MATHEMATICAL MODELLING OF MANURE PRODUCTION BY PIG FARMS. EFFECT OF FEEDING AND HOUSING CONDITIONS.

MODÉLISATION MATHÉMATIQUE DES REJETS EN PRODUCTION PORCINE. INFLUENCE DE L'ALIMENTATION ET DU LOGEMENT.

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ABSTRACT

A mathematical model was developed from literature data to predict the volume and composition of the effluent produced by pig farms. In the model, all nutrient fluxes starting from those entering the farm with the feeds up to those leaving the piggery with the slurry are considered. The first set of data predicted by the model is related to the environmental risk : nitrogen, phosphorus, copper, zinc and organic matter content of the slurry, and ammonia emitted to the air. The second set of data is related to the value of the slurry as fertiliser : dry matter, total and available N, organic matter, K, P and Ca. The main sources of variation considered in the model are those related to animals (number of pigs and performance), feeds (feed intake, feed composition and water consumption) and housing (ambient temperature, ventilation rate, frequency of slurry removal and cleaning). The model was validated using 19 experimental studies, most of them on growing pigs, performed in conditions close to those of commercial farms. Validation results showed that the model is precise and robust when predicting slurry volume (R^2=0.96), and slurry nitrogen (R^2=0.91), phosphorus (R^2=0.95) and dry matter (R^2=0.75) contents. The model is an efficient tool to calculate nutrient balances in commercial conditions, to improve slurry management and to reduce environmental risk. It is also an excellent tool to simulate the effect of production alternatives, such as feeding strategy, animal performance or housing conditions, on slurry production and composition. This is illustrated through different examples.

RÉSUMÉ

Un modèle de prédiction du volume et de la composition des effluents produits par un élevage de porcs a été développé et validé à partir de la bibliographie. On considère dans ce modèle les flux générés par l'atelier de production depuis l'entrée des aliments jusqu'à la sortie des effluents. La première catégorie de variables prises en compte dans le modèle concerne l'évaluation du risque pour l'environnement. Il s'agit principalement des composés azotés présents dans l'effluent ou émis dans l'air (NH_3), du phosphore, des éléments trace métalliques (cuivre et zinc) et de la matière organique (MO). La seconde catégorie concerne les variables liées à l'utilisation agronomique des effluents, en particulier la teneur en matière sèche, la disponibilité de l'azote et les teneurs en matière organique, K, P et Ca. Les principaux facteurs de variation intégrés dans le modèle concernent la gestion des animaux (effectifs, performances), la gestion de l'alimentation (quantité et composition des aliments, abreuvement) et la gestion du bâtiment (température ambiante, niveau de ventilation, rythme d'évacuation des lisiers, lavage). Le modèle a été validé à partir de 19 études expérimentales réalisées dans des conditions proches du terrain, principalement chez le porc à l'engraissement. Le modèle s'est avéré plutôt fiable et robuste pour la prédiction du volume de lisier produit (R^2 = 0,96) et sa composition en azote (R^2 = 0,91), en phosphore (R^2 = 0,95) et en matière sèche (R^2 = 0,75). Ce type de modèle peut être utilisé pour réaliser des bilans en situations réelles d'élevage contribuant ainsi à une meilleure gestion des effluents

et à une réduction des risques pour l'environnement. C'est également un outil intéressant pour simuler l'impact de différents paramètres (conduite d'élevage, logement) sur les flux d'effluents. Ceci est illustré au travers de quelques exemples.

Introduction

The reduction of environmental impact of pig production is of prime importance for its durability, as well as the decrease of production cost or the improvement of meat quality. To some extent, this environmental impact may also affect the perception of pork meat by consumers, thus participating to the overall product quality. Environmental impacts related to animal production mainly concern the risks of water pollution by nitrates, phosphorus, organic matter, micro-organisms or trace elements, the risks of air pollution by ammonia (acidification and aerosols), N_2O and CH_4 (global warming effect) emissions and the risks of soil pollution by excessive accumulation of phosphorus or trace elements (Cu, Zn). In fact, these negative environmental effects of swine production systems are often the result of inadequate utilisation of manure as fertiliser. That is why a precise evaluation of the amount and composition of manure produced by pig production systems is required. This can be reached through sampling and analysis, but this approach is expensive and difficult to achieve in commercial conditions, except perhaps for N for which rapid analysis procedures are available. A more promising alternative is the development of mathematical models that predict these environmental hazards from the available information on-farm.

Thus, the objective of the present work was to develop a mathematical model predicting the volume and composition of the effluents produced by pig farms, according to housing, feeding techniques and animal performance. Nutrient losses occurring during the storage of manure outside the building and during spreading are not considered. The main model parameters are those describing the animals (number and performance), the feeds (amount and composition, and water supply) and the housing (ambient temperature, ventilation, frequency of slurry evacuation).

Model description

To improve on-farm slurry management and to avoid the risks associated with inadequate fertilisation, the model produces two kinds of outputs. The first one allows the evaluation of the environmental risk of pig farms, including their impact on water, air and soil quality. The second one evaluates the fertiliser value of the slurry.

Dry matter and organic matter balance *(Table 1)*

The amount of dry matter (DM) and organic matter (OM) excreted in faeces can be calculated from feed DM and OM digestibility coefficients (dC_{DM}, Eq. 1.1 and dC_{OM}, 1.4). When these coefficients are not available, they can be estimated from digestible energy (DE, MJ/kg), minerals (MM, g/kg) and fibre (NDF, g/kg) contents of the diet. Specific equations are used for growing pigs (Eq. 1.2 and 1.5) and reproductive sows (Eq. 1.3 and 1.6) to take into account their specific digestive efficiencies (Le Goff and Noblet (2001); Le Goff, personal communication).

The amount of OM from faeces degraded into biogas during the storage of slurry inside the building is estimated taking into account the duration of the storage and the daily degradation of OM, the later being proportional to OM content. The value of the coefficient of degradation of OM (d, %) depends on the DM content and the temperature of the slurry (Aarnink et al., 1992). For an initial DM content of 56 and 89 g/kg, the value of d is of 0.280 and of 0.187% at 15°C, and of 0.343 and 0.229% at 20°C (Aarnink et al., 1992), respectively. Others situations are interpolated. The average duration of storage is supposed to be half of the interval between two successive flushing of the slurry ($Int_{Flushing}$, d) (Eq. 1.7).

