Reduction of ammonia emissions from dairy cattle cubicle houses via improved management- or design-based strategies: A modeling approach

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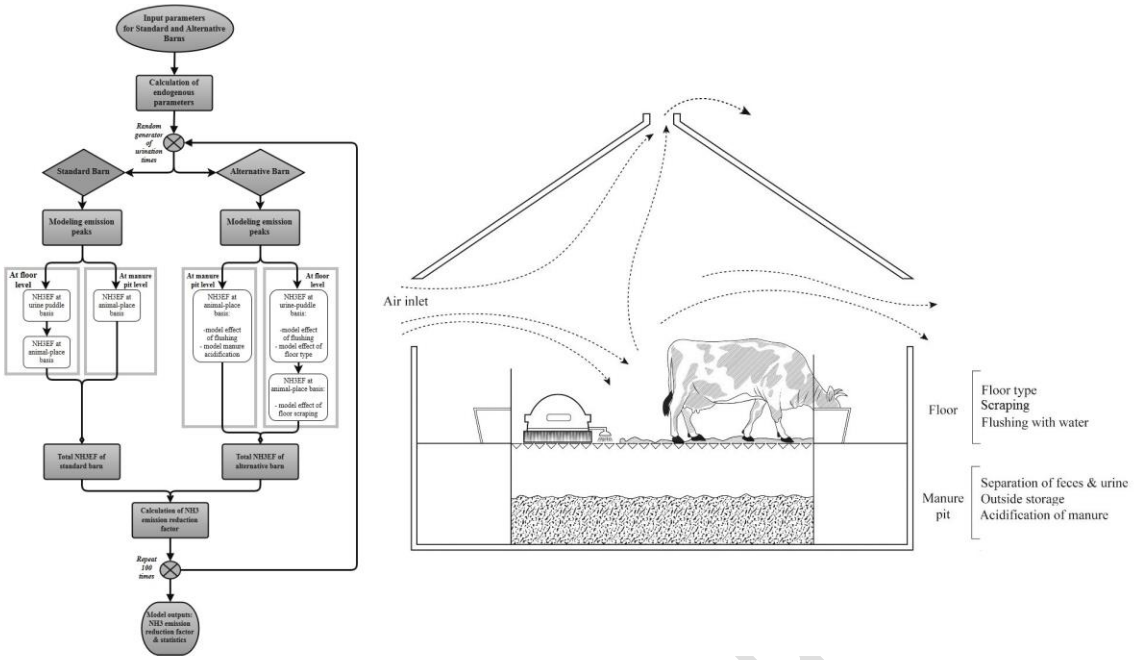
A manuscript accepted for publication at the Journal ***Science of the Total Environment***
Sci Total Environ. 2016 Sep 17; 574:520-531. doi: 10.1016/j.scitotenv.2016.09.079.

Abstract

Given the current scarcity of empirical data on ammonia (NH_3) emissions from dairy cattle under different management-based mitigation techniques, a modeling approach to assess potential NH_3 emission reduction factors is needed. This paper introduces a process-based model that estimates NH_3 emission reduction factors for a dairy cattle barn featuring single or multiple management-based NH_3 emission mitigation techniques, as compared to another barn, to which no mitigation measure is applied. The model accounts for the following emission mitigation measures: (a) floor scraping, (b) floor type, (c) floor flushing with water and (d) indoor acidification of manure. Model sensitivity analysis indicated that manure acidification was the most efficient NH_3 emission reduction technique. A fair agreement was observed between reduction factors from the model and empirical estimates found in the literature. We propose a list of combinations of techniques that achieve the largest reductions. In order of efficiency, they are: (a) floor scraping combined with manure acidification (reduction efficiency 44 - 49 %); (b) solid floor combined with scraping and flushing (reduction efficiency 21 - 27 %); (c) floor scraping combined with flushing and (d) floor scraping alone (reduction efficiency 17 - 22 %). The model is currently being used to advise the Flemish Government (Belgium), on the performance of certain NH_3 emission reduction systems for dairy barns in Flanders.

