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Prediction of nutrient flows with potential impacts on the environment in a rabbit farm: a modelling approach

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Abstract. To face the increasing demand for animal products throughout the world, livestock-farming systems have been intensified. This intensification has proven to be economically effective but is noted for its negative impact on the environment through the production of ammonia (NH₃) and the greenhouse gases nitrous oxide (N₂O) and methane. In this context, dynamic models are useful tools to evaluate the effects of farming practice on nutrient flows and losses to the environment. This paper presents the development of a model simulating the flows of nitrogen (N) and phosphorus (P) in a rabbit production farm. The model is comprised of two submodels. The first submodel simulates the number of animals in the farm (births, deaths, culling of does/fatteners) and their respective performances (growth, feed intake, milk production). The second one simulates the excretion of N and P for each animal category using a mass-balance approach between intake (feed and/or milk intake) and exports (body deposition, milk production, gestation). Specific emission factors are then applied to the excreted N amounts to estimate total N, NH₃ and N₂O losses in the housing unit and during manure storage. Methane emissions from enteric fermentations and manure are also estimated. A simulation example based on French technico-economic data illustrates how the model could be used to study the dynamics of animal populations within the system and of nutrient flows. Finally, there is a need for new knowledge (experimental data) to improve the model and help design more sustainable rabbit production systems by identifying best practices that minimise environmental impacts.

Additional keywords: ammonia, excretion, gas emission, greenhouse gas, manure.

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Introduction

In recent decades, livestock-farming practices have evolved considerably. To face the increasing demand for animal products throughout the world, small farms with traditional systems have been replaced by more intensive and confined farming systems with higher stocking densities. This intensification of livestock-farming systems has proven to be economically effective but is noted for its negative impact on the environment (FAO 2006) through the production of ammonia (NH₃) and greenhouse gases (GHG) and a high usage of natural and non-renewable resources. Ammonia contributes to water pollution via eutrophication and soil pollution via acidification (Bouwman *et al.* 2002), whereas methane (CH₄) and nitrous oxide (N₂O) are two major GHG responsible for global warming and likely climate change (IPCC 2007). In livestock systems, these gases are emitted mainly from manure in housing,

in storage facilities or during spreading and grazing and are the main source of pollution of livestock-farming systems. Moreover, the misuse of manure (amounts, spreading dates) can also lead to pollutions such as nitrate leaching, phosphorus (P) runoff or ecotoxicity due to heavy metal accumulation (FAO 2006).

Therefore, an accurate knowledge of the dynamics of nutrient flows in livestock-farming systems would help to design more sustainable systems regarding both their economic (e.g. improvement of feed conversion ratio) and environmental performances. In practice, nutrient flows in livestock systems can be evaluated through sampling and chemical analyses and using zootechnical data, but this approach is expensive, takes time and is difficult to carry out in commercial farms. A dynamic approach is also needed because pollutant leaks to groundwaters or the atmosphere can mainly be explained by a lack of synchronisation or an imbalance between their production

(nitrates, NH_3 , GHG) and their consumption or recycling into the agro-ecosystem. Furthermore, in order to prevent pollution swapping, studies should be comprehensive and developed at a large scale i.e. at the farm scale rather than at the animal scale (Rotz 2004; Monteny *et al.* 2006).

Concerning rabbit production, some studies dealing with the on-farm production of compounds with a potential impact on the environment can be found in the literature (Maertens *et al.* 2005; Calvet *et al.* 2008, 2011). They mostly dissociated nutrient excretion from gas emissions (NH_3 , GHG) whereas these two phases should be considered together to assess the proportion of nutrients lost to the atmosphere and therefore identify the best farming practices to reduce polluting gas emissions. Such a relation between farming practices and gas emissions has been previously shown using a life cycle assessment approach (Zened *et al.* 2013). In this study, the authors showed that global emissions of GHG and NH_3 could be decreased by $\sim 10\%$ in a rabbit farms when rabbits are submitted to a feed intake limitation during fattening rather than *ad libitum* feeding, due to a decrease in mortality, direct and indirect inputs use and manure production.

In such a context, modelling appears as a relevant tool to predict quickly and at a low cost the influence of farming practices (feed composition, reproduction and manure management) on nutrient flows at farm scale. Several models with such characteristics (sensitivity to practices, farm scale, dynamic and permitting a multi-criteria assessment) have been developed in the past but were mostly focussed on swine, dairy or poultry productions (Sise *et al.* 2011; Chardon *et al.* 2012; Méda *et al.* 2012; Rotz *et al.* 2012), and no model was found in the literature concerning rabbit production. Thus, the aim of this paper is to present a dynamic model able to predict the consequences of farming practices on nutrient [nitrogen (N) and phosphorus (P)] flows in rabbit farms.

Model description

The model runs on a daily time step and is composed of two submodels, the first one being dedicated to the simulation of animal populations and performance (mortality, growth, feed intake, milk production, fertility and prolificacy of does) and the second one to the simulation of nutrients flows (excretion, gas emissions). The nutrient flows taken into account in this submodel are represented in Fig. 1a. Input parameters (i.e. chosen by the user) and constants used in the model are described in Table 1.

The model describes a rabbit breeding-fattening farm composed of two identical housing units (1 and 2) in which the animals are managed under all-in/all-out principles. In such systems, does are transferred from one housing unit to the other at each weaning of young rabbits (age_W), whereas the fattened rabbits remain in the same unit from their birth until their slaughter (age_S). This system allows maintaining a depopulation period [$t_{DepoP} = (t_{Cycle} + age_W) - age_S$] in each housing unit between the slaughter of rabbits and the next arrival of does (Fig. 1b).