The total amount of DM in the slurry is obtained by adding fecal and urinary DM (Eq. 1.8). Because of the rapid conversion of urea to ammonia and CO_2 in the slurry, all urinary N is assumed to be in the form ammonia. Thus, urinary DM is equivalent to the amount of N excreted in the urine minus N volatilisation as ammonia (Eq. 3.8). The total amount of OM in the slurry is calculated in the same way as for DM (Eq. 1.9).

Table 1. Equations used for the determination of dry matter (DM) and organic matter (OM) contents of the effluent

Faecal excretion of DM and OM (kg / d)	
DM_{Faeces} = Feed x DM x (1 – dCDM)	Eq. 1.1
$dCDM_{grow}$ = (0.709 + (17.94 DE – 0.49 NDF – 1.09 MM) / DM)	Eq. 1.2
$dCDM_{sow}$ = (0.630 + (21.57 DE - 0.26 NDF – 1.21 MM) / DM)	Eq. 1.3
OM_{Faeces} = Feed x OM x (1 – dCOM)	Eq. 1.4
$dCMO_{grow}$ = (0.744 + (14.69 DE – 0.50 NDF – 1.54 MM) / DM) / (OM / DM)	Eq. 1.5
$dCMO_{sow}$ = (0.674 + 19.14 DE – 0.28 NDF – 1.63 MM) / DM) / (OM / DM)	Eq. 1.6
Conversion of fecal OM to biogas	
$OM_{biogas} = OM_{Faeces}$ x d x $Int_{Flushing}$ / 2	Eq. 1.7
Amount of dry matter and organic matter in the effluent	
$DM_{Effluent} = DM_{Faeces} – OM_{Biogas} + (N_{Urine} – N_{Volatisation})$ x 17 / 14	Eq. 1.8
$OM_{Effluent} = OM_{Faeces} – OM_{Biogas} + (N_{Urine} – N_{Volatisation})$ x 17 / 14	Eq. 1.9

Water balance *(Table 2)*

The amount of water in the slurry is calculated from the water balance, determined for both the animal and the building, and the amount of water used for cleaning (Eq. 2.1). Water balance is calculated (Eq. 2.2) as the difference between inputs (drinking and feed water, metabolic water) and outputs (water retention in animals and water evaporation).

The amount of water in the feed (Eq. 2.4) is calculated from its DM content. Drinking water is considered as an input (Eq. 2.3). Water retention in animal's body ($Water_{Body}$) is determined (de Greff, 1995, Eq. 2.6) from body protein content (see below, Eq. 3.3). For reproductive sows, the amount of water retained in uterine contents ($Watert_{Uterus}$) or in suckling piglets ($Water_{Piglets}$) (Eq. 2.5) is also considered. Total weight of uterine contents is determined from litter weight at farrowing (Dourmad et al., 1997; Eq. 2.7) and its water content is assumed to be 84.3% (Noblet et al., 1990). During lactation, water content of litter weight gain is fixed to 68% (Noblet and Etienne, 1987; Eq. 2.8).

To evaluate the amount of water generated by the oxidative metabolism it is assumed that one molecule of H_2O is produced for each molecule of CO_2 (Oliveira, 1999). Thus, the production of 22.4 L of CO_2 (1 mol) is associated with 18 g water (1 mol) (Eq. 2.9). The amount of CO_2 produced is determined from heat production on the basis of 0.163 L/hour CO_2 per Watt of heat (CIGR, 1984). At thermoneutrality, heat production corresponds to the sum of maintenance energy and the fraction of the metabolisable energy (ME) which is not retained in he body (Noblet et al., 1989; Noblet et al, 1990). This last fraction is determined from ME and net energy (NE) contents of the feed. Specific equations are used for growing pigs (Noblet et al., 1989; Eq. 2.10_a), reproductive sows (Noblet et al., 1990; Eq. 2.10_b) and post-weaning piglets (Noblet et Etienne, 1987; Eq. 2.10_c). Below thermoneutrality, the metabolisable energy required for thermoregulation has to be added (Quiniou et al., 2001; Noblet et al., 1989).

Table 2. Equations used for the determination of the water balance

Amount of water in the effluent (kg / pig)	
$Water_{Effluent} = Water_{Balance} \times duration + Water_{Cleaning}$	Eq. 2.1
Water balance (kg / d)	
$Water_{Balance} = Water_{Drinking} + Water_{Feed} + Water_{Mebalolic} - Water_{Retained} - Water_{Evaporation}$	Eq. 2.2
$Water_{Drinking} = Feed \times dilution\ rate$ *(input data)*	Eq. 2.3
$Water_{Feed} = Feed \times (1 - DM_{Feed})$	Eq. 2.4
$Water_{Retention} = Water_{Body} + (Water_{Uterus}) + (Water_{Piglets})$	Eq. 2.5
$Water_{Body} = 5.38 \times 4.889 \times Prot_{Body}^{0.885}$	Eq. 2.6
$Water_{Uterus} = 0.84 \times (0.3 + 1.329 \times \text{litter weight at birth})$	Eq. 2.7
$Water_{Piglets} = 0.68 \times \text{lactation litter weight gain}$	Eq. 2.8
$Water_{Metabolic} = (0.163 \times HeatProd) / 22.4 \times 0.018$	Eq. 2.9
$HeatProd_{Fattening}$ (Watt)= $(750\ BW^{0.60} + (1 - NE/ME) \times ME \times feed) / 86.4$	Eq. 2.10_a
$HeatProd_{Sow}$ (Watt)= $(326\ BW^{0.75} + (1 - NE/ME) \times ME \times feed) / 86.4$	Eq. 2.10_b
$HeatProd_{Litter}$ (Watt)= $284 + 6.44 \times ADG_{Litter}$[a]	Eq. 2.10_c
$Water_{Evaporated}$ (kg/d) = $Heat_{Latent} / 680.6 \times 24$	Eq. 2.11
$Heat_{Latent}$ (Watt)= $HeatProd \times (0.2 - 1.85\ 10^{-7} \times (T° + 10)^4)$	Eq. 2.12
Amount and volume of effluent	
$Effluent_{Amount} = Water_{Effluent} + DM_{Effluent}$	Eq. 2.13
$Effluent_{Volume} = Effluent_{Amount} / Density_{Effluent}$	Eq. 2.14
$Density_{Effluent} = 1000 + 0.49\ DMC_{Effluent}$(g/kg)	Eq. 2.15

[a]ADG : average daily litter weight gain during lactation.