Keywords: Process-based model; NH_3 emissions mitigation; Low NH_3 emission dairy barn; Policy making.

Graphical abstract



Research highlights

- Modeled NH_3 emission reduction factors agreed with empirical data from literature
- Scraping and flushing of floor, floor type and manure acidification were modelled
- Floor scraping combined with manure acidification yielded highest emission reductions

1. Introduction

The amount of scientific evidence on the negative impacts of excessive gaseous ammonia (NH_3) emissions from livestock systems on Earth biomes is significant (ApSimon et al., 1987; Sutton et al., 2013; Sutton et al., 2008). In different parts of the world, simultaneous efforts are underway in order to reduce NH_3 emissions. For instance, since 1992 a multinational effort has been underway in Europe to tackle the most urgent environmental issues including the deposition of excess of reactive nitrogen from all sectors of European society, including agriculture, into natural environments (Natura2000, 1992). In 2000, the European Parliament indicated that the Member States (EU28) should set their maximum allowed levels for NH_3 emissions. This resulted in NH_3 emission restrictions specifically for livestock farms (NEC-Directive, 2001). In the United States, the Emergency Planning and Community Right-To-Know Act (EPCRA) established since 1986, requires that livestock systems' NH_3 releases exceeding 45 kg d^{-1} (in a per barn basis or per operation basis where multiple barns may be used) must be reported (USEPA, 1986).

Agriculture in Europe is responsible for about 90% of NH_3 emissions (Sutton et al., 2013), a considerable part of which comes from cattle manure operations. These operations vary considerably in terms of design and management, depending on the country and region. The type of system discussed and modeled in this paper is typical in northern Europe, and is defined by Mosquera et al. (2014) as loose housing with cubicles, where the animals are kept loose in a barn divided into rows of individual cubicles, feeding and walking alleys. In these barns the floor is usually slatted, and the manure (mixture of feces and urine) is regularly removed from the floor and stored in a manure pit inside the barn. The barns are usually naturally ventilated, with air entering through openings at the walls' sides, being exhausted through the opposite opening and ridge, and the animals are confined year round. As for diets, cows are usually fed roughage (grass and maize silage) and concentrate.

The accurate determination of NH_3 emission factors from commercial naturally ventilated dairy cattle barns is currently a challenge (Calvet et al., 2013; Ogink et al., 2013; Takai et al., 2013). Multiple recent studies attempt to develop an emission measurement method for this type of barns (De Vogeleer et al., 2016; Joo et al., 2014; Van Overbeke et al., 2016, 2015, 2014a, 2014b), but experimentally determined management based NH_3 emission factors for real-scale dairy cattle barns in general are currently still non-existent. While a technique for accurate empirical assessment of NH_3 emission factors from this type of barns isn't established, the use of modeling approaches has proven to be beneficial.

Rotz and Oenema (2006) developed a mechanistic model to predict NH_3 emissions from dairy and beef cattle barns. Their model was validated with data from other studies that included emissions from cattle manure at multiple stages, i.e. in animal housing, storage, field application and during grazing. Elzing and Monteny (1997a, 1997b) assembled a process-based model that estimates NH_3 emissions from dairy cattle manure, which includes the most relevant physico-chemical properties related with NH_3 emissions. Their model was validated for laboratory conditions. Later, Monteny et al. (1998) scaled the model up to a full dairy cattle barn. A similar procedure was followed by Aarnink & Elzing, (1998), who developed a model scaled up to a pig barn. Although the NH_3 emission models of Rotz and Oenema (2006), Monteny et al., (1998) and Aarnink & Elzing, (1998) can predict emissions at a barn scale, they are not designed to systematically assess the impact of barn management and design aspects that might mitigate emissions.

When it comes to animal housing, some specific changes in barn design have significantly reduced emissions in laboratory conditions. Such management techniques include scraping manure off the floor (Braam et al., 1997; Ogink and Kroodsma, 1996), flushing the floor with water (Bleijenberg et al., 1995; Braam et al., 1997; Ogink and Kroodsma, 1996) and indoor manure treatment, such as acidification (Bleijenberg et al., 1995; Kai et al., 2008). In addition, barn design aspects such as floor type have significantly changed the shape of NH_3 emission sources, i.e. area and depth of urine puddles (Snoek et al., 2014; Snoek et al., 2010). These types of emission reduction means have not yet been consistently tested in full-scale commercial dairy cattle barns because of the current technological limitations for determination of emission factors in these types of barns, as already mentioned.

