body composition in multiparous sows (Table 7). Data on body composition of gestating sows are scarce; however, based on available data, the evaluation showed that the model needs an improvement to accurately estimate changes in body composition (Table 8). For example, body fat gain was predicted with 24% RMSPE as a percentage of observed mean. Body fat at d 1 of gestation was less well predicted compared to body fat at d 115 (Table 8). An increased RMSPE in the predictions of body fat loss from gestation contributed to reduced accuracy of body fat prediction at d 1 of lactation (Table 9). Similarly there was a greater mean bias of predicting body protein at d 1 compared to d 115 (Table 8). The bias also related to greater uncertainty in predicting body protein loss in the lactation module (Table 9), even though the majority of the error was random. The ability of the model to predict changes in body lipid and protein from farrowing to weaning was evaluated using data from the literature (Dourmad et al., 1998; Sauber et al., 1998; Jones and Stahly, 1999; McNamara and Pettigrew, 2002; Gill, 2006; Table 10). Four of the studies (Dourmad et al., 1998; Sauber et al., 1998; Jones and Stahly, 1999; Gill, 2006) tested the effect of different dietary Lys or protein levels, whereas the last study (McNamara and Pettigrew, 2002) also evaluated the effects of dietary fat level on body composition. The model evaluation was performed on the change in body fat and protein from d 1 to 28 of lactation and was presented as the loss of body fat and protein (Table 9). Table 9 and Fig. 5 show that the lactation module predicted changes in body protein and fat better than the gestation module.

Nitrogen Balance. The ability of the model to predict N balance was tested using the data from King et al. (1993). The feed composition reported by King et al. (1993) was used as inputs to the model. The calculated N intake was adjusted to be similar to the N intakes reported by King et al. (1993). Six groups of sows were fed different levels of dietary protein (6 to 24% CP) and N balances [N intake, urinary and fecal N, total N retention (including milk), and maternal N retention] were

Table 8. Evaluation of the gestation module by mean square prediction error (MSPE); root MSPE (RMSPE) with break down to the error due to central tendency (ECT), regression (ER), and disturbance (ED); and concordance correlation coefficient (CCC)[1]

Tested variable	Predicted mean	Observed mean[2]	MSPE	RMSPE	ECT % of RMSPE	ER % of RMSPE	ED % of RMSPE	CCC
Body fat gain, kg	8.60	9.81	5.56	2.36	26.2	6.94	66.8	0.80
Body fat at d 1, kg	28.8	41.6	265	16.3	62.1	0.49	37.5	-0.24
Body fat at d 115, kg	41.6	38.6	76.0	8.71	12.0	32.0	56.1	0.41
Body protein gain, kg	5.43	3.63	5.03	2.24	64.1	30.9	5.00	-0.02
Body protein at d 1, kg	31.6	21.6	122	11.0	81.7	0.77	17.6	0.50
Body protein at d 115, kg	31.8	25.3	69.7	8.35	57.7	0.35	41.9	0.30

[1]The evaluation was for the total protein and fat gain during gestation and the content of body fat and protein at d 1 and 115 of gestation.

[2]The ability of the model to predict changes in body protein and fat during gestation was tested using inputs and results by Dourmad et al. (1996) and Gill (2006).

Table 9. Evaluation of the lactation module by mean square prediction error (MSPE); root MSPE (RMSPE) with break down to the error due to central tendency (ECT), regression (ER), and disturbance (ED); and concordance correlation coefficient (CCC)[1]

Tested variable	Predicted mean	Observed mean[2]	MSPE	RMSPE	ECT % RMSPE	ER % RMSPE	ED % RMSPE	CCC
Changes in body composition								
Body fat loss, kg	−5.32	−6.54	25.5	5.05	3.62	35.3	61.0	0.71
Body protein loss, kg	−3.09	−3.07	3.78	1.94	0.00	1.46	98.5	0.74
N balance								
N intake, g/d	93.2	95.4	85.7	9.26	5.57	4.00	90.4	0.97
N in urine, g/d	37.4	34.6	38.3	6.19	14.6	2.14	83.3	0.94
N in feces, g/d	10.7	10.9	1.18	1.09	1.56	69.9	28.5	0.95
N in milk, g/d	64.4	65.6	25.7	5.07	3.85	51.5	44.7	0.80

[1]The evaluation was for the total body fat and protein loss during lactation and the N balance expressed as the average daily N intake, urinary N, fecal N, and N excreted in milk.