Water evaporation is determined from latent heat production (Eq. 2.11) assuming that on average 680.6 Watts are required to evaporate one kg of water/hour (CIGR, 1984). The empirical equation proposed by CIGR (1984, Eq. 2.12) is used for the partitioning of total heat production between latent and sensible heat, according to ambient temperature (T°).

The total weight of the effluent is then obtained by adding the amounts of water and dry matter (Eq. 2.13). The volume of the effluent is calculated from its density (Eq. 2.14), the later being obtained from an empirical equation relating slurry dry matter concentration and density (Bertrand and Arroyo, 1993; Eq. 2.15).

Nitrogen balance *(Table 3)*

Nitrogen excretion is calculated as the difference between N intake and retention (Eq. 3.1), as already proposed in similar mathematical models (Aarnink et al, 1992; Dourmad et al., 1992). The amount of N retained in body tissues is determined from empty body weight (EBW) according to an allometric relationship (Dourmad et al., 1992) relating carcass N and lean meat contents at usual slaughter weights (Eq. 3.3). For reproductive sows the amount of N retained in uterine products during gestation and in the body of suckling piglets during lactation are also considered.

The amount of N excreted in faeces is calculated from N digestibility coefficient (dCN; Eq. 3.4). When this coefficient is not available, it can be estimated from DE, MM and NDF contents of the diet, as previously indicated. Specific equations are used for growing pigs (Eq. 3.5) and reproductive sows (Eq. 3.6) to take into account their specific digestive efficiencies (Le Goff et Noblet, 2001 and Le Goff, personal communication). Urinary N is then calculated as the difference between total and faecal N excretion (Eq. 3.7).

Table 3. Equations used for the determination of the N flow

Nitrogen excretion	
$N_{Excreted} = N_{Intake} – N_{Retained}$	Eq. 3.1
$N_{Retained} = N_{Body}(final) – N_{Body}(initial)$	Eq. 3.2
$N_{Body} = e^{(-0.9892 – 0.0145 Lean\%)} \times EBW^{(0.7518 + 0.0044 Lean\%)} / 6.25$	Eq. 3.3
$N_{Faeces} = N_{Intake} \times (1 – dCN)$	Eq. 3.4
$dCN_{Grow} = (-0.128 + (7.80 DE + 0.87 CP) / DM) / (CP / DM)$	Eq. 3.5
$dCN_{Sow} = (-0.108 + (6.17 DE + 0.92 CP) / DM) / (CP / DM)$	Eq. 3.6
$N_{Urine}= N_{Excreted} - N_{Faeces}$	Eq. 3.7
Volatilisation of N as ammonia	
$N_{Volat} = N_{Excreted} \times Coeff_{Volat}$	Eq. 3.8
$Coeff_{Volat} = 0.24 \times Effect_{NDilution} \times Effect_{Temp} \times Effect_{AirRenewal} \times Effect_{Floor} \times Effect_{Frequency}$	Eq. 3.9
$Effect_{NDilution}= 1+ 0.21 (N_{Am} – 0.51)$	Eq. 3.10
N_{Am} (mol/kg) = $(N_{Urine} / 14) / Effluent_{Amount}$	Eq. 3.11
$Effect_{Temp}= 1 + 0.053 (Temp_{Effluent} – 22)$	Eq. 3.12
$Temp_{Effluent} = -0.012 T^2 + 1.1816 T + 1.6064$	Eq. 3.13
$Effect_{AirRenewal} = 1 + 0.636 (Rate_{Renewal} – 0.6)$	Eq. 3.14
$Effect_{Floor}$ = 1.00 (concrete fully slatted); 0.85 (metallic fully slatted); 0.80 (partially slatted)	Eq. 3.15
$Effect_{Frequency}$ = 1.00 ($\geq$ 4 weeks), 0.90 (2 weeks), 0.80 (1 week), 0.65 ($\leq$ 1 day)	Eq. 3.16
N in the effluent	
$N_{Effluent} = N_{Excreted} (1 – Coeff_{Volat})$	Eq. 3.17
$NConc_{total}$ (g/kg) = $N_{Effluent} / Effluent_{Amount}$	Eq. 3.18
$N_{Ammonial =} = N_{Urinaire} - N_{Volat} + N_{Faeces} \times c \times Int_{flushing} / 2 / 2$	Eq. 3.19
$NConc_{Ammonia}$ (g/kg) = $N_{Ammonia} / Lisier_{Quantité}$	Eq. 3.20
N in the air	
$N_{Air} = N_{Excreted} \times Coeff_{Volat}$	Eq. 3.17
$NH_{3Air}= N_{Air} \times 17 / 14$	Eq. 3.18
$ConcNH_{3Air}$ (ppm) = $1.41 NH_{3Air} / (Air_{Renewal} \times BW \times 24)$	Eq. 3.19

Air losses of ammonia from the building are estimated by applying a volatilisation coefficient to N excretion ($Coeff_{volat}$; Eq. 3.8). The default value for this coefficient is 0.24, which was estimated from literature data for fattening pigs housed on fully slatted floor (Dourmad et al., 1999). This coefficient is modulated to take into account the numerous factors of variation associated with ammonia volatilisation (Guingand, 1996), mainly slurry dilution ($Effect_{NDilution}$), slurry temperature ($Effect_{Temp}$), air renewal ($Effect_{Renewal}$), type of floor ($Effect_{Floor}$) and frequency of slurry evacuation ($Effect_{Frequency}$). In the model, these effects are evaluated through empirical relationships available in the literature or adapted from the model proposed by Aarnink and Elzink (1998) (Eq. 3.9).

