MOLDAVI: A model to predict environmental and economic performances of broiler farming systems

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Modelling is a relevant tool to study both environmental and economical performances of livestock systems. The aim of this paper is to present MOLDAVI, a model of broiler farming systems management under animal performances, environmental and economical issues. The system is a combination of four sub-models representing the animals, the poultry house, the manure and the outdoor run for free-range systems. Animal performances (growth, feed intake, mortality) are simulated in relation with birds' characteristics (growth rate), feeding (nutrient composition) and rearing environment (temperature, animal density). Concerning environmental issues, the model predicts NH_3, N_2O and CH_4 emissions from manure and outdoor droppings as well as abiotic CO_2 emissions from fossil fuel use (e.g. propane for heating). Manure characteristics are estimated using a mass balance approach between animal excretion and gaseous losses. Energy and water use from the system are also estimated. Economical performances are calculated from bio-technical results (animal performances, energy and water use) simulated by the model and economical references (€ per kg of live weight produced, price of feed) given as model inputs. In order to improve broiler farming systems performances, MOLDAVI has been developped to be sensitive to a large panel of farming practices including flock management (animal density, feeding strategies…), housing characteristics (type of ventilation, outdoor access…) and manure management (manure type…). Simulations could help understanding complexity in broiler farming systems and stress synergical or compensation effects. As an example, the decrease of feed nitrogen content could lead to a decrease in nitrogen excretion and gaseous losses, but it could aleviate growth performances and therefore economical profit. Moreover, to take into account indirect environmental impacts associated to feed production, MOLDAVI outputs could be used in combination with Life Cycle Assessment.

1. Introduction

Poultry production is noted for its negative impact on the environment through the production of ammonia (NH_3) and greenhouse gases (N_2O, CH_4), and because of its high on-farm energy consumption (fossile fuels for example). In order to design sustainable poultry farming systems by decreasing environmental impacts and improving economical performances, a precise knowledge of nutrient and energy dynamics is required. In practice, nutrient and energy flows in rearing systems can be evaluated through experimental work, but this approach is expensive, takes time and is often difficult to achieve in commercial conditions. Modelling appears as a relevant tool to study these flows and their consequences on environmental and economical performances.

Sectorial models have been developed to study nutrients and/or energy flows and focused on the animals (CIGR, 2002; CORPEN, 2006), manure and gaseous emissions (IPCC, 2006) or housing (CIGR, 2002; Hassouna et al., 2011). Yet, these models do not generally take into account the wide range of farming practices. A dynamic approach is also needed because pollutant leaks to groundwater or to the atmosphere can often be explained by a lack of synchronisation or an imbalance between their production and their consumption or recycling by the agro-ecosystem. Furthermore, in order to prevent pollution swapping, models should be comprehensive and developed at least at the farming-system scale. Finally, these models should be integrated and focus on (at least) environmental and economical performances in order to assess the sustainability of the tested scenarios. However, integrated models with such characteristics (sensitivity to farming practice, farming-system scale, dynamic and multricriterion) are still missing for poultry production whereas they have already been developed for pig and dairy productions (Berntsen et al., 1999; Chardon et al., 2007; Rotz et al., 2011). Thus, the aim of this paper is to present MOLDAVI, a model of broiler farming systems management under animal performances, environmental and economical issues.

2. Model description

In MOLDAVI, the broiler farming system is composed of four sub-models representing the animals, the broiler house, the manure and the outdoor run for free-range systems, as shown in Figure 1. The main mass and energy flows represented in the model are also shown in Figure 1, as well as model inputs and outputs. MOLDAVI has been implemented using VENSIM®, a software for the developpement of compartment models with a hourly simulation time step. Equations used for the implementation of the biotechnical model are fully described and discussed in Meda (2011).