Animal performances submodel

Births, deaths and replacement of missing does

In each stocking unit, the dynamics of three animal populations (does, replacement does and fatteners) are simulated using different equations (Eqns 1– 8) respectively

for death + culling of does, replacement of does and birth and death of fatteners during maternity or fattening. The variation in the number of does $n_{Does}(t_{After_Part})$ is calculated according to Eqn 1 according to time after the last parturition of does (t_{After_Part} , $0 \leq t_{After_Part} \leq age_W$) with two parameters: the maximal number of does in the farm (n_{Does_max} calculated from the average number of does on the farm n_{Does_av} , Eqn 2) and a mortality + culling rate per batch (R_{M+C_Does} , %). At each weaning (age_W), the does are transferred to the other housing unit (Fig. 1b), and the missing does are replaced (n_{Rdoes} , Eqn 3) at each artificial insemination so that the number of does is equal to n_{Does_max} . t_{Cycle} represents the duration of the reproduction cycle (time interval between two consecutive parturitions, day) and is calculated as the sum of the gestation duration (31 days) and the time interval between parturition and artificial insemination (input parameter, t_{Part_AI} , day).

$$\text{If } t_{After_Part} = t_{Part_AI}, \text{ then } n_{Does} = n_{Does_max}, \quad (1)$$

$$\text{else } n_{Does}(t_{After_Part}) = n_{Does}(t_{After_Part} - 1) - n_{Does_max} \\ \times (R_{M+C_Does}/t_{cycle}),$$

$$n_{Does_max} = n_{Does_av}/[1 - (R_{M+C_Does}/2)] \text{ and} \quad (2)$$

$$n_{Rdoes} = n_{Does_max} \times R_{M+C_Does}. \quad (3)$$

For each parturition (every t_{Cycle} time steps, Eqn 4), the number of live-born in the housing unit is calculated according to Eqn 5 using the number of does n_{Does} and the following two input parameters: $R_{Prolificacy_Does}$, the prolificacy of does (i.e. the number of newborn kept per doe after equalisation of litter size among does) and $R_{Fertility_Does}$, the fertility rate of does (i.e. the percentage of successful parturitions after artificial insemination, %).

$$t_{Cycle} = 31 + t_{Part_AI}, \quad (4)$$

$$n_{Tot_LB} = n_{Does} \times R_{Fertility_Does} \times R_{Prolificacy_Does}. \quad (5)$$

The number of rabbits (Eqn 6) in each fattening unit is then calculated using mortality rates per batch ($R_{M_Fatt_Maternity}$, $R_{M_Fatt_Fattening}$, %) for maternity and fattening periods (input parameters) respectively the age of the fatteners in each unit (age_{Fatt} , day), the age at weaning and slaughter (age_W , age_S , day) and the total number of live-born in the unit n_{Tot_LB} . To simplify our approach, we considered that the number of replacement does (n_{Rdoes}) remains constant over time, i.e. not affected by mortality during nursing or fattening. The number of sucklings per lactating doe (n_{Litter}) is calculated using Eqn 7. The number of weaned rabbits (without considering n_{Rdoes}) per batch (n_{Tot_W}) is calculated according to Eqn 8.

$$\text{If } age_{Fatt} = 0, \text{ then } n_{Fatt_Unit} = n_{Tot_LB} + n_{Rdoes}. \quad (6)$$

$$\text{If } age_{Fatt} \neq 0 \text{ and } age_{Fatt} \leq age_W, \text{ then } n_{Fatt_Unit}(age_{Fatt}) \\ = n_{Fatt_Unit}(age_{Fatt} - 1) - [n_{Tot_LB} \\ \times (R_{M_Fatt_Maternity}/age_W)] + n_{Rdoes}.$$

$$\text{If } age_{Fatt} > age_W, \text{ then } n_{Fatt_Unit}(age_{Fatt}) = n_{Rdoes} \\ + n_{Fatt_Unit}(age_{Fatt} - 1) - [n_{Tot_W} \\ \times (R_{M_Fatt_Fattening}/(age_S - age_W))],$$