The ammonia concentration of fresh slurry is calculated from urinary N, assuming that all the urea is converted to ammonia. Based in the same data used to estimate the average 0.24 value of $Coeff_{volat}$, the ammonia content of fresh slurry is on average of 0.50 mol/L, which is also the reference value given by Aarnink and Elzink (1998). For this ammonia concentration the value of $Effect_{NDilution}$ is fixed to 1 and it becomes 0.88 and 1.13 when ammonia concentration decreases or increases by 20%, respectively (Aarnink and Elzink, 1998; Eq 3.10). This allows evaluating the effect of slurry dilution resulting from increasing water consumption on ammonia production.

The effect of slurry temperature on ammonia volatilisation is adapted from the model of Aarnink and Elzink (1998). When slurry temperature is of 22°C, which was the average value in the studies reviewed by Dourmad et al. (1999), the value of $Effect_{Temp}$ is fixed to 1. It becomes 0.77 and 1.24 when slurry temperature decreases or increases by 20%, respectively (Aarnink and Elzink, 1998; Eq 3.12). Slurry temperature is estimated from ambient temperature (T°) using the relationship (Eq. 3.13) derived from the study of Granier et al. (1996).

To take into account the effect of air speed over the surface of the slurry on ammonia volatilisation, it is assumed that changes on air speed are proportional to changes of air renewal rate. When air renewal rate is of 0.6 m^3/kg BW, which was the average value in the studies reviewed by Dourmad et al. (1999), the value of the coefficient $Effect_{Renewal}$ is fixed to 1.The effect of air renewal rate on ammonia volatilisation is then estimated according to Aarnink and Elzink (1998), the coefficient $Effect_{Renewal}$ becoming 0.92 and 1.08 when air renewal rates are decreased or increased by 20%, respectively (Eq 3.14). According to Massabie et al. (1999) and Aarnink (1997), the rate of air renewal would be more important than type of ventilation, and from the available information there is no clear evidence that the ventilation system by itself has to be considered in addition to rate of air renewal.

Results concerning the effect of floor design and materials on ammonia emission are to some extent controversial. When totally slatted concrete floor was replaced by partially slatted floor, Hoeksma et al. (1992) and Aarnink et al. (1995) measured a reduction of about 20 to 25% of ammonia emissions. However, this was not corroborated by Guingand and Granier (2001) who concluded that this effect is dependant on the design of the slatted floor and the ambient temperature. Also, compared to concrete slatted floor, metallic slatted floors might reduce ammonia volatilisation by 15% (Hoeksma et al., 1992). Finally, the effect of frequency of slurry flushing has also been included in the model (Eq. 3.16). Ammonia volatilisation is higher when the slurry is stored for long periods of time under the animals, as it is often the case in France, and decreases when the frequency of slurry removal increases (Hoesksma et al., 1992; Voermans et van Poppel, 1993, Guingand, 2000). For instance, a weekly or a daily flushing of the slurry reduces ammonia emissions by 20 and 35%, respectively, compared to a storage exceeding than 4 weeks.

Total N content of slurry is determined by difference between N excretion and N losses in the air (Eq. 3.18). The amount of N present in the form of ammonia (Eq 3.19) is calculated assuming that all urea N is converted to ammonia and that the rate of mineralisation of faecal organic N is the same as for organic matter (Eq. 1.7). The concentration of ammonia in the effluent is then obtained from rates of ammonia volatilisation and air renewal rates (Eq. 3.18 and 3.19).

Mineral balance (P, Ca, K, Cu, Zn) *(Table 4)*

Mineral balance is calculated by difference between mineral intake and retention (Eq. 4.1). For growing animals retention is the difference between mineral body content at the beginning and at the end of the fattening period. For reproductive sows the amount of minerals retained in uterine contents during gestation and in the body of suckling piglets during lactation are also accounted for (Eq. 4.2). Data from the literature were used to estimate the amount of P (Rymarz et al., 1982; Rymarz, 1986; Jongbloed, 1987; Hendriks and Moughan, 1993; Mahan and Newton, 1995; Mahan and Shields, 1998; C. Pomar, unpublished data; P.S. Revy et al., unpublished data; Eq. 4.3), Ca (Rymarz et al., 1982; Rymarz, 1986; Jongbloed, 1987; Hendriks and Moughan, 1993; Mahan and Newton, 1995; Mahan and Shields, 1998; C. Pomar, unpublished data; Eq. 4.4), K (Manners and McCrea, 1963; Mudd et al., 1969; Rymarz et al., 1982; Rymarz, 1986; Mahan and Newton, 1995; ; Hendriks and Moughan, 1993; Mahan and Shields, 1998; Eq. 4.5), Cu (Mahan and Newton, 1995; Kirchgessner et al., 1994; P.S. Revy et al., unpublished data; C. Pomar, unpublished data; Eq. 4.6.) and Zn (Manners and McCrea, 1963; Kirchgessner et al., 1994; Mahan and Newton, 1995; Mahan and Shields, 1998; P.S. Revy, unpublished data; Eq. 4.7.).

Table 4. Equations used for the determination of mineral balance (P, Ca, K, Cu, Zn)

Minerals excretion	
$(P,Ca,K,Cu,Zn)_{Excreted} = (P,Ca,K,Cu,Zn)_{Intake} - (P,Ca,K,Cu,Zn)_{Retained}$	Eq. 4.1
Minerals retention	
$(P,Ca,K,Cu,Zn)_{Retained} = (P,Ca,K,Cu,Zn)_{Body}$ (final) - $(P,Ca,K,Cu,Zn)_{Body}$(initial)	Eq. 4.2
P_{Body} (g)= 5.39 x EBW (n=89, R^2 = 0.97)	Eq. 4.3
Ca_{Body} (g)= 8.56 x EBW (n=89, R^2 = 0.95)	Eq. 4.4
K_{Body} (g)= - 0.0041 x EBW^2 + 2.68 x EBW (n=72, R^2=0.98)	Eq. 4.5
Cu_{Body} (mg)= 1.1 x EBW (n=54, R^2 = 0.91)	Eq. 4.6
Zn_{Body} (mg)= 20.6 x EBW (n=52, R^2 = 0.95)	Eq. 4.7

Validation

Volume of effluent

The model was validated by comparing its results to those available in literature. Only studies including measurements of the volume of slurry produced and the required data to run the model were used in this section (Chosson et al., 1988; Latimier and Chatelier, 1992; Quiniou et al., 1993; Latimier and Pointillart, 1993; Latimier et al., 1993; Granier and Texier, 1993; Latimier et al., 1994; Henrich, 1994; Chauvel and Granier, 1994, Chauvel and Granier, 1996; Albar and Granier, 1996; Latimier et al., 1996; Castaing et al., 1997; Chauvel et al., 1997; Latimier and Paboeuf, 1997; Valaja, 1998; de Oliveira, 1999; Paboeuf et al., 2000; Levasseur and Texier, 2001; Guingand and Granier, 2001). Most of these studies concerned fattening pigs (55 experimental groups from 19 publications) but only two publications were found for each of the other production stages (post-weaning, gestation and lactation).