The first known modeling attempt to estimate NH_3 emission factors from different barn management strategies is the work of Rotz et al. (2014). In their study, the developed model calculates emissions across different barns with or without floor scraping and flushing systems as well as different floor types. A model-based tool that is able to evaluate the intensity, duration and combination of multiple management techniques such as floor scraping and flushing, and the effects of different floor types and manure treatment on NH_3 emission reduction is still lacking in current scientific literature. Such model would be useful, not only to assess the current management practices and designs, but also to propose a suite of the best measures that can be used in combination to develop 'low NH_3 emission' housing barns for dairy cattle.

The aims of this research study were therefore to: (a) develop a process-based NH_3 emission model which is able to calculate the NH_3 emission reduction potential of new or adapted dairy cattle barns comprising individual or combined management- or design-based emission reduction techniques; (b)validate the model results by comparing them with empirical emission reduction factors from other studies using combinations of mitigation measures; (c) use the model to quantify the NH_3 emissions reduction potential of the following management-based techniques: floor scraping, flushing with water, indoor manure acidification and use of different types of floor; and (d) use the model to propose 'low NH_3 emission' housing barns for dairy cattle.

1.1 Theory on NH_3 emission from cattle manure

A common pathway of nitrogen (N) flow in livestock systems generally involves its uptake, metabolism, excretion, hydrolysis, mineralization, nitrification, denitrification and volatilization in various gaseous forms. In dairy cattle barns, the main form of N uptake by the animals is via the protein present in feed (forage + supplements), which is then partially metabolized into live weight gain and/or milk production. The remaining N consumed is excreted on the floor in the form of urine and feces. The parcel of urine on the floor will have its urea mineralized into ammonium (NH_4^+) which might in turn be transformed into gaseous N (N_2), nitrous oxide (N_2O) and NH_3 (Sutton et al., 2013). The remainder of urine and feces falls through the floor slats into the pit, where urine and feces are mixed together originating manure. In the manure pit, a series of enzymatic reactions including bacteriological degradation will occur in addition to urea mineralization, ultimately leading to gaseous emissions of N_2, N_2O and NH_3.The mechanistic model developed and used in this study only takes into account the enzymatic processes that lead to volatilization and emission of NH_3 from cattle manure.

Three main physico-chemical mechanisms are responsible for the emission of NH_3 from cattle urine or manure: (1) Enzymatic conversion of urea ($CO(NH_2)_2$) into ammonium (NH_4^+) and carbon dioxide (CO_2) in the presence of water and the enzyme urease; (2) The dissociation of liquid NH_4^+ into NH_3 as a function of media pH and air temperature (T), and (3) the convective mass transfer of volatilized NH_3, which in its turn is a function of wind speed (v)

Urea is abundantly present in cattle urine while urease is supplied by feces and naturally present in the environment. The enzymatic conversion of urea into NH_3 in the presence of water is described in equation 1 (table 1). This table gives the complete list of equations for the main chemical and physical processes, including the process constants included in the model. The degradation of urea into NH_3 can be mathematically represented by the Michaelis-Menten kinetics (Johnson and Goody, 2011), shown in equation 2. However, since urea degradation is not an instantaneous process, a linear increase of maximum urinal urea conversion rate (K_m) was applied, as suggested by Elzing and Monteny, (1997a), in equation 2 was adopted.

In cattle urine and manure, lNH_4^+ will co-exist in equilibrium with liquid NH_3. As the media pH increases, NH_4^+ is converted into NH_3, or vice versa in case the pH decreases, as described by the reversible chemical reaction in equation 3. This conversion is a function of the dissociation constant (k_D). Equation 4 represents the volatilization of liquid NH_3 from the emission source, a reaction characterized by the Henry constant (H). Under isothermal conditions, for pH > 9.4, the fraction of liquid NH_3 in the emission source is higher than that of NH_4^+, and the equilibrium of equations 3 and 4 is shifted to the right and consequently, more gaseous NH_3 will be formed.