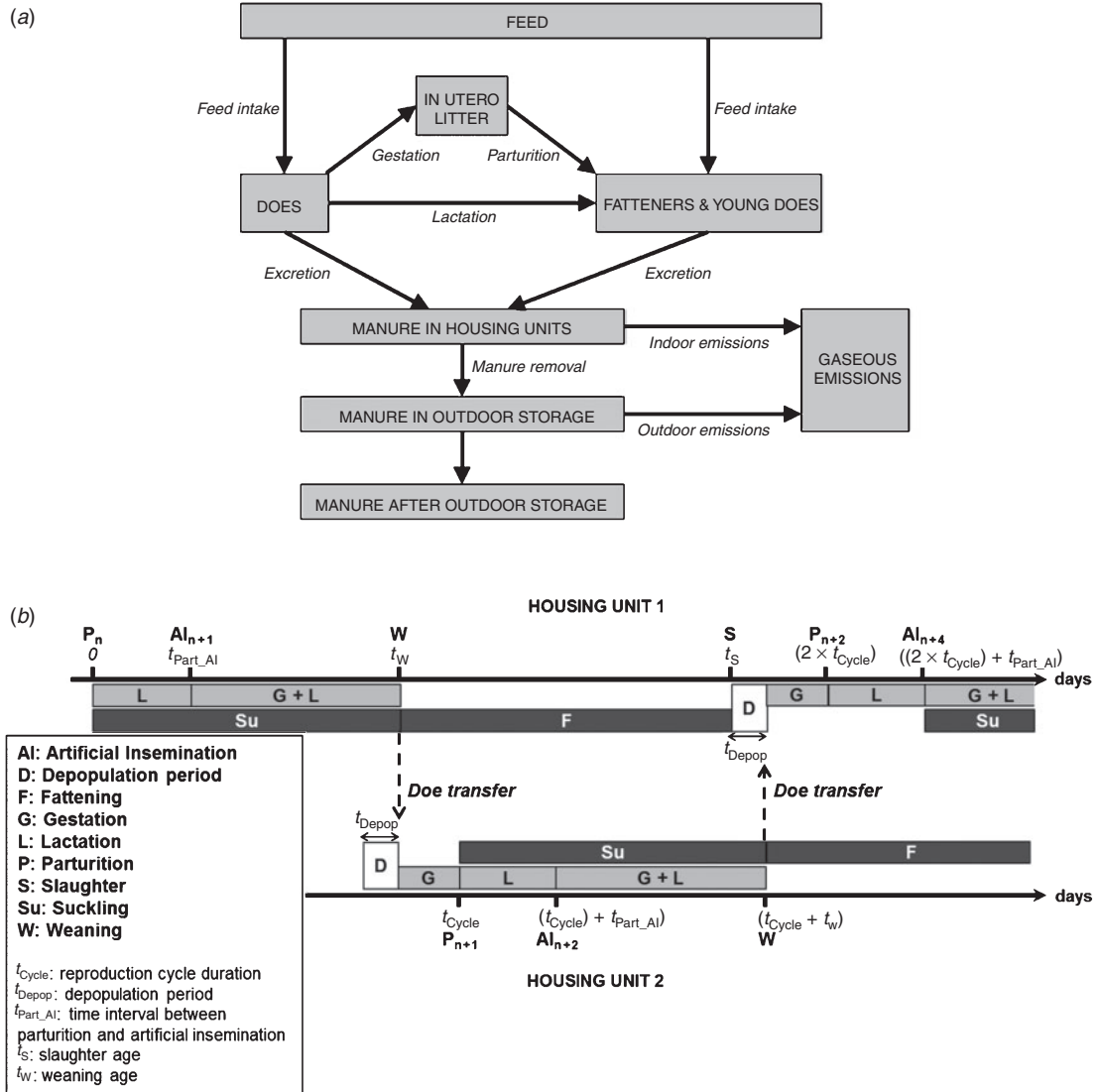


Fig. 1. General overview of the model. (a) Diagram representing the flows of nitrogen and phosphorus simulated in the model. (b) Schematic representation of an all-in/all-out rabbit production system simulated in the model according to reproduction management (t_{Cycle} , $t_{\text{Part_AI}}$) and fattener management (t_W , t_S).

$$n_{\text{Litter}} = n_{\text{Fatt_Unit}} / (n_{\text{Does}}), \quad (7)$$

$$n_{\text{Tot_W}} = n_{\text{Tot_LB}} \times (1 - R_{\text{M_Fatt_Maternity}}). \quad (8)$$

Bodyweight, in utero litter growth, feed intake and milk production of the does

Several studies showed that during a reproduction cycle, doe bodyweight is subject to changes due to accretion and depletion of reserves (Feugier and Fortun-Lamothe 2006). However, the dynamics of these changes are difficult to represent in a modelling approach. Therefore, in our model, we considered that the empty bodyweight of the doe (BW_{Doe}) is constant over time and that the *in utero* growth of the litter + fetal annexes ($DWG_{\text{Litter_in_utero}}$) is the only change in the bodyweight of does. The growth of *in utero* litter + fetal annexes ($DWG_{\text{Litter_in_utero}}$, g/day.animal) is calculated using Eqn 9. To estimate the parameters of this equation, we assumed that at parturition, final weight of

litter + fetal annexes is ~125% of total weight of live-born kits and that at 24 days of gestation ($t_{\text{Gest}} = 24$), the litter + fetal annexes represented ~20% of total weight of live-born kits ($n_{\text{Litter_atPart}} \times BW_{\text{B}}$; Fortun *et al.* 1993):

$$DWG_{\text{Litter_in_utero}} = a_{\text{fetal_growth}} \times \exp(a_{\text{fetal_growth}} \times t_{\text{Gest}} + b_{\text{Fetal_growth}}), \quad (9)$$

$$\text{with } a_{\text{fetal_growth}} = [\ln(1.25 \times (n_{\text{Tot_LB}} / n_{\text{Does_max}}) \times BW_{\text{B}}) - \ln(0.2 \times (n_{\text{Tot_LB}} / n_{\text{Does_max}}) \times BW_{\text{B}})] / (31 - 24),$$

$$b_{\text{Fetal_growth}} = \ln[1.25 \times (n_{\text{Tot_LB}} / n_{\text{Does_max}}) \times BW_{\text{B}}] - 31 \times a_{\text{fetal_growth}}.$$

According to Maertens *et al.* (2006), milk production of does is influenced by many factors such as parity order, gestation overlapping degree, and genotype. The number of suckling kits is

Table 1. Input parameters (user choice) used in the model. The values of input parameters were used to simulate a typical French rabbit farm (on the basis of technico-economic results of 2012)

Dml, dimensionless

Symbol	Description	Unit	Value	Reference
age_{1st_AI}	Age at first artificial insemination	Day	137	L. Fortun-Lamothe, pers. comm.
$ages$	Age of fatteners at slaughter	Day	73	ITAVI (2013)
age_w	Age of fatteners at weaning	Day	35	ITAVI (2013)
Ash_{Diet_Doe}	Ash content of diet offered to does ^A	Dml	7.3%	Zened <i>et al.</i> (2013)
Ash_{Diet_Fatt}	Ash content of diet offered to fatteners ^B	Dml	7.6%	Zened <i>et al.</i> (2013)
BW_B	Bodyweight of fatteners at birth	g	55	Feugier and Fortun-Lamothe (2006)
BW_{Doe}	Bodyweight of a doe	g	4500	L. Fortun-Lamothe, pers. comm.
BW_S	Bodyweight of fatteners at slaughter	g	2460	ITAVI (2013)
d_{Diet_Doe}	Digestibility of diet offered to does ^A	Dml	65%	Zened <i>et al.</i> (2013)
d_{Diet_Fatt}	Digestibility of diet offered to fatteners ^B	Dml	59%	Zened <i>et al.</i> (2013)
DFI_{av_Doe}	Average daily feed intake of a producing doe	g	350	Nicodemus <i>et al.</i> (2004)
$DFI_{Rdoes_flushing}$	Daily feed intake of a young doe during flushing	g	220	L. Fortun-Lamothe, pers. comm.
$DFI_{Rdoes_restricted}$	Daily feed intake of a young doe when restricted	g	130	L. Fortun-Lamothe, pers. comm.
FCR_{Fatt_av}	Global feed conversion ratio during fattening period	kg/kg BW	2.94	Maertens (2009)
FCR_{Fatt_W}	Feed conversion ratio at weaning	kg/kg BW	1.91	Maertens (2009)
GE_{Diet_Doe}	Gross energy content of diet offered to does ^A	MJ/kg	18.2	Zened <i>et al.</i> (2013)
GE_{Diet_Fatt}	Gross energy content of diet offered to fatteners ^B	MJ/kg	17.7	Zened <i>et al.</i> (2013)
M_{System}	Manure management system ^C	–	S or DP	–
N_{Diet_Doe}	Nitrogen content of diet offered to does ^A	g N/kg	28.3	Zened <i>et al.</i> (2013)
N_{Diet_Fatt}	Nitrogen content of diet offered to fatteners ^B	g N/kg	25.2	Zened <i>et al.</i> (2013)
n_{Does_av}	Average number of does in the farm	Dml	605	ITAVI (2013)
P_{Diet_Doe}	Phosphorus content of diet offered to does ^A	g P/kg	5.7	Zened <i>et al.</i> (2013)
P_{Diet_Fatt}	Phosphorus content of diet offered to fatteners ^B	g P/kg	5.3	Zened <i>et al.</i> (2013)
$R_{Fertility_Does}$	Fertility rate of does	Dml	82.5	ITAVI (2013)
$R_{M_Fatt_Fattening}$	Mortality rate of fatteners during fattening period	Dml	8%	ITAVI (2013)
$R_{M_Fatt_Maternity}$	Mortality rate of fatteners during maternity period	Dml	8%	ITAVI (2013)
$R_{M + C_Does}$	Mortality + culling rate of does	Dml	16.3%	ITAVI (2013)
$R_{Prolificacy_Does}$	Prolificacy of does (i.e. number of live-born per doe) ^D	Dml	9.2	ITAVI (2013)
t_{Part_AI}	Time interval between parturition and insemination	Day	11	ITAVI (2013)

^AThis diet is offered to does from parturition to 25 days after parturition, and from weaning to parturition. Therefore, it is also offered to fatteners from birth to 25 days of age.