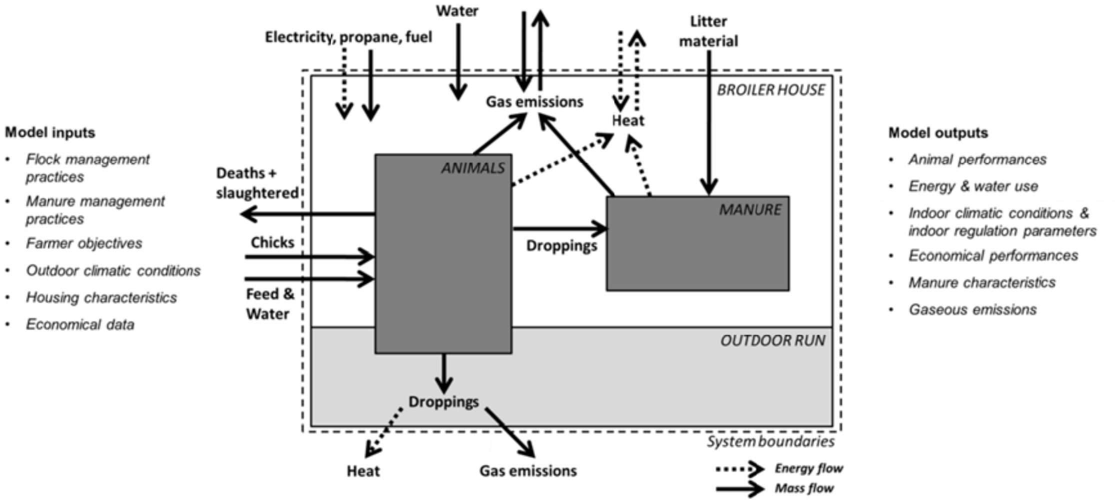

Figure 1. Graphic representation of MOLDAVI components and model inputs/outputs.

2.1. “Animals” sub-model

The “Animals” sub-model simulates the performances of the animals. The number of broilers in the system is simulated from a mortality rate (model input) and modulated by environmental factors such as temperature (heat stress). Live weight gain is calculated according to a modified Gompertz function taking into account genetics of the animals and modulated by nutritionnal and environmental factors (feed composition, temperature, density) according to Quentin (2004). Feed consumption is simulated from a feed conversion ratio (model input) applied to live weight gain, while water consumption is calculated from a water:feed ratio given as a model input. Total excretion of nutrients is calculated by a mass balance approach between feed intake and body retention of nutrients, calculated from French references (CORPEN, 2006) applied to live weight gain. Finally, broiler heat production as well as CO_2 and water vapour from respiration are calculated according to CIGR (2002) references applied to live weight of broilers. Economical performances are calculated as the difference between sales (live weight) and feed and chicks costs.

2.2. “Manure” sub-model

The “Manure” sub-model simulates the evolution of the manure produced in the broiler house. Manure heat production is estimated as a percentage of broiler heat production (Hassouna et al., 2011). Manure characteristics are estimated by a mass balance approach between litter amount (straw, sawdust) + animal excretion and gaseous losses. N losses from manure are mainly NH_3, N_2O and N_2 emissions, and several factors can influence them. Therefore, emissions are estimated in the model with emission factors (EFs) applied to nitrogen excreted and then modulated with variation factors (VFs) using the methodology developed by Rigolot et al. (2010). EFs are defined for total N, NH_3 and N_2O emissions. N_2 emissions are calculated as the difference between total N losses and NH_3 and N_2O emissions. EFs and VFs were identified from a literature survey (Meda et al., 2011) and expert’s judgment. CH_4 emissions are estimated using IPCC Tier-2 methodology (2006). Contents of P, K, Cu and Zn in manure are calculated as the sum of excreted amounts and amounts in bedding material (straw). N, dry matter and water masses in manure are calculated as the difference between inputs (straw, excretion) and outputs (gaseous emissions). Manure mass is calculated as the sum of water and dry matter masses.

2.3. “Broiler house” sub-model

The “Broiler house” sub-model simulates the climatic conditions (temperature, relative humidity) in the broiler house using an energy balance to reach target conditions defined by the model user. To that purpose, algorithms for the regulation of ventilation rate, heating and evaporative cooling were taken from Hassouna et al. (2011). These algorithms take into account heat production of broilers and litter, heat losses (thermal insulation) and outdoor climatic conditions. Energy used by heating and ventilation, as well as water used by cooling are also estimated. Energy and water costs are then calculated from economical references given as model inputs.

2.4. “Outdoor-run” sub-model

The “Outdoor run” sub-model simulates the outdoor excretion of broilers based on total excretion simulated by the “Animals” sub-model and on an outdoor presence time given as a model input. Nitrogen losses on the outdoor run are calculated from specific EFs adapted for outdoor conditions and applied to N outdoor excretion. Yet, given the poor knowledge on these outdoor emissions (Meda et al., 2011), no VF is applied to the outdoor EFs. Outdoor CH_4 emissions are estimated using IPCC Tier-2 methodology (2006) applied to outdoor excretion. The amounts of nutrients that accumulate in soil are calculated as the difference between excretion and gaseous emissions on the outdoor run.