[2]The ability of the model to predict changes in body protein and fat during lactation was tested using inputs and results by Dourmad et al. (1998), Sauber et al. (1998), Jones and Stahly (1999), McNamara and Pettigrew (2002), and Gill (2006). The prediction of the N balance was tested using inputs and results from King et al. (1993).

measured in early (d 12) and late (d 25) lactation (King et al., 1993). The evaluation was presented as the average N intake, N in urine, feces, and milk. Results were given in Table 9 and Fig. 6. Predictions of N intake and urine N excretion had only 9.7 and 17.9% RMSPE as a percentage of the respective observed mean. The majority of error came from random error. Predictions of N in feces and milk were more challenging with error due to regression contributing the greatest amounts of total error. However, predicted fecal N had only 10.0% RMSPE as a proportion of the observed value. Predictions of milk N had 7.7%. In general, there is a need to evaluate the model with more recent and larger data sets so that further improvements can be targeted and the dynamic aspect of the model tested. Data from future experiments that investigate the relationship between the production

Table 10. Summary of references used to evaluate changes in body protein and fat during lactation

Reference	Group	No. of sows	Parity	Lactation	Body component loss			
					Fat	SD	Protein	SD
				d	kg			
Dourmad et al. (1998)	1	10	1	22	–6.6	0.6	–2.5	0.2
	2	12	1	22	–6.5	0.6	–1.6	0.2
	3	11	1	22	–5.2	0.6	–1.9	0.2
	4	10	1	22	–5.8	0.6	–1.5	0.2
Sauber et al. (1998)	1	8	1	28	–10.9	0.23	–6.2	0.13
	2	6	1	28	–15.3	0.23	–7.3	0.13
	3	7	1	28	–18.9	0.23	–6.3	0.13
	4	7	1	28	–20.6	0.23	–4.9	0.13
	5	9	1	28	–4.8	0.23	–8.8	0.13
	6	9	1	28	–5.8	0.23	–7.8	0.13
	7	7	1	28	–8.7	0.23	–7.2	0.13
	8	7	1	28	–7.1	0.23	–6.7	0.13
Jones and Stahly (1999)	1	18	1	20	–11.9	0.1	3.0	0.06
	2	18	1	20	–8.9	0.1	–2.5	0.06
McNamara and Pettigrew (2002)	1	6	2.5	21	–5.0	6.6	–3.0	2.6
	2	6	2.5	21	–2.8	6.6	–0.9	2.6
	3	6	2.5	21	1.4	6.6	–1.0	2.6
	4	6	2.5	21	–0.6	6.6	–3.7	2.6
	5	6	2.5	21	3.5	6.6	–1.0	2.6
	6	6	2.5	21	2.8	6.6	–0.2	2.6
Gill (2006)	1	5	1	25	–2.9	3.4	0.3	1.6
	2	6	1	25	–5.1	3.1	–2.2	1.4
	3	5	1	25	–7.1	3.4	1.2	1.6
	4	6	1	25	–4.0	3.1	–1.0	1.4

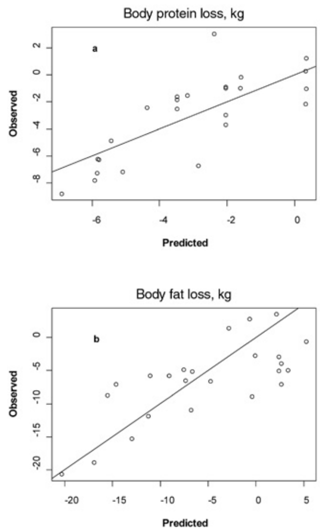

Figure 5. Evaluation of the models ability to predict (A) body protein loss and (B) body fat loss during lactation based on literature. Inputs for the simulation (e.g., feed composition) were taken from the different studies used for the evaluation. Observed values were plotted against predicted values.