^BThis diet is offered to fatteners from 25 days of age to slaughter. Therefore, it is also consumed by does between Day 25 after parturition and weaning of fatteners.

^CS, slurry; DP, deep-pit. Both manure management systems are simulated and discussed in the text.

^DKept after equalisation of litter size among does.

also a factor affecting milk production and we used the equation of Maertens *et al.* (2006) to estimate the average milk production of does (DMP_{av} , g/day.animal, Eqn 10). At each time step, the actual daily milk production (DMP_{Doe}) can be calculated using Eqn 11, which simulates a lactation curve calibrated with DMP_{av} , age_w , and milk production at weaning (DMP_w , g/day.animal) with a lactation peak occurring 19 days after parturition. DMP_w is calculated according to Eqn 12 using t_{Cycle} (L. Fortun-Lamothe, pers. comm.).

$$DMP_{av} = 37.47 \times n_{Litter}(t_{After_Part} = 0) - 1.56 \times n_{Litter}(t_{After_Part} = 0)^2. \quad (10)$$

$$\text{If } t_{After_Part} \leq 19, \text{ then } DMP_{Doe} = a_{1_DMP} \times t_{After_Part}. \quad (11)$$

$$\text{If } 19 < t_{After_Part} \leq age_w, \text{ then } DMP_{Doe} = a_{2_DMP} \times t_{After_Part} + b_{2_DMP}.$$

$$\text{If } t_{After_Part} > age_w, \text{ then } DMP_{Doe} = 0,$$

$$\text{with } a_{1_DMP} = a_{2_DMP} + b_{2_DMP}/19,$$

$$a_{2_DMP} = [2 \times (DMP_{av} \times age_w) - DMP_w \times (2 \times age_w - 19)]/[19 \times age_w - age_w^2],$$

$$b_{2_DMP} = DMP_w - a_{2_DMP} \times age_w,$$

$$DMP_w = 2.19 \times t_{Cycle} + 81.09. \quad (12)$$

Finally, daily feed intake of does (DFI_{Doe} , g/day.animal) is calculated according to Eqn 13. This equation is calibrated using an average daily feed intake (DFI_{av_Doe}) provided as a model input. We also assumed that DFI_{Doe} is maximal 19 days after parturition (Maertens *et al.* 2006) and that does stop eating 2 days before parturition (L. Fortun-Lamothe, pers. comm.; Pascual *et al.* 2006):

$$\text{if } t_{After_Part} \leq 19, \text{ then } DFI_{Doe} = a_{1_DFI_Doe} \times t_{After_Part} + b_{1_DFI_Doe}. \quad (13)$$

$$\text{If } 19 < t_{After_Part} \leq t_{Cycle} - 3, \text{ then } DFI_{Doe} = a_{2_DFI_Doe} \times t_{After_Part} + b_{2_DFI_Doe}.$$

$$\text{If } t_{After_Part} > t_{Cycle} - 3, \text{ then } DFI_{Doe} = 0,$$

$$\begin{aligned} \text{with } a_{1_DFI_Doe} &= [a_{2_DFI_Doe}/19] \times [19 - (t_{\text{Cycle}} - 3)], \\ a_{2_DFI_Doe} &= 2 \times [(DFI_{\text{av_Doe}} \times (t_{\text{Cycle}})) - (250 \\ &\times (t_{\text{Cycle}} - 3))]/[(t_{\text{Cycle}} - 3) \times (19 - (t_{\text{Cycle}} - 3))], \\ b_{1_DFI_Doe} &= 250, \\ b_{2_DFI_Doe} &= 250 - a_{2_DFI_Doe} \times (t_{\text{Cycle}} - 3). \end{aligned}$$

Growth, milk and feed intakes of fatteners

From birth to slaughter, the bodyweight of fatteners (BW_{Fatt} , g) is simulated using the Gompertz-modified function proposed by van Milgen *et al.* (2008) using age and bodyweight at birth (0 days) and at slaughter (age_{B} , BW_{B} , age_{S} , BW_{S}) and a precocity parameter (B_{G}) describing the shape of the growth curve (Eqn 14). The B_{G} was estimated to a value of 0.0314 by fitting the growth model on growth data provided by a rabbit genetic selection company. At each time step, the bodyweight gain of fatteners ($DBWG_{\text{Fatt}}$, g/day) can be estimated according to Eqn 15:

$$\begin{aligned} BW_{\text{Fatt}} &= BW_{\text{S}} \times (BW_{\text{S}}/BW_{\text{B}})^{[-(\exp[-B_{\text{G}} \times (age_{\text{S}} - age_{\text{B}})] \\ &- \exp[-B_{\text{G}} \times (age_{\text{Fatt}} - age_{\text{B}})])]/(-1 + \exp[-B_{\text{G}} \\ &\times (age_{\text{S}} - age_{\text{B}})])], \end{aligned} \quad (14)$$

$$DBWG_{\text{Fatt}} = dBW_{\text{Fatt}}/dAge_{\text{Fatt}}. \quad (15)$$

Before weaning, the daily milk intake (DMI_{Fatt}) of fatteners is calculated as the ratio between milk production per doe (DMP_{Doe}) and litter size (n_{Litter}) according to Eqn 16. It has also been observed that after 17 days of age, fatteners start to consume solid feed offered to the doe. Therefore, using the data published by Orengo and Gidenne (2007), a linear model was fitted to predict the feed intake of the fattener (DFI_{Fatt}) between birth and weaning (Eqn 17). After weaning, we considered that DFI_{Fatt} is equal to the product of $DBWG_{\text{Fatt}}$ by the feed conversion ratio of the fattening period (FCR_{Fatt}). According to Maertens (2009), FCR_{Fatt} increases linearly from weaning to slaughter, therefore we considered such an evolution in Eqn 18 using an average FCR for the whole fattening period ($FCR_{\text{Fatt_av}}$) and a FCR value at weaning ($FCR_{\text{Fatt_W}}$) as input parameters (Table 1).