The empirical models proposed by Hashimoto & Ludington, (1971) and applied by Elzing & Monteny, (1997b) were used to calculate k_D (equation 5) and H (equation 6) because their coefficients were determined from experiments made with cattle manure. The fraction of NH_3 in the emission source (F), as a function of pH and k_D, was calculated with equation 7.

The exchange between gaseous and liquid NH_3 is influenced by the properties of airflow (Ni, 1999) just above the liquid surface, which drives the convective transfer of gaseous NH_3, disturbing the equilibrium and stimulating the formation of more gaseous NH_3. This process is related to the volume of the emission source (e.g. urine puddle on the floor or manure in the pit) and its nitrogen content (urea in urine and total ammoniac-nitrogen or TAN at manure pit). According to Ni (1999), two models have been used to explain the convective transfer of volatilized NH_3: the two-film theory and the concentration boundary layer theory. The latter was used in the developed model. Both theories are dependent on an NH_3 mass transfer coefficient (k), and have been applied to describe NH_3 transfer from agricultural sources, such as animal manure. In this study the equation proposed by Liang et al, (2002), and also used by Monteny et al., (1998) (equation 8), was applied to estimate k, mainly because the conditions of the study of Liang et al. (2002) are relatively similar to those that we want to emulate with our model.

The conditions of use of the ammonia emission model as applied in this study are valid for the first centimeters above emission surface and similar to those specified by Snoek et al., (2014).

2. Material and methods

2.1 Overall model architecture

In general terms, the model described in this paper estimates the NH_3 emission factors for a dairy cattle barn that has at least one NH_3 emission mitigation technique (alternative barn), and compares it to a standard barn. We define as 'standard' a barn to which no relevant emission mitigation method has been applied. In terms of the model presented in this study, the characteristics of the standard barn are given in table 2. For the parametrization of the standard barn given in table 2, we took into account the descriptions of traditional dairy cattle barns in Northern Europe, as given by Monteny et al. (1998), Dai and Karring, (2014) and Ogink et al., (2014). The comparison between standard an alternative barns yields an NH_3 emission reduction factor, expressed in percentage. The calculation algorithm was designed according to the following steps:

(1) All input parameters for both alternative and standard dairy cattle barns were listed. Then, the endogenously calculated parameters related to the processes of NH_3 formation and emission were calculated.

(2) A set of numbers fit to an Exponential-Weibull probability distribution function was randomly generated, in order to represent an animal's urination behavior during a 24 hour period.

(3) Via nitrogen mass balance, emissions of NH_3 from a single urine puddle were calculated at standard and alternative barn conditions. A description of how N mass balance at urine puddle level is given in section 2.2.

(4) NH_3 emissions from all possible urine puddles were integrated and an averaged emission rate value was obtained on an animal-place basis (the barn floor area occupied by one animal).

(5) Emissions at the manure pit level in both barns were calculated assuming that manure under given environmental conditions and TAN content emits NH_3 at a constant rate, because it is continuously being loaded with fresh feces and urine.

(6) Floor and manure pit level emissions were aggregated to yield NH_3 emission factor of the standard barn, in a per animal-place basis. The following two steps were then run concomitantly: (6.a) For the alternative barn, the effect of floor scraping, flushing and floor type were modeled and accounted for in the total floor emissions, while the effects of flushing and manure acidification were accounted for in manure pit emissions. (6.b) Resulting floor and manure pit level emissions were aggregated to yield the total NH_3 emissions of the alternative barn.

(7) All the steps above were repeated 100 times, each time with a new set of randomly generated urination events. In each event, urination frequency and volume remained constant and equal to the values presented in table 2.

A flowchart of the calculation steps described above is presented as fig. 1. A more detailed description of the model is given in the following sections.