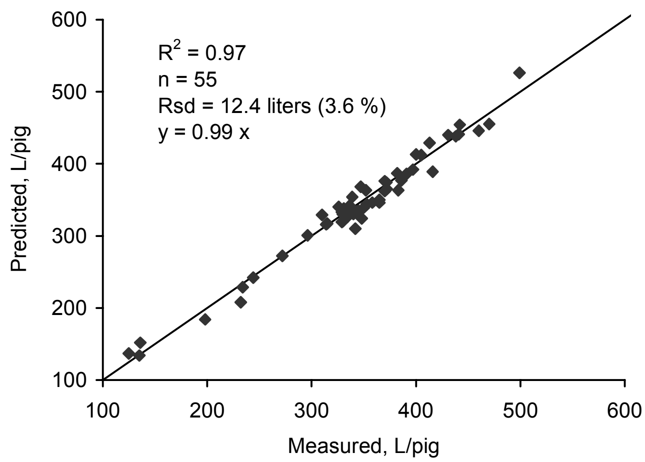

Figure 1 – Relationship between predicted and measured volume of slurry

For the fattening period, model predictions of slurry volume were precise and robust (figure 1) as shown by the fact that the slope of the linear relationship between predicted and observed values was close to one and that determination coefficient (R^2) reached 0.97. The standard error was of 12.4 litres, which represents 3.6% of the observed average slurry volume (344 L/pig). For the post-weaning period, the predicted values for the two available studies (51.8 et 47.0 L/piglet) are also in good agreement with the measured values (52 et 46 l/piglet). Similar results were observed for lactating sows although the volume of produced slurry differed widely between the two studies (predicted: 1490 and 508 L/sow versus measured 1420 and 520 L/sow). For gestating sows, the predicted volume of slurry tended to be slightly higher than measured volumes, especially in the study of Levasseur and Texier (2001) in which water consumption was extremely high.

It appears from the model that most important information required for a precise prediction of effluent volume are the precise measurement of water utilisation (for drinking and cleaning) and the measurement of ambient temperature.

Amount and concentration of N in the slurry

The same literature data used in previous section were also used to validate the prediction of N content in the slurry. During the fattening period, average predicted total amount of N in the slurry (2.53 $\pm$ 0.26 kg/pig) was close to the measured value (2.56 $\pm$ 0.22 kg/pig). The slope of the regression between predicted and measured values (figure 2) is close to one (1.007) and the determination coefficient is high (R^2 = 0.97). The standard error is of 0.09 kg N/pig that represents 3.7% of the average observed value. Model also predicts satisfactorily the N concentration of slurry. Average calculated and measured values of this parameter are of 7.07 $\pm$ 1.43, and 7.16 $\pm$ 1.33 g N/kg, respectively. The slope of the regression is 0.99 (figure 2), R^2 is 0.95 and the standard error 0.30 g N/kg, the later representing 4.2% of the observed average value.

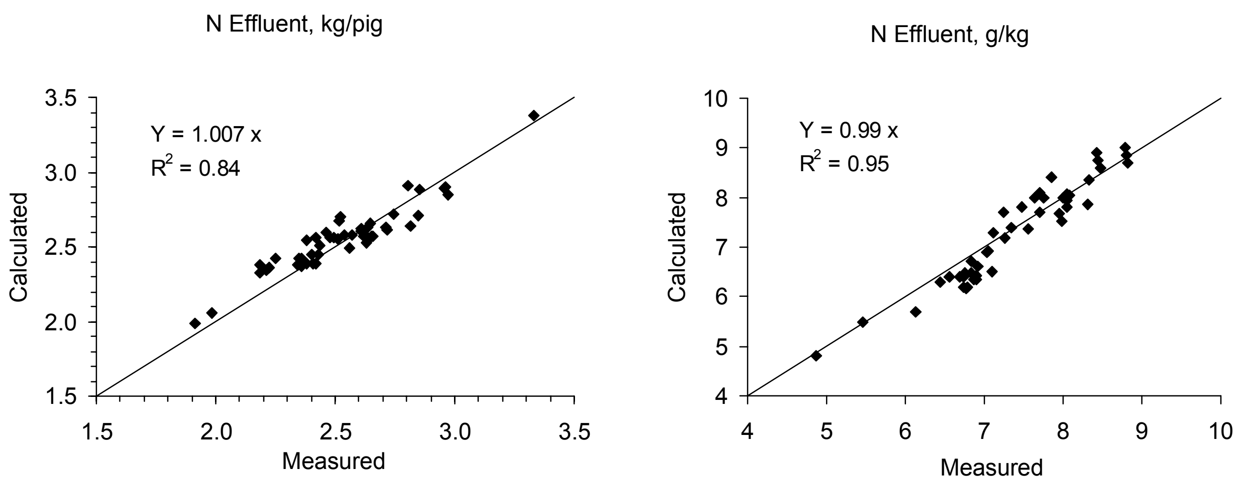

Figure 2 – Relationship between predicted and measured values of total amount and concentration of N in the slurry.