3. Model validation

A full validation of model at the scale of a farming system is often difficult to perform because information is often missing in protocol description from published studies. In fact, all the inputs required to run the model are generally not given in the material and methods sections of publications (i.e. outdoors climatic conditions or housing characteristics). Therefore, the validation of the model was performed as far as possible with published data and, when data was not available, by expert knowledge and by checking carefully simulation coherency. Yet, we propose here the comparison between data from an experimental study at the scale of the rearing system, in which many parameters were studied and, and the predictions by the model. The experimental study took place between December 2008 and January 2009 in a French broiler house of 1163 m² where broilers were reared at a stocking rate of about 18.5 animals per m² during about 55 days. We present here the comparison of animal performances, manure amount and DM, N, P and K contents between observed and simulated values (Table 1). More details are given in Meda (2011).

Table 1. Comparison of animal performances, gaseous emissions and manure characteristics from an experimental dataset and simulated with MOLDAVI.

	Measurements	**Simulation**
Animal performances		
Weight at slaughter (kg)	2.16	2.18
Feed consumption (kg)	103620	104055
Feed Conversion Ratio (kg feed/kg	2.31	2.31
Water consumption (kg)	181671	182096
Gaseous emissions (kg)		
N total losses	771	591
NH_3	334	440
N_2O	27	24
CH_4	0	139
Manure amount (kg)	43860	45595
Manure composition		
Dry Matter (%)	54	56
N (g/kg)	17.1	20.3
P (g/kg)	5.3	7.0
K (g/kg)	14.9	16.0

Model predictions for animal performances (body weight, feed consumption) were accurate in comparison to the experimental data, with errors about 1% between predicted and measured values. The good prediction of animal perfomances leads to a good prediction of nutrient excretion but larger errors were observed (Table 1) concerning manure composition and gaseous emissions. A part of errors on the prediction of gaseous emissions could be explained by the fact that the Manure sub-model (2.2.) does not take into account all the factors that could influence gaseous emissions. Furthermore, the default emission factor used in MOLDAVI may not have been adapated to this experimental study. Another source of difference between measured and simulated values is the uncertainty in the measurement methods used in the experimental study. For instance, the model predicted CH_4 emissions whereas in the exeprimental study, no emission was measured, probably because CH_4 concentration in air was below the detection level of the gas analyser. Similarly, differences in manure composition could be explained by uncertainties during manure sampling and chemical analysis. Further details are given in Meda (2011). However, given these sources of uncertainties on the measurements methods we can consider that MOLDAVI is a good tool to study environmental performances in poultry farms.

4. Simulations

4.1. Influence of the reduction of feed crude protein content on economic and environmental performances of a broiler farming system

A simple example is given to illustrate how the model might be used to assess the impact of feeding strategies on both economical and environmental performances. In this example, three feeding strategies were studied by changing the crude protein (CP) content of feed distributed to broilers. In the simulations, a broiler house of 1000 m² with a stocking density of 20 animals per m² was simulated during winter in Western France. In the Reference scenario, feed CP content follows to breeder recommendations (ROSS PM3) whereas in the two others scenarios (Environmental friendly 1 & 2), feed CP content is reduced respectively by 10 and 20 g CP per kg of feed. The main objective of this feeding practice is to decrease the amount of N excreted by the broilers, and thus help to mitigate gasesous losses having a potential negative effect on the environment (i.e. NH_3 responsible for eutrophication and N_2O responsible for climate change).

Lowering feed CP content had an effect on growth performance of broilers as shown in Table 2. In the “Environmental friendly” scenarios, live weight at slaughter (LW) are decreased respectively by 5 and 9% respectively when feed CP content is reduced by 10 and 20 g / kg feed. However, other animal performances such feed conversion ratio and mortality remained unchanged. As a consequence, total margin over feed and chicks costs (calculated as the difference between broilers sale and costs of feed and chicks) decreased by 9 and 16% in the “Environmental friendly” scenarios, assuming that one kg of feed has the same cost.

Table 2. Influence of feed crude protein content on the economical and environmental performances of a broiler farming system in France.