2.2 Modeling NH_3 emissions at floor and manure pit levels

At first, a single urine puddle is considered as a control volume. A mass balance for NH_3 involving the temporal change in its concentration (C_{NH3}), as released from the urine puddle was performed. The change in C_{NH3} was written as a function of change in urea concentration (C_U) minus the emitted NH_3 (equation 10). With equation 10, the term dC_U/dt and the variable E were replaced by equations 2 and 8, respectively, yielding a first order ordinary differential equation.

This equation was solved using Euler's Method (Higham., 2001) with Δt = 30 s, and by setting $C_U(t=0) = 4.75\ kg\cdot m^{-3}$ and $C_{NH3}(t=0) = 0\ kg\cdot m^{-3}$ (table 2). Instant NH_3 emission rate values at floor levels were then obtained for floor conditions as a function of t. Plots of C_{NH3} versus t yielded NH_3 emission peaks with the shape described in fig. 2.

The total number of times (n) in which a single urine puddle is reloaded with fresh urine was calculated with equation 11. In order to be used in the model, the value n was rounded to a positive integer. In the case of this study, n was equal to 2.286 ~ 2. The rounded value of n was interpreted here as the possible number of times in the course of a 24 h period that a single urine puddle location containing relatively "old" urine was replenished with "fresh" urine. In the case of this study (n = 2) the first urination was set to happen at the start of the 24 h period (t = 0 s), while the remainder urination event was randomly picked with the aid of a random number generator, following an Exponential-Weibull distribution. The generic form of the Exponential–Weibull distribution function was adjusted so that the probability of occurrence of a certain urination event is relatively lower immediately after a urination just occurred, while this probability increases as time passes.

Next, floor level NH_3 emissions were converted from a single urine puddle basis to an animal-place basis (fig. 1), with equation 12.

While calculations of emissions from the floor involved two steps, pit emissions were determined with a single step. Emissions of NH_3 at the manure pit were calculated from TAN, A_{pit}, k_{pit}, F_{pit} and H_{pit} with equation 13. It was assumed that the manure pit is an 'infinite' source of NH_3, and was constantly emitting it, hence negating the need to model emission peaks at manure pit level.

Lastly, total emission rate in a 'per cow' basis (E_{cow}) was calculated by adding up the floor and pit emissions for the same barn with Eq. 14.

2.3 Calculation of total barn NH_3 emissions and NH_3 emission reduction coefficient

The procedures described in section 2.2 were performed simultaneously for both standard and alternative barns. The emission mitigation strategies applicable to the alternative barn were modeled, as described in section 2.4. With the NH_3 emission factors obtained for both standard and alternative barns, an emission reduction factor was calculated with equation 15.

In order to account for the variability due to the random urine puddle generation feature of this model, as described in section 2.2, NH_3 emission reduction factors calculated in each simulation were averaged after 100 automatic calculations, *ceteris paribus* and randomly determined urination times.

2.4 Modeling specific management-based NH_3 emission mitigation strategies

In fig. 3-A several management-based NH_3 emission mitigation strategies are illustrated, related either to floor and manure pit levels.

2.4.1 Use of different floor types

The effect of two different floor types, namely slatted and solid, was taken into account in the model by implementing different values of urine puddle area (A) and depth (d). The floor considered in the standard barn was a slatted floor ($A = 0.77\ m^2$; $d = 4.8\times10^{-3}$ m, table 2). One alternative floor type was taken into account in this study, i.e. a solid floor (A = 1.2 m^2, d = 4.8×10^{-3} m). When a solid floor was considered, the contribution of NH_3 emissions from the manure pit to total emissions was set to zero.

2.4.2 Floor scraping

In this study, floor scraping refers to the use of manure scrapers (either robot or cable pulled). The effect of a scraper was taken into account in the alternative barn by multiplying the NH_3 emission factor at floor level on an animal-place basis ($E_{cow,floor}$, equation 12) by a 'scraping inefficiency' factor (η), the higher the η the less efficient floor scraping was. The η was dynamic, and defined by the pulse function in equation 16, which depended on the time elapsed after a scraping event (t_{ac}). The function in equation 16 was adjusted to the experimental data of Dai & Karring, (2014), who monitored the dynamics of urease activity of mixtures of fresh urine and feces from dairy cows in the laboratory.