$$\text{If } age_{\text{Fatt}} \leq age_{\text{W}}, \text{ then } DMI_{\text{Fatt}} = DMP_{\text{Doe}}/n_{\text{Litter}}, \quad (16)$$

$$\text{else } DMI_{\text{Fatt}} = 0.$$

$$\text{If } age_{\text{Fatt}} \leq 17, \text{ then } DFI_{\text{Fatt}} = 0. \quad (17)$$

$$\begin{aligned} \text{If } age_{\text{Fatt}} > 17 \text{ and } age_{\text{Fatt}} > age_{\text{W}}, \text{ then } DFI_{\text{Fatt}} &= 2.81 \\ &\times age_{\text{Fatt}} - 50.06. \end{aligned}$$

$$\text{If } age_{\text{Fatt}} \geq age_{\text{W}}, \text{ then } DFI_{\text{Fatt}} = FCR_{\text{Fatt}} \times DBWG_{\text{Fatt}},$$

$$FCR_{\text{Fatt}} = a_{\text{FCR_Fatt}} \times age_{\text{Fatt}} + b_{\text{FCR_Fatt}}, \quad (18)$$

$$\text{with } a_{\text{FCR_Fatt}} = (FCR_{\text{Fatt_S}} - FCR_{\text{Fatt_W}})/(age_{\text{S}} - age_{\text{W}}),$$

$$b_{\text{FCR_Fatt}} = FCR_{\text{Fatt_W}} - a_{\text{FCR_Fatt}} \times age_{\text{W}},$$

$$FCR_{\text{Fatt_S}} = 2 \times FCR_{\text{Fatt_av}} - FCR_{\text{Fatt_W}} (FCR_{\text{Fatt_S}}: \text{FCR at slaughter}).$$

Rearing of replacement does

At each batch, replacement does represent ~15–20% of the total number of does (Maertens *et al.* 2005). In our model, we

considered that these young does are bought and arrive at 1 day of age in the farm. They are adopted by lactating does and are reared as fatteners born on the farm up to slaughtering age (growth and feed intake described using Eqns 14–18). Between slaughtering age and first insemination ($age_{1\text{st_AI}}$), replacement does continue to grow (up to BW_{Doe}) with a constant daily gain DWG_{Rdoes} (Eqn 19) Moreover until first parturition (i.e. at $age_{1\text{st_AI}} + 31$ days), replacement does are mostly feed restricted (except around first AI i.e. flushing). In our model, we therefore considered feed intake during preparation (DFI_{Rdoes}) using Eqn 20 with $DFI_{\text{Rdoes_restricted}}$ and $DFI_{\text{Rdoes_flushing}}$ daily feed intakes during feed restriction or flushing (g/day.animal) whereas after parturition Eqn 13 for DFI was used.

$$DWG_{\text{Rdoes}} = [(BW_{\text{Doe}} - BW_{\text{S}})/(age_{1\text{st_AI}} - age_{\text{S}})]. \quad (19)$$

If $age_{\text{Rdoes}} < (age_{1\text{st_AI}} - 7)$ or $age_{\text{Rdoes}} > (age_{1\text{st_AI}} + 4)$,

$$\text{then } DFI_{\text{Rdoes}} = DFI_{\text{Rdoes_restricted}}. \quad (20)$$

If $age_{\text{Rdoes}} \geq (age_{1\text{st_AI}} - 7)$ and $age_{\text{Rdoes}} \leq (age_{1\text{st_AI}} + 4)$,

$$\text{then } DFI_{\text{Rdoes}} = DFI_{\text{Rdoes_flushing}}.$$

Manure and gaseous emissions submodel

Nutrient excretion

For females, at each time step, we assumed that empty bodyweight of does is constant over time (i.e. no variation in body reserves). Therefore, the excretion of the nutrient X per doe ($X_{\text{Excretion_Doe}}$, g/day.animal) with X being either N or P, can be calculated as the difference between daily feed intake (DFI_{Doe}) and daily milk production (DMP_{Doe}) and daily weight gain of *in utero* litter ($DWG_{\text{Litter_in_utero}}$) according to Eqn 21. When does stop eating just before parturition, we considered that excretions of N and P were respectively 5 g N/day and 1 g P/day (extrapolation of excretion rates simulated by our model just before does stop eating). For replacement does, Eqn 22 is used during their preparation (i.e. before $age_{1\text{st_AI}}$). For non-lactating does (first gestation or failed AI), Eqn 21 is used but milk production is not taken into account ($DMP_{\text{Doe}} = 0$). For fatteners, the \times excretion per fattener ($X_{\text{Excretion_Fatt}}$, g/day.animal) is calculated as the difference between intake (milk, DMI_{Fatt} ; feed, DFI_{Fatt}) and body retention (DWG_{Fatt}) according to Eqn 23. Values of milk composition were respectively of 19.7 g N/kg and 2.4 g P/kg (Maertens *et al.* 2006). Body composition (*in utero* litter, bodyweight) was considered to be constant with values of 29 g N/kg and 5 g P/kg respectively (Maertens *et al.* 2005).

$$\begin{aligned} \text{If } DFI_{\text{Doe}} \neq 0, \text{ then } X_{\text{Excretion_Doe}} &= DFI_{\text{Doe}} \times X_{\text{Diet_Doe}} \\ &- DMP_{\text{Doe}} \times X_{\text{Milk}} - DWG_{\text{Litter_in_utero}} \times X_{\text{Litter}}, \end{aligned} \quad (21)$$

$$\text{else } N_{\text{Excretion_Doe}} = 5 \text{ AND } P_{\text{Excretion_Doe}} = 1.$$

$$\begin{aligned} X_{\text{Excretion_Rdoes}} &= DFI_{\text{Rdoes}} \times X_{\text{Diet_Rdoes}} - DWG_{\text{Rdoes}} \\ &\times X_{\text{Body_Rdoes}}, \end{aligned} \quad (22)$$

$$\begin{aligned} X_{\text{Excretion_Fatt}} &= DFI_{\text{Fatt}} \times X_{\text{Diet_Fatt}} + DMI_{\text{Fatt}} \times X_{\text{Milk}} \\ &- DWG_{\text{Fatt}} \times X_{\text{Body_Fatt}}. \end{aligned} \quad (23)$$