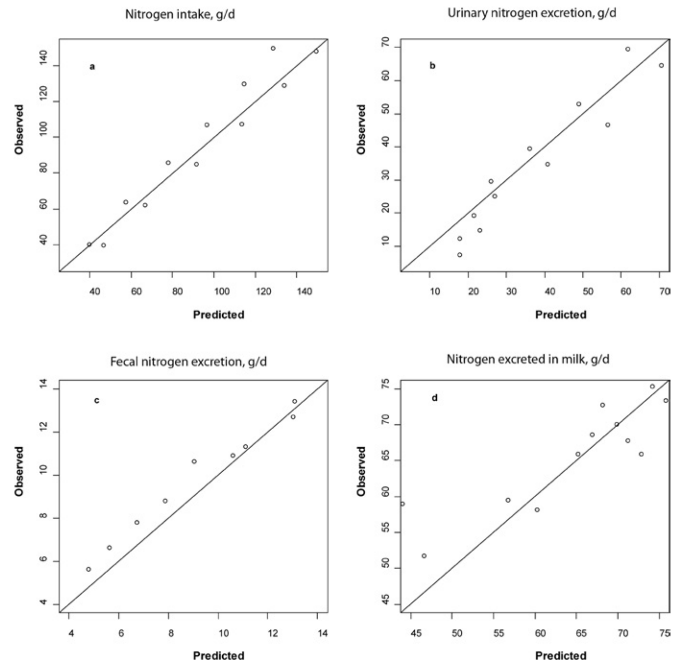

Figure 6. Evaluation of the models ability to predict (A) N intake, (B) urinary N excretion, (C) fecal N excretion, and (D) N excretion in milk during lactation based on literature. Inputs for the simulation (e.g., feed composition) were taken from the different studies used for the evaluation. Observed values were plotted against predicted values.

level of the sow (e.g., milk production) and the changes in body composition would improve the model accuracy. Additionally, more studies should be focused on studying individual AA and the efficiencies of using dietary AA for different functions (e.g., fetal growth, maternal growth, or milk production). This would enable a more precise estimation of the AA requirements and, thereby, reduce the use of excess AA and N excretion.

Model Application

Accurate assessment of air emissions from swine farms with emission factors is difficult due to (1) high variability in the quality and quantity of animal waste and (2) the numerous factors affecting the biogeochemical transformations of manure during collection, storage, and field application. Measurement programs are essential but expensive. Thus, programs have not been extensively implemented. Therefore, models that incorporate mass balance constraints are needed to extrapolate air emissions in both space and time (NRC, 2003). The U.S. Environmental Protection Agency has not yet developed such a model. The agency relies, instead, on a simplified methodology for estimating air emissions from individual farms, using "model" farms based on typical animal confinement, manure collection, solid separation, manure storage and stabilization, and techniques for land application of manure (EPA, 2002). The model developed in this study can be modified to quantify the emissions that come directly from the animal (in this case gestating and lactating sows) and produce inputs required to simulate biogeochemical transformations of manure during storage and after field application. Although the contribution to the total methane emission and N excretion from the sow operation will be small, the nutrient and energy metabolism, and excretion of the nursing piglets should also be included for practical application. Therefore, the sow module developed provides a framework for assessing nutrient flow in the animal component of the farm and opens an opportunity for integration with other process-based models for whole-farm estimations of emissions.

In conclusion, the process-based gestation and lactation modules developed in this study have the potential to predict body composition changes during the different stages of a sow's life, as well as nutrient excretion from sow operations. However, further refinements and evaluations are needed in some aspects of the model for a more accurate assessment of mitigation options to reduce or optimize nutrient utilization by gestating and lactating sows.

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