During a scraping event, η was set to a minimum value (η_{min}), which reflects the 'clean' state of the floor, immediately after a scraper passed. Although no information could be found in the peer-reviewed literature concerning quantification of scraper cleaning efficiencies in dairy cattle barns, it is known from observation in practice that η_{min} will rarely be zero, i.e., perfect scraping. Instead, some manure and urine is usually left behind, which will depend on factors such as floor type, scraper model and maintenance conditions. Because no information for η_{min} exists, a fixed value of 0.4 was chosen based on expert judgement. This assumed value implies that immediately after a scraping event happened, a residual NH_3 emission of 40% was present. This is a rather conservative value, and attempts to account factors such as floor type, (im)proper maintenance and management of the scraping system.

The duration of a scraping event (t_{dc}) was calculated with equation 17 and represents the total time needed for the scraper to clean the floor area occupied by one cow. It is estimated as a function of the length (L_{alley}) and number of walking alleys (n_{alleys}) in the barn and the traveling speed (S) of the scraper. A traveling speed value of 0.07 $m\cdot s^{-1}$ was applied in this study based on the results presented by Sagkob et al. (2011) and Buck et al., (2013).

The effect of floor scraping on mitigation of NH_3 emissions was modeled as the number of times per day that the floor was scraped (scraping frequency). In the calculation of the emission reduction factor when floor scraping was applied to the alternative barn, no floor scraping was considered in the standard barn.

2.4.3 Flushing the floor with water

Floor flushing is defined in this study as homogeneously spraying water on the emitting surfaces, with the purpose of rinsing off the urine puddles existing on the floor. The modeling approach for flushing with water was based on the stoichiometry of a mixture of two solutions (urine and fresh water) with two different pH values. The pH of a solution is the negative logarithm of the total concentration of hydrogen ions (C_{H+}) in this solution. Hence, mixing solutions with different pH values can be interpreted as mixing solutions with different C_{H+}, the resulting C_{H+} gives the pH of the mixture.

The calculated pH of the mixture remained between those of the two solutions. Since the pH of water is usually lower than that of cattle urine, a mixture of urine and water will normally lead to a solution with resulting pH lower than that of pure urine. The pH decrease will shift the equilibrium between NH_3 and NH_4^+ (equation 3) to the left and consequently reduce emissions. In the calculation of resulting pH, we consider that enough water (> 5 L·animal-place^{-1}·d^{-1}) is sprayed on the floor, so that the pH buffering capacity of urine is negligible.

The calculation of the pH of the mixture of urine and water was based on given values of flushing rate (L·animal-place^{-1}·d^{-1}) of water and pH (adopted water pH was 8.2, as typically found in Flanders, Belgium), as well as production rates and pH of urine and feces.

Both flushing rate and flushing efficiency (parcel of the sprayed water that remained on the floor) were included as input variables to the calculation tool. The pH of the total volume of urine, feces and water mixture that reaches the pit was calculated and the resulting pH at the manure pit (assuming homogeneous mixing) was recalculated as well.

2.4.4 Acidification of manure in the manure pit

As described by Kai et al. (2008a), the effect of acidification is achieved in practice by mixing acid to the manure, and implementing an efficient (homogeneous) mixing system in the pit. Assuming that good mixing is achieved, the effect of acidification was applied to the alternative barn by lowering the pH of the manure. Values for pH between 5.0 and 6.5 have been achieved in practice (Kai et al., 2008), thus a manure pH value of 5.0 was adopted to represent manure acidification in this study. This procedure caused manure pit emissions (equation 13) to become zero.

2.5 Model sensitivity analysis and comparison with results from other studies

A sensitivity analysis of the model for the tested management techniques was performed by changing input values according to the following: flushing rate, 5 to 30 L·d^{-1}·animal-place^{-1}(at increments of 5 L·d^{-1}·animal-place^{-1}); acidification of manure, by changing manure pH from 4 to 8 (at pH increments of 1); and scraping frequency, 2 to 24 d^{-1} (at levels of 2, 4, 8, 12, 16, 20 and 24 d^{-1}). During the sensitivity analysis simulations, only the above mentioned parameters were modified, while all other model parameters remained the same in both standard and alternative barns. The values that were not changed were equal to those presented in table 2.