Daily total excretion of X (g/day) of animals in each category (does, replacement does and fatteners) at the farm scale are then

calculated by multiplying individual excretion by the total number of animal of each category (Eqns 24–26). Total excretion over time at the farm scale of X ($X_{\text{Total_Excretion_Farm}}$, g) is calculated according to Eqn 27.

$$X_{\text{Total_Excretion_Does}} = X_{\text{Excretion_Doe}} \times n_{\text{Does}}, \quad (24)$$

$$X_{\text{Total_Excretion_Rdoes}} = X_{\text{Excretion_Rdoe}} \times n_{\text{Rdoes}}, \quad (25)$$

$$X_{\text{Total_Excretion_Fatt}} = (X_{\text{Excretion_Fatt}} \times n_{\text{Fatt}})_{\text{Housing_Unit1}} + (X_{\text{Excretion_Fatt}} \times n_{\text{Fatt}})_{\text{Housing_Unit2}}, \quad (26)$$

$$X_{\text{Total_Excretion_Farm}} = \int (X_{\text{Total_Excretion_Does}} + X_{\text{Total_Excretion_Rdoes}} + X_{\text{Total_Excretion_Fatt}}). \quad (27)$$

Gaseous N losses

In rabbit farms, manure can be managed as slurry (daily removed from the housing units before being stored for several months outdoors, called S hereafter) or as solid manure (accumulated in deep pits below animals for several months before being removed once or twice a year, called DP hereafter). With our model, it is possible to simulate both manure management systems (input parameter M_{System} , Table 1). However, very few data concerning gas emissions from rabbit manure are available in the literature to calibrate our model. Therefore, data for slurry management were taken from pig references.

According to the EMEP/EEA methodology (EEA 2013), gaseous N emissions from manure originate from total ammoniacal N excreted (TAN_{ex}), which represents 60% of total N excreted ($TAN_{\text{content_ex}}$) in S or DP systems (Eqn 28). Among the N-compounds emitted in the housing units, NH_3 is the most important and represent ~25 of TAN excreted ($EF_{NH_3_Housing}$) by the animals in S or DP systems respectively (EEA 2013). However, a daily removal of slurry from housing units is known to greatly decrease N losses (~35%) according to Rigolot *et al.* (2010). Therefore, we considered that in the S system, $EF_{NH_3_Housing}$ represents only 65% of the default emission factors of 25% (i.e. $EF_{NH_3_Housing} = 16.25\%$). NH_3 -N emissions in housing units are then estimated using the EMEP/EEA methodology (EEA 2013) and converted into NH_3 emissions ($E_{NH_3_Housing}$, g NH_3) by multiplying this value by a 17/14 factor (Eqn 29). Total losses of N through gas emissions in the housing units ($E_{N_Losses_Housing}$, g N) were assumed to represent, in both manure management systems, 30% ($EF_{N_{\text{tot}}_Housing}$) of excreted TAN as the emission of N-compounds other than NH_3 (N_2O , NO, N_2) is very limited in rabbit manure (M. Hassouna, pers. comm.; Rigolot *et al.* 2010). For the S system, this default emission factor was also weighted by a 65% factor to take into account the daily removal of slurry (Rigolot *et al.* 2010). Total N gaseous losses in housing units are then calculated using respectively Eqn 30 ($E_{N_Losses_Housing_Farm}$, g N).

$$TAN_{\text{ex}} = N_{\text{Total_Excretion_Farm}} \times TAN_{\text{content_ex}}, \quad (28)$$

$$E_{NH_3_Housing} = TAN_{\text{ex}} \times EF_{NH_3_Housing} \times (17/14), \quad (29)$$

$$E_{N_Losses_Housing_Farm} = TAN_{\text{ex}} \times EF_{N_{\text{tot}}_Housing}. \quad (30)$$

TAN in manure entering storage (TAN_{stored}) can be calculated using Eqn 31, assuming that in the S system 10% of non-ammoniacal N has been transformed into ammoniacal N before entering storage and that, in the DP system, 0.67% of remaining TAN is immobilised in organic matter (EEA 2013). Data concerning the storage of rabbit manure according to manure management system are scarce. Therefore, we considered that emissions of NH_3 during storage ($E_{NH_3_Storage_Farm}$, g NH_3) are the same in both S and DP systems. They are calculated using Eqn 32 assuming that 14% ($EF_{NH_3_Storage}$) of TAN_{stored} are lost (EEA 2013). Total N losses ($E_{\text{Total_N_Losses_Storage_Farm}}$, g N) during storage are calculated using Eqn 33 assuming that 14.31% (EEA 2013) of TAN_{stored} is lost in both manure management systems.

$$TAN_{\text{stored}} = (TAN_{\text{ex}} - E_{N_Losses_Housing_Farm}) + 0.1 \times [N_{\text{Total_Excretion_Farm}} - (TAN_{\text{ex}} - E_{N_Losses_Housing_Farm})] \quad \text{for slurry systems,} \quad (31)$$

$$TAN_{\text{stored}} = (TAN_{\text{ex}} - E_{N_Losses_Housing_Farm}) \times (1 - 0.0067) \quad \text{for deep-pit systems,}$$

$$E_{NH_3_Storage_Farm} = TAN_{\text{stored}} \times EF_{NH_3_Storage} \times (17/14), \quad (32)$$

$$E_{\text{Total_N_Losses_Storage_Farm}} = TAN_{\text{stored}} \times EF_{N_{\text{tot}}_Storage}. \quad (33)$$

For N_2O -N emissions, we considered the Tier 2 approach proposed by the IPCC (2006). A global emission factor ($EF_{N_2O_Farm}$) is used to evaluate N_2O emissions in housing units and during outdoor storage. This value is 0% in the S system and 0.2% of $N_{\text{Total_Excretion_Farm}}$ in the DP system. N_2O -N emissions are converted into N_2O ($E_{N_2O_Farm}$, g N_2O /day) using a 44/28 factor (Eqn 34):

$$E_{N_2O_Farm} = N_{\text{Total_Excretion_Farm}} \times EF_{N_2O_Farm} \times (44/28). \quad (34)$$