Amount and concentration of phosphorus in the slurry

The relationships between predicted and measured values of total P excretion and concentration in the slurry are presented in figure 3. On average, predicted values are higher than observed values, in both cases by about 13% (618 $\pm$ 182 *versus* 537 $\pm$ 137 g/pig and 1.86 $\pm$ 0.57 *versus* 1.46 $\pm$ 0.42 g/L, respectively). However, the correlation between predicted and observed values remains high for both the total amount of P excreted (slope = 1.16; R^2 = 0.86) and for P concentration (slope = 1.20; R^2 = 0.89). The model overestimation of P excretion cannot be explained by an underestimation of P retention in the pig's body because this would be equivalent to 30% reduction in P retention. Moreover, values of P retention in the body are in good agreement with literature (Jongbloed, 1987). Furthermore, in all studies the dietary phosphorus content was chemically determined and therefore, the discrepancy between predicted and observed values cannot originate from an overestimation of dietary P content. Therefore, the more factual explanation of this difference between predicted and observed values is related to an underestimation of the observed amount of P in the slurry. This underestimation might result from the difficulties normally encountered for the representative sampling of pig's manure. In fact, if only the trials in which slurry was sampled after mixing or collected in metabolic cages are considered, the predicted and observed values of P excretion are very close (547 and 545 g/pig). Furthermore, the discrepancy increases in the studies in which core sampling was used (532 *vs* 631 g/pig). Indeed, during storage, phosphorus deposits in the bottom layers of the pit and the core sampling technique would underestimate their contribution.

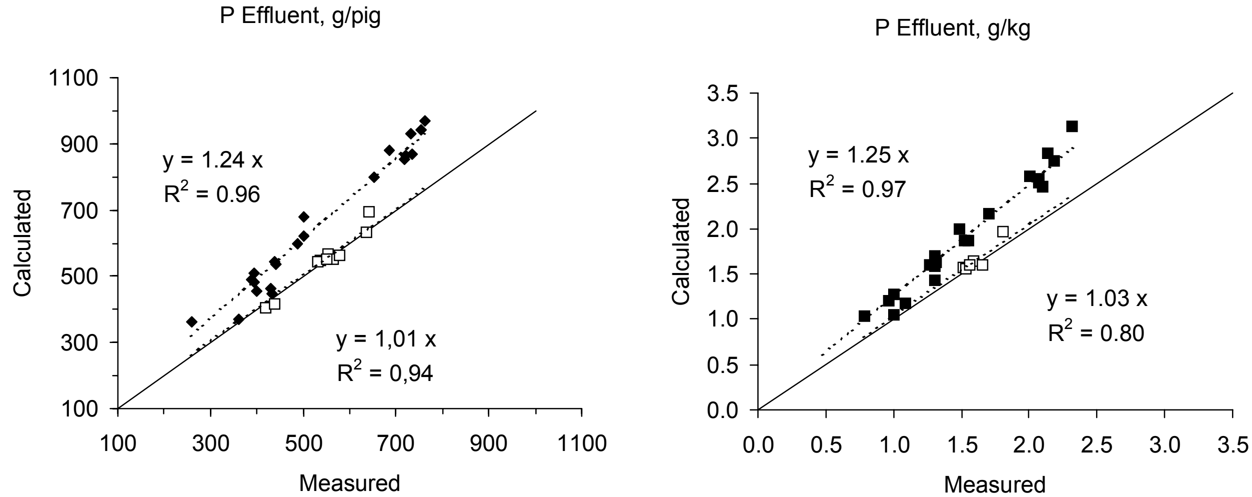

Figure 3 – Relationship between predicted and measured values of total amount and concentration of P in the slurry (■ core sampling, □ sampling after mixing)

Amount and concentration of dry matter in the slurry

The relationship between predicted and observed values of DM in the slurry is presented in figure 4. On average, predicted total DM content (23.3 $\pm$ 2.2 kg/pig) is close to observed value (23.9 $\pm$ 3.8 kg/pig), but the correlation is poor (slope = 1.03, R^2 = 0.35). For the concentration of DM in slurry, average predicted value is also in good agreement with the average observed value (6.91 $\pm$1.06 and of 6.96 $\pm$1.42 g/kg, respectively) and the R^2 coefficient is higher than that obtained for total amount of DM, because of the good prediction of water content of the slurry (slope = 1.01, R^2 = 0.75).

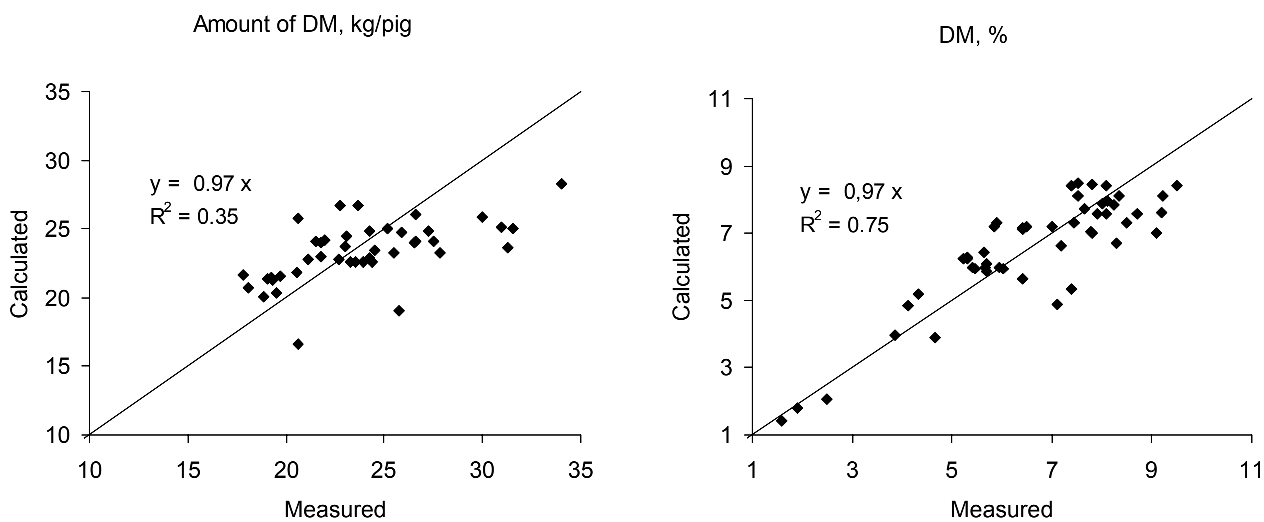

Figure 4 – Relationship between predicted and measured values of total amount and concentration of DM in the slurry.