Comparisons of model output with those from other studies were also performed. Namely, the model was used to simulate scenarios that were similar to those in the referred studies. Scenario 1 consisted of solid floor combined with floor scraping. Scenario 2 consisted of solid floor combined with scraping and flushing, both scenarios were studied by Braam et al. (1997). In scenario 3, floor scraping and flushing were applied to a dairy cattle installation with slatted floor, to emulate the study conditions of Bleijenberg et al. (1995). In scenarios 4 to 7, the effects of manure acidification alone or combined with floor scraping and flushing were modeled in order to reproduce the conditions of the study of Bleijenberg et al. (1995).

3. Results and discussion

3.1 Modeling NH_3 emission peaks

One essential part of the model is the proper calculation of the NH_3 emission peaks. The dynamics seen in fig. 2 indicate that when fresh urine meets urease (assumed to be abundantly available at the floor), NH_3 emissions reach a peak value and start to deplete. The shape and maximum height of the emission curve presented in fig. 2 are similar to the results presented by Elzing & Monteny (1997b), who developed a laboratory-scale validation study for NH_3 emission peaks from dairy cattle manure, under conditions similar to those considered in this study. The model emulates the effect that, when undisturbed and if conditions are constant and favorable, the parcel of nitrogen from urea in the urine puddle will get nearly depleted by emitting NH_3, and eventually get exhausted before it is replaced by a new puddle.

The effect of randomly assigning urination times to puddle generation and NH_3 emission can be seen in fig. 4-A, which shows samples of hourly and cumulative NH_3 emissions for 10 distinct runs.

Each run in fig. 4-A represents the occurrence of two NH_3 emission peaks, representative of two urinations. The first urination always occurred at t = 0 s, while the second was randomly generated. In fig. 4-B, one can see how different urination times for different runs affected the cumulative emissions of NH_3. For the runs in which the emission peaks occurred further away from one another, the daily cumulative NH_3 emission was higher (e.g. runs 3 to 10).

Conversely, for the runs in which the emission peaks were closer (e. g. runs 1 and 2), the daily cumulative emissions reached lower values. The lowest cumulative emission occurred for run 2, to which the urination times of both peaks occurred at the same time, meaning that only one emission peak took place over the course of 24 h.

The effect of different urination times on daily cumulative emissions was taken into account by automatically repeating the calculation 100 times, and averaging these for the final emission factor.

An important aspect to consider is that, for modeling purposes, floor level NH_3 emissions is first calculated at a single puddle basis, this is done with equation 9 (table 1). Then emissions are converted to an 'animal-place' basis with equation 12 (table 1), taking into account aspects such as stocking density and cow's urination behavior. Most of the NH_3 emission mitigation techniques are modeled at this broader 'animal-place' level. In the conditions of the standard barn, we consider a total of 10 urinations per day in the floor area occupied by one single cow of 3.9 m^2 (table 2), these urinations events will take place randomly as explained in section 2.2. This means that the floor area allocated per cow remains mostly covered with urine, and one can think of for floor area occupied by a one animal as a single urine puddle composed of multiple puddles, some older some newer.

In this context, instead of occupying floor area and replace urine, the fraction of feces that remain at the floor will be eventually covered by or mixed with urine (transforming into manure), and thus will continue to emit as well. Cow's activity on the walking alley likely enhances feces and urine mixing at floor level.

If floor is not cleaned, the gradual increase of dirt causes the layer thickness or depth of urine puddle to increase in time (see equation 10 in table 1), in fact floor dirt encloses urine, hence increasing volumes of puddles, preventing them from drying out or drain into the manure pit. In such cases, the emission peak described in fig. 2 will take much longer to start descending, leading to higher emissions.