Scenario	Reference	Environmental friendly 1	Environmental friendly 2
Economical performances			
Live weight at slaughter (LW) (kg)	1.99	1.89	1.81
Feed Conversion Ratio (kg feed/kg LW)	1.79	1.79	1.79
Mortality rate (%)	4%	4%	4%
Total feed consumption (t)	67.0	63.6	60.8
*Total margin over feed and chicks costs (€)**	8 623	7 858	7 246
Environmental performances			
NH_3 emissions (g/kg LW)	8.18	7.67	7.04
N_2O emissions (g/kg LW)	0.50	0.46	0.43
CH_4 emissions (g/kg LW)	1.61	1.65	1.67
Water use (L/kg LW)	3.4	3.5	3.5
Propane use (kg/kg LW)	111	117	122

*Broilers sale minus feed and chicks costs

When comparing environmental peformances in our scenarios, it appears that reducing feed CP content decreases gaseous emissions of N compounds (NH_3 and N_2O) respectively by 11% and 22% in comparison with the Reference scenario. This can be explained by the fact that the decrease in feed CP content led to a decrease in total excretion of nitrogen, and therefore to lower N gaseous emissions. However, when expressed as a percentage of total N excretion, these emissions remained unchanged. Reducing, feed CP content did not affect water use, since in MOLDAVI water consumption is calculated from a water:feed ratio and from feed consumption which is identical in the three scenarios. Finally, in terms of total emissions at the system scale, CH_4 emissions and propane use are identical in the three scnearios (about 45 kg CH_4 and 4230 kg propane) but since total LW produced is lower in the “Environmental friendly” scenarios, it led to higher emissions of CH_4 emissions and propane use when expressed per kg LW produced.

However, these simulations show the interest of reducing crude protein content of feed in order to reduce the emissions of gaseous N compounds such as NH_3 (responsible for eutrophication) and N_2O (responsible for climate change) with, nevertheless, a decrease in animal and thus, in economical performances.

4.2. Influence of housing characteristics on economic and environmental performances during a heat wave of a broiler farming system

When broilers are reared above their zone of thermal comfort, decrease in performance (growth, feed intake) and higher mortality rates can be observed. In order, to limit the economical losses during these periods, heat abatement techniques (increased air speed above animals, evaporative cooling, outdoor access and lowering animal density) can be used. Two scenarios were compared based on a heat wave which occurred in Western France in the summer of 2003. A broiler house of 1000 m² with a stocking density of 20 animals per m² was simulated. Using MOLDAVI, we compared the animal, economical and environmental performances of a broiler house which is not equipped with heat abatement systems vs. a house using an evapourative cooling system (ECS). The heat wave occurred during the last 10 days of the batch with an average outdoor temperature of 25°C and average maximal and minimal outdoor temperatures of 33 and 18°C, respectively.

Outdoor temperatures used for the simulations as well as indoor temperatures for the two houses compared to targeted indoor temperature are presented in Figure 2. In the simulations, indoor temperature was higher than target indoor temperature in both broiler houses but temperature was higher in the house not using an ECS than in the house using an ECS. This result confirms the efficiency of an ECS to decrease indoor temperature during heat waves in combination with adapted ventilation rates.

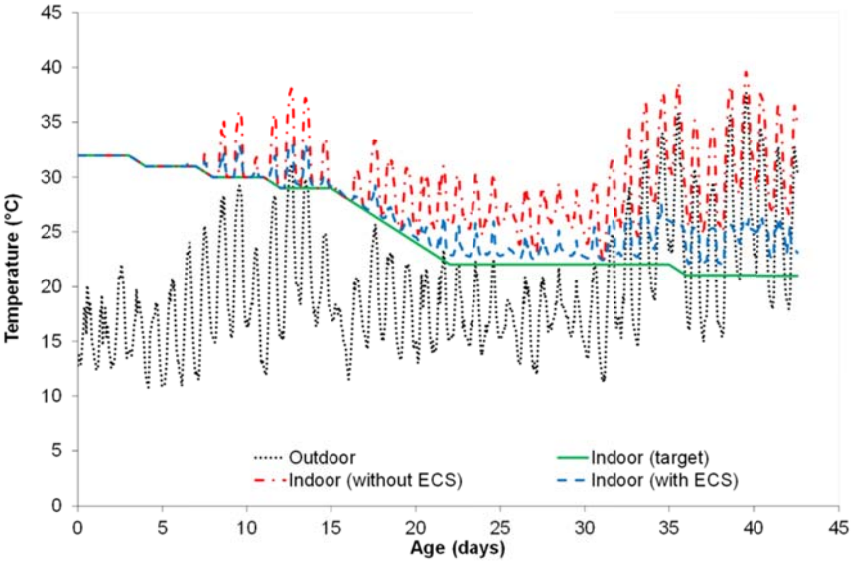

Figure 2. Comparison of predicted indoor temperatures in two broiler houses using or not an evaporative cooling system (ECS), during a heat wave in Western France in 2003.