The model appears less accurate for the prediction of DM than of water, N or P. Dry matter in the slurry is predicted from DM digestibility and the rate of conversion of OM to biogas during storage. A first reason for this poor prediction of DM could be the variability of these processes, which might not be sufficiently precisely considered in the model. However, this information is seldom available. The other reason could be the sampling technique, which could be not appropriate for the estimation of the amount of DM contained in the slurry. Considering that predictions for P and DM are completely independent, the relationship existing between discrepancies on P and DM (R^2 = 0.37) suggests that measurements of these two parameters could play a role.

Simulations

The proposed model is of interest for on-farm use and can contribute to improve practical management of manure. Even so, the model is also a powerful tool to simulate and evaluate the effect of different production strategies on volume and composition of the slurry produced in pig farms. This is illustrated below through the evaluation of the effect of pig performance, dietary protein and phosphorus concentrations and ambient temperature on these environmental parameters.

Effect of pig performance

Three levels of performance (low, medium and high) of growing-fattening pigs are compared (figure 5). The same ratio water/feed of 2.5 is used for the three situations and protein and phosphorus contents are 16.6% and 0.52% for the growing period, and 15.5% and 0.45% for the finishing period, respectively. Improving pig's performance from low to high reduces by 20% the volume of slurry (from 410 to 330 L/pig), whereas DM, N and P contents remain unchanged. Consequently, the amounts of N in the slurry, N in the air and phosphorus in the slurry per pig are reduced by 19, 23 and 19%, respectively. Air quality within the building is also improved, as a result of higher protein efficiency and a faster growth.

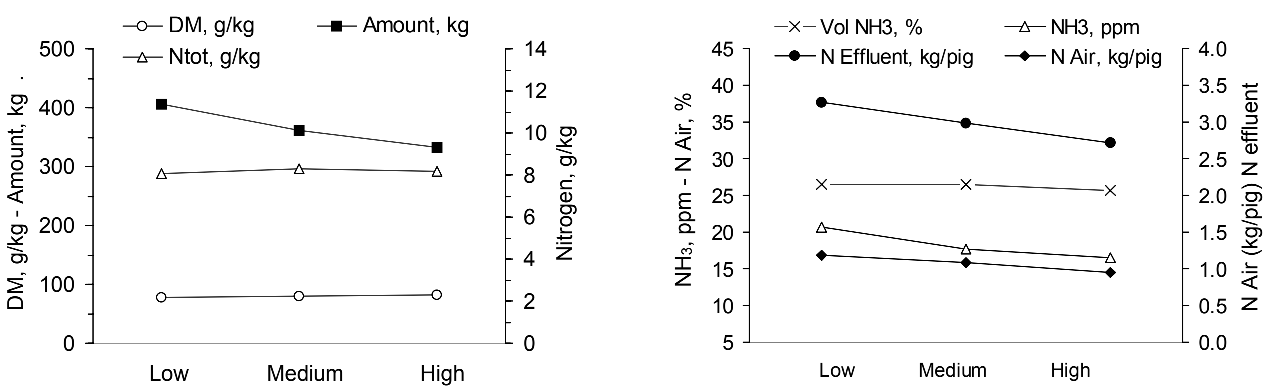

Figure 5. Effect of performance of growing-finishing pigs on the amount and composition of the effluent (Low : FCR=3.1, ADG = 680g; medium : FCR=2.9, ADG = 750g; High : FCR=2.7, ADG = 810g) .

Effect of dietary protein content

The effect of dietary crude protein (CP) content on the amount and composition of the effluent is presented in figure 6. For this simulation two hypotheses of water supply are considered, because many studies have shown that water intake, when available *ad libitum*, decreases with dietary protein concentration (Albar and Granier, 1996). Thus, water intake has been supposed to be either restricted (2.50 kg/kg feed) or to increase with protein supply (water/feed ratio varying from 2.50 for 14% CP to 3.25 for 20% CP in diet). For a controlled water supply, the amounts of slurry is not affected by CP content of the diet whereas it increases from 350 to 500 kg/pig when water is available *ad libitum*. Increasing the CP content of the diet results in a drastic increase of the total amount of N in the slurry, whereas N concentration is mainly affected when water supply is restricted. Air quality is much more degraded with increasing levels of CP when water supply is restricted than when given *ad libitum*. This difference results mainly from the effect of slurry dilution on ammonia volatilisation and can help to explain the contradictory results observed in the literature concerning the effect of dietary CP on ammonia concentration in the air.

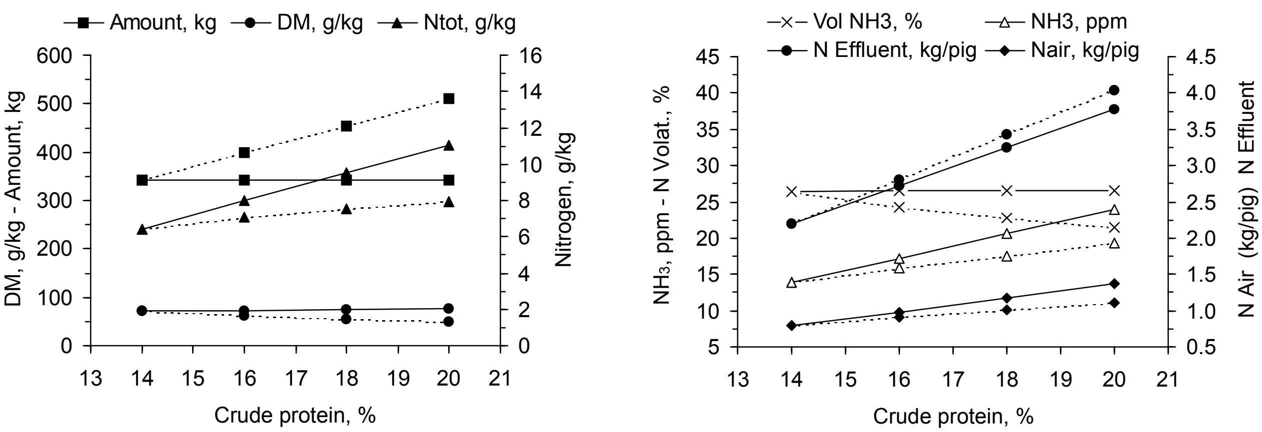

Figure 6 – The effect of dietary crude protein (CP), with water available *ad libitum* (- - - -) or restricted (——), on the amount and composition of the effluent from fattening pigs.