Final nutrient amounts in manure after storage

The final amount of N in manure after storage ($N_{\text{inManure_After_Storage_Farm}}$) is calculated with Eqn 35 as the difference between amount total N excreted and total N losses in housing units and during storage. For P, as it is non-volatile, the final amount was assumed to be the same as total excretion (Eqn 36), even though this amount may be lower when manure is spread due to the sedimentation of P in the storage pit (Levasseur *et al.* 2007).

$$N_{\text{inManure_After_Storage_Farm}} = N_{\text{Total_Excretion_Farm}} - (E_{\text{Total_N_Losses_Housing_Farm}} + E_{\text{Total_N_Losses_Storage_Farm}}), \quad (35)$$

$$P_{\text{inManure_After_Storage_Farm}} = P_{\text{Total_Excretion_Farm}} \quad (36)$$

Enteric and manure CH_4 emissions

Data from *in vivo* and *in vitro* studies showed that in rabbit species enteric CH_4 production is much lower than in ruminant herbivorous such as the cow and is highly variable between individuals. Those studies also showed a strong effect of diet composition (e.g. fibre and starch contents) and of age with essentially no emissions for young rabbits (Piattoni *et al.* 1996; Marounek *et al.* 1999; Belenguer *et al.* 2011; Franz *et al.* 2011). Therefore, in this model, we considered that CH_4 enteric emissions were negligible before weaning and that after

weaning they represent ~0.4% of gross energy intake (GEI, MJ/day). Enteric emissions ($E_{CH_4_Enteric}$, g CH₄/day) were then calculated using IPCC approach (2006) (Eqn 36) with 55.65, the energy content of CH₄ (MJ/kg CH₄) and GEI calculated according to Eqn 37 from gross energy content of diet (GE_{Diet} , MJ/kg) and daily feed intake (DFI):

$$E_{CH_4_Enteric} = 1000 \times GEI/55.65, \quad (37)$$

$$GEI = GE_{Diet} \times (DFI/1000). \quad (38)$$

Concerning total daily CH₄ emissions from manure, the Tier 2 approach proposed by the IPCC (2006) was used. For each animal category (does, replacement does and fatteners), excretion of manure volatile solids (VS, kg/day.animal) at the origin of CH₄ emissions is estimated using Eqn 38 with d_{Diet} being the diet digestibility (%), the urinary energy (UE) considered to represent 3% of GEI (Xiccato and Trocino 2010), the ash content of the diet (Ash_{Diet}) and 18.45 the conversion factor for dietary GE per kg of dry matter. Indoor and outdoor CH₄ manure emissions ($E_{CH_4_Manure}$, g CH₄/day.animal) are estimated for each animal category respectively with Eqn 39 with B_0 being the maximum CH₄ producing capacity [0.058 m³ CH₄/kg VS according to Ferrer *et al.* (2011)], 0.67 the conversion factor of m³ CH₄ to kg CH₄ and MCF_{Manure} the respective CH₄ conversion factor. MCF_{Manure} was set to 29% (IPCC 2006) assuming that annual outdoor average temperature is below 16°C and can be applied for the two manure management systems described earlier (S or DP).

$$VS = [GEI \times (1 - d_{Diet}) + (UE \times GEI)] \times [(1 - Ash_{Diet})/18.45], \quad (39)$$

$$E_{CH_4_Manure} = VS \times B_0 \times 0.67 \times MCF_{Manure}/1000. \quad (40)$$

Simulation of a typical French rabbit farm with a reproduction cycle of 42 days according to manure management systems

In this section, we present and discuss the results obtained from the run of the model applied to a theoretical typical French rabbit

farm: 605 does and 42 days reproduction rhythm (ITAVI 2013) for two different manure management systems (S or DP). Average annual results were calculated from 5-year simulation runs. Data and references used for the parameterisation of the simulations are given in Table 1.

Nutrient intake, excretion and final amount in manure

Nitrogen and P intake are given in Table 2. At the farm scale, ~8 t and 1.6 t of N and P were consumed by animals (feed) of which 70% have been consumed by fatteners. Total excretion at farm scale of N and P represent respectively ~61% and 68% of total intake. For fatteners, excretion represents a much higher percentage of intake than for does (respectively 68% vs 47%). In our simulation, excretion of N and P per doe differs from values proposed by Maertens *et al.* (2005) but is consistent with the French steering committee for environmental-friendly farming practices (CORPEN 1999) (8.2 vs 7.4 vs 8.1 kg N and 1.8 vs 2.1 vs 1.9 kg P respectively). Differences in N and P excretion values between our study and that of Maertens *et al.* (2005) can be explained by a higher N intake in our study (13.2 vs 11.0 kg N) and a higher P body deposition (0.9 and 0.6 kg P) for a similar intake (2.7 kg P). In our study, N excretion per kg produced (53.9 g) is ~30% higher than the value of 41.3 g N per kg produced proposed by Calvet *et al.* (2008). That might be explained by the difference in slaughter weight in both studies (2.46 and 1.8 kg BW) because feed efficiency decreases in heavier animals (higher excretion rate).

After storage, the remaining N in manure represents 50% and 47% of total N intake in the farm in the S and DP systems respectively (Table 2). The value for the DP system is inconsistent with the value proposed by CORPEN (27%; 1999). However, this can be explained by the lower proportion of total N excreted that is lost in housing and during storage in our model (24% vs 60%). Concerning P, our results show a small decrease in the ratio P in manure after storage/P intake between our model output data (Table 2) and CORPEN (1999) data (68% vs 71% respectively), which can be related to the improvement of feed efficiency of animals between CORPEN study (1999) and ours.