Animal and economical are presented performances in Table 3. The absence of an ECS in the broiler house led to a very high mortality rate compared to the expected performances (35% versus 4% respectively) which is consistent with on-farm observations during summer 2003. The high indoor temperature also affected growth performances with a live weight at slaughter reduced by 22% compared to expected weight (1.56 and 1.99 kg respectively). On the opposite, in the broiler house using an ECS, animal performances were almost those expected. Live weight at slaughter was only 6% lower than expected while mortality rate and feed conversion ratio remained unchanged (4% and 1.79 kg feed/kg LW respectively), confirming the interest of equipping the broiler house with an ECS. As a consequence, total margin over feed and chicks costs of the system using an ECS is only decreased by 11% in comparison with the expected margin, whereas the margin in the system without an ECS is negative, which means that the system is unprofitable in such climatic conditions (Table 3).

Table 3. Comparison of economical and environmental performances of a broiler farming system using or not an evaporative cooling system (ECS), during a heat wave in Western France in 2003.

Scenario	Expected performances	Heat wave without an ECS	Heat wave with an ECS
Economical performances			
Live weight at slaughter (LW) (kg)	1.99	1.56	1.86
Feed Conversion Ratio (kg feed/kg LW)	1.79	2.36	1.79
Mortality rate (%)	4%	35%	4%
Total feed consumption (t)	67.0	46.6	62.7
Total margin over feed and chicks costs (€)*	8 623	-1 818	7 655
Environmental performances			
NH_3 emissions (g/kg LW)	8.18	10.89	8.21
N_2O emissions (g/kg LW)	0.50	0.62	0.50
CH_4 emissions (g/kg LW)	1.61	2.15	1.62
Water use (L/kg LW)	3.4	4.5	6.1
Propane use (kg/kg LW)	17	32	18

*Broilers sale minus feed and chicks costs

Environmental performances of the two farming systems are also presented in Table 3. In the system using an ECS, gaseous emisssions and propane consumption are equivalent to the expected performances. This can be explained by the fact that both systems have the same animal performances, leading to the same amount of nitrogen and organic matter excreted, and to the same heat production by broilers. Yet, total water consumption is higher in the system using the ECS compared to the expected consumption. This higher consumption (+80%) can be explained by the use of water by the ECS during the simulation (about 2L/kg LW), but this supplementary consumption generates a reasonable supplementary financial cost (less than 0.02 €/kg LW). However, to assess the final economical performances of such a system, investment and maintenance costs should also be taken into account.

5. Conclusions

The model MOLDAVI was built in order to study the effects of farming practices (feeding strategies, manure management) and climatic conditions on animal, economical and environmental performances. The accuracy of the model outputs depends mainly on the quality of predictive equations and the associated parameters. The development of MOLDAVI revealed some gaps and improvement margins in the knowledge of broiler farming systems at different scales (animal, housing, manure) and will be enriched with new knowledge from the litterature. Furthermore, this model was developed for broiler systems but could be adapted to other meat-poultry species such as turkeys or ducks providing the use of adapted parameters and inputs. But once again, there is a lack of knowledge especially concerning gaseous emissions from litter (turkey, ducks) or slurry (ducks) as reported by Meda et al. (2011).

However, despite the need for further improvements, the current version of MOLDAVI could already be a useful tool to help to design more sustainable broiler farming systems. Synergies and trade-off effects can also be identified through practices combination. For example, we showed in this paper that a decrease in feed CP content could result in a decrease of pollutants emissions such as NH_3 and N_2O. However, this decrease of environmental impacts is associated to a decrease of animal performances (growth) and therefore of economical performances.

Furthermore, in order to prevent pollution swapping between housing and storage, the developpement of a “Manure storage” sub-model is required to take into account the environmental performances during this stage according to manure management practices (e.g. covered storage or turning effect) and climatic conditions. Likewise, farming practices and their effects on animal, economical and environmental performances should be evaluated at the scale of the farm rather than at the scale of the rearing system. Therefore, our model could be used in combination with farm scale models, which include crop and other animal productions (Berntsen et al., 1999; Chardon et al., 2007; Rotz et al., 2011).

Finally, in order to take into account indirect environmental impacts (e.g. impacts of feed production). we also propose to use MOLDAVI in combination with other tools for the assessement of farming systems sustainability such as Life Cycle Assessment.

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