Effect of phosphorus content of the diet

Three strategies of phosphorus-feeding strategies are compared. In the first strategy the same growing finishing diet containing 0.55 % total P is given over the entire fattening period. In the second and the third strategies a growing diet, with addition of microbial phytase, and a finishing diet, with (strategy 3) or without (strategy 2) addition of microbial phytase are fed during the growing and the finishing period, respectively. The model predicts that the volume of the produced slurry (370 L/pig) is similar for the three strategies. Compared to strategy 1, phosphorus-feeding strategies 2 and 3 resulted in 25 and 35% reduction on the P contained in the slurry, respectively.

Table 5. The effect of three phosphorus-feeding strategies on the amount and composition of the effluent.

	Phosphorus feeding strategy		
	Strategy 1	Strategy 2	Strategy 3
Total P content			
growing	0.55	0.48	0.46
finishing	0.55	0.44	0.40
P on the slurry *(P_2O_5)*			
g/pig	786 *(1801)*	579 *(1327)*	509 *(1166)*
g/L[1]	2.12 *(4.87)*	1.56 *(3.59)*	1.38 *(3.15)*

[1] for 370 L of effluent / pig

Effect of ambient temperature

The effect of ambient temperature on the amount and composition of the effluent is presented in figure 7. As in previous simulations, two hypotheses are considered for water intake, which also vary with ambient temperature (Quiniou et al, 2001). The model was set to simulate feed intake and growth performance for each ambient temperature according to the values observed for these parameters by Massabie et al.

(1996). Simulation results indicate that for a controlled water supply, the amount of slurry produced decreases when ambient temperature increases, from 430 kg/pig at 17°C to 210 kg at 28°C, whereas N, P and DM contents increase. When water is available *ad libitum*, the volume of slurry is little affected by ambient temperature and then, N and DM concentration tends to decrease when ambient temperature increases. Increasing ambient temperature results in a decrease in the amount of N in the slurry per pig, this effect being more marked with a restricted water supply. Air ammonia concentration increases slightly with ambient temperature when water supply is restricted whereas it decreases when water is given *ad libitum*.

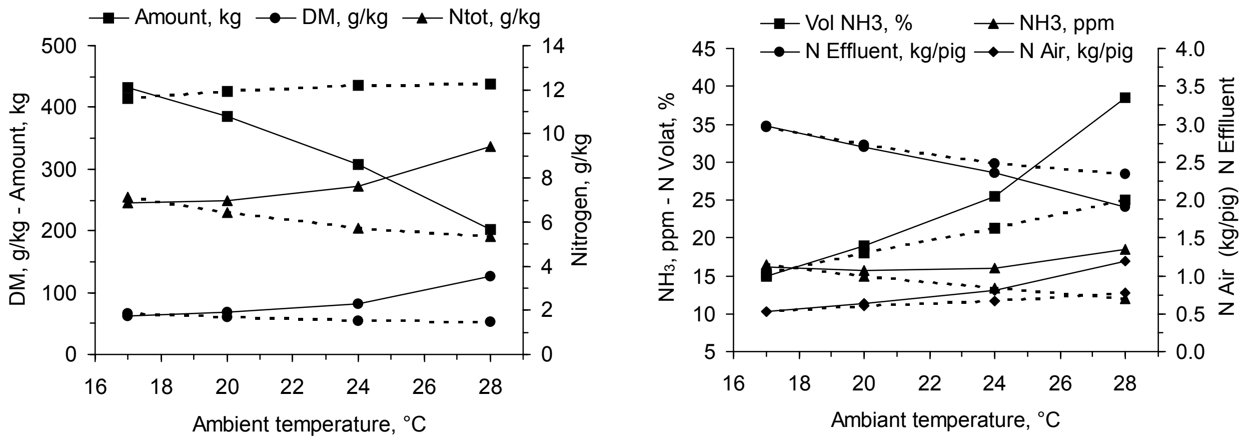

Figure 7 – The effect of ambient temperature, with water available *ad libitum* (- - - -) or restricted (——), on the amount and composition of the effluent from fattening pigs .

Changing ambient temperature affects many parameters related to the animal (feed efficiency, growth performance, and feed and water intake) and to the building (ventilation, evaporation), all of them effecting ammonia volatilisation. The fact that so many parameters are implicated in the emissions of ammonia can explain the contradictory results observed in the literature (Granier et al., 1996). In particular, increasing ambient temperature in some studies resulted in an important increase of ammonia volatilisation while in others the effect was more limited. In fact, the model indicates that increasing ambient temperature results in an increase of ammonia volatilisation, which is partially compensated by the concomitant improvement of feed efficiency and the increase of water consumption.

Conclusion

The model described in this paper allows to precisely predict the volume and composition of the slurry coming out from the piggery. It was developed on the basis of available recent knowledge on nutrient utilisation by the pig.

Similar models have already been published in the literature. The model developed by Aarnink (1992) allows comparable predictions as the present one, but only for fattening herds. The model proposed by Dourmad et al. (1992) considers all stages of production but predicts only the N flow. A more integrated model was described by Goss et al. (1999) for the prediction of liquid or solid manure produced by dairy or pig farms, but this model being less mechanistic, many important effects were not considered. It is difficult to compare the prediction capabilities of these models because they often have not been extensively published, and the parameters they use are different. The validation of such models is a difficult task. For instance, the model published by Aarnink et al. (1992) and Dourmad et al. (1992) were both validated with a limited number of data, few of them coming from practical situations. Since at that time many studies have been conducted to evaluated the effect of different practices (related to nutrition or housing) on amount and composition of slurry. The present work confirms that such models are very promising tools for slurry management in pig farms, which could contribute to the development of environmental management systems for the pig industry (Montel, 2001).

This model is the first step of a more general model that will also integrate the effects of storage, treatment and spreading of slurry. Others types of slurry collection such as straw of sawdust bedding will also be integrated in the future.

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