Table 2. Performances of a typical French rabbit farm of 605 does for nitrogen (N) and phosphorus (P) intake, excretion and final amount in manure after storage according to manure management system (slurry or deep-pit)

LW, liveweight. Total does include rearing of replacement does. Values per doe are total farm amount divided by the average number of does on farm ($n_{Doe_av} = 605$). Rabbit meat includes also the meat from 2/3 of culled does (see Maertens *et al.* 2005)

	Total does (kg/year)	Total fatteners (kg/year)	Total farm (kg/year)	Per produced fattener (g)	Per doe (g)	Rabbit meat (g/kg LW)
<i>Nitrogen</i>						
Intake	2438	5562	8000	215.9	13.2	87.4
Excretion	1147	3787	4934	133.1	8.2	53.9
<i>In manure after storage</i>						
Slurry system	925	3054	3979	107.4	6.6	43.5
Deep-pit system	872	2879	3751	101.2	6.2	41.0
<i>Phosphorus</i>						
Intake	493	1120	1613	43.5	2.7	17.6
Excretion	332	767	1100	29.7	1.8	12.0
<i>In manure after storage</i>						
Slurry system	332	767	1100	29.7	1.8	12.0
Deep-pit system	332	767	1100	29.7	1.8	12.0

Gaseous emissions

Table 3 summarises annual gaseous emissions of CH₄, NH₃ and N₂O of the simulated farm. Ammonia is the first compound emitted with 1030 and 1248 kg per year for the S and DP systems respectively. Even though the order of magnitude of total emissions is similar, the partition between housing and storage emissions is different in the S and DP systems. Ammonia emissions from housing units represent indeed ~72% of total farm emissions in the DP system whereas they represent only 57% in the S system. Moreover, NH₃ emissions due to excretion of fatteners are the main source of NH₃ with ~77% of total farm emissions in relation with the larger contribution of fatteners to N excretion. Concerning N₂O, because the emission factor is 0% in the S system, emissions are observed only in the DP system and represent 16 kg per year with a similar repartition between fatteners and does as for NH₃ (77% vs 23%). Thus, the S system with a daily removal appears to be a more efficient manure management system for rabbit manure to decrease the emissions of NH₃ and N₂O. This is in agreement with the IPCC BREF document (European Commission 2003), which considers that removing manure frequently is a best available technique in pig or laying hen housings. Furthermore, a reduction of indoor NH₃ emissions is also beneficial regarding animal and farmer welfare (decrease of respiratory diseases) as reported by Kristensen and Wathes (2000) and Whyte (1993) respectively.

Concerning CH₄ emissions, total farm emissions are the same in both manure management systems (1626 kg) in relation to the identical emission factors used in both simulations. Manure is the main source of CH₄ with ~73% of total emissions in comparison with enteric fermentation (27%). Fatteners are the largest producers of CH₄ with ~70% of total emissions (Table 3).

Very few experimental references concerning gas emissions from rabbit farms are available in the literature. Calvet *et al.* (2011) proposed respective values for maternity and fattening units with the DP manure management system. Our NH₃ values are higher than those of Calvet *et al.* (2011) (1.93 vs 1.34 g NH₃/

doe.day and 0.22 vs 0.24 g NH₃/fattener.day respectively) but in our approach we also considered storage emissions. When considering only indoor emissions, values are much closer respectively with 0.22 vs 0.24 g NH₃/fattener.day and 1.39 vs 1.34 g NH₃/doe.day respectively. The N₂O emissions for does + litter are more than 10 times higher in Calvet *et al.* (2011) than in our study (0.247 vs 0.03 g N₂O/doe.day respectively) whereas during fattening emissions are very low in both studies (<5 mg per day per animal). Our value should have been higher than the value proposed by Calvet *et al.* (2011) as it also includes storage emissions. However, it is difficult to explain this difference of does + litter emissions between both studies because there are large uncertainties both on emissions factors from the literature (Méda *et al.* 2011) and on the measurement technique used in the experimental study of Calvet *et al.* (2011). Issues of over- and underestimation of emissions (due to interferences between gases) have indeed been reported in the literature (Hassouna *et al.* 2013) when they are measured using infrared spectrometry.

In our model, we used reference methodologies for the estimation of emissions from livestock (IPCC 2006; EEA 2013) and we tried to take into account the influence of manure management on these emissions by considering specific emissions factors for the two major manure management systems in rabbit (S or DP). However, our approach was limited by the lack of data specifically dedicated to rabbit farms. For instance, in the S system, pig slurry references were used for NH₃ emission factors and for storage emissions, so we assumed that NH₃ and total N emissions factors were the same in both systems. Even though specific emission factors are always associated with uncertainties, the acquisition of specific emission factors for rabbit farms according to manure management system is required. These experiments should be based on referenced and reliable measuring techniques such as mass balances, infrared spectrometry and gas chromatography. This will be the most efficient way to improve and develop modelling approaches such ours and therefore decrease uncertainties in these models and in national inventories based on these models (Méda *et al.* 2011).

Table 3. Emissions of ammonia (NH₃), nitrous oxide (N₂O) and methane (CH₄) from a typical French rabbit farm of 605 does

LW, liveweight. Values for total does and total fatteners include storage emissions. Values for does + litter emissions include emissions from growing rabbits before weaning and emissions associated to the rearing of replacement does. Rabbit meat also includes the meat from 2/3 of culled does (see Maertens *et al.* 2005)

	Total does (kg/year)	Total fatteners (kg/year)	Total farm (kg/year)	Does + litter emissions (g/doe.day)	Fattening emissions ^A (g/fattener.day)	Rabbit meat (g/kg LW)
<i>Slurry system</i>						
NH ₃	240	793	1033	1.60	0.25	11.29
N ₂ O	0	0	0	0.00	0.00	0.00
Manure CH ₄	354	922	1276	2.40	0.28	13.95
Enteric CH ₄	113	237	350	0.51	0.09	3.83
<i>Deep-pit system</i>						
NH ₃	290	958	1248	1.93	0.30	13.65
N ₂ O	4	12	16	0.02	0.00	0.17
Manure CH ₄	354	922	1276	2.40	0.28	13.95
Enteric CH ₄	113	237	350	0.51	0.09	3.83

^Ai.e. after weaning.

Moreover, in our model we only considered the influence of manure management system and slurry removal frequency. However, many other factors (temperature, ventilation rate, feed composition) are known to influence gas emissions (Méda *et al.* 2011) and could be added to our modelling approach in order to decrease uncertainties in our simulation results. Yet, as stated earlier, very few data are available in the literature concerning rabbit production and new experiments should be designed in order to better assess the influence of these factors on emissions.

Conclusions

This paper presents an original simulation model to study the environmental impact of rabbit production at the farm level. It should help investigate the influence of farming practices (animal feeding, reproduction and manure management) on several environmental criteria such as manure production or NH₃ and GHG emissions (N₂O and CH₄). Moreover, it focuses both on N and P to prevent pollution swapping. Even though the model considers the influence of manure management system on gas emissions, further improvements are required to improve the accuracy of the model and reduce uncertainties in simulation results. Yet, these improvements will only be possible with the acquisition of experimental knowledge specific to rabbit farms (emission factors, controlling factors). Finally, in order to design more sustainable livestock-farming systems, this model should be combined with an economical approach in order to identify the best farming practices both on environmental and economic points of view.

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