3.2 Modeling floor scraping

Fig. 5 is an example of the dynamics of NH_3 emissions from the floor in a 'per cow' or 'animal-place' basis, over a period of 24 h, both when no scraping is applied and when floor scraping frequency is 6 d^{-1}. The effect of scraping inefficiency (η_{min}) can be seen in this figure, i.e. when the scraper is active, emissions from the alternative barn (orange line) are dropped down to about 40% of emission from the reference barn (blue line). The sudden interruption of the average emissions, by removing the emitting source is what characterizes the emission reduction effect of floor scraping, since it means that regardless of η_{min}, emissions will drastically drop with a scraping event.

These results stress the importance of floor cleanliness (with η_{min} as close to 0 as possible) to ensure that the use of a scraper is an efficient NH_3 emission mitigation technique. This can be achieved in practice by the appropriate choice of floor scraping system, and proper maintenance.

Ceteris paribus and increasing scraping frequency from 2 to 12 times decreased floor NH_3 emissions by 9% to 24% respectively (as compared to a floor under similar conditions without scraping) (fig. 6). These results reveal the potential of hygienic practices and barn scrape management to reduce emissions.

3.3 Model sensitivity analysis and comparison of outputs with results from other studies

The results of the sensitivity analysis performed on the model (fig. 7) indicate that reduction efficiency increased in a non-linear fashion with increasing flushing rate, manure acidity and scraping frequency. These results suggested that in practical terms, manure acidification is a more efficient means for reducing emissions, because a relatively small change in pH leads to the maximum reduction efficiency of 27%. Such reduction can only be achieved, for instance, via floor scraping at relatively high scraping frequencies (> 16 d^{-1}). However, we recommend that the decision of which of the three management-based emission reduction means only be made after an appraisal of the economic costs, which is outside the scope of this study.

We rather suggest that, instead of relying on a single management technique, several should be applied simultaneously whenever feasible. Model simulations with combinations of multiple techniques yielded reduction coefficients that are cumulative. Results from the model combining multiple mitigation techniques are presented in section 3.4.

Concerning the results of the sensitivity analysis for manure acidification, we would like to highlight the hazards of this practice and potential drawbacks of it. The developed model makes no distinction of the type of acid used. However, in practice the addition of sulfuric acid, for instance will lead to the introduction of additional environmental contaminants. If nitric acid is used, then more N is added to the manure for land application. Furthermore, in fig. 7 it can be seen that decreasing manure pH from 5 to lower doesn't lead to any improvement of the emission reduction factor. In fact, a manure pH of 5 is potentially a hazardous situation for employee contact and under application conditions, and should be avoided.

The comparison (table 3) of the results of the model with those from the studies of Braam et al., (1997) and Ogink and Kroodsma, (1996) shows generally good agreement, indicating that the model can be used to simulate the effects of floor type, floor scraping and flushing and manure acidification on NH_3 emission reduction factors from dairy cattle barns. As for the comparison of the reduction factors obtained with the model when used to simulate the conditions of the study of Bleijenberg et al., (1995), and presented in table 3 (scenarios 3 to 7), consistently underestimated the reduction factors from that study. This systematic underestimation might have stemmed from the rather conservative choice of scraping efficiency applied to the alternative barn (η_{min} = 0.4). However, we consider an underestimation of the emission reduction factor is less of a problem with regard to the use of this model for regulatory purposes.

3.4 NH_3 emission reduction factors from alternative 'low emission' dairy cattle barns

The model was used to estimate NH_3 emission reduction factors of a few alternative 'low emission' barns. Namely, effect of floor scraping alone, floor scraping combined with manure acidification, floor scraping combined with flushing with water, and the use of solid floors instead of slatted floors (table 4).

Floor scraping frequencies of 6 and 10 d^{-1} were simulated and yielded reduction factors of 17 and 22%, respectively (table 4). The adoption of lower frequencies (< 6 d^{-1}) might require increasing the assumed η values, since a larger amount of manure would have to be removed every time. On the other hand, floor scraping frequencies > 10 d^{-1} might be economically challenging, since it would probably imply the use of more than one scraping robot. Furthermore, higher frequencies might affect the welfare of the cows in the cubicles as described by Buck et al. (2013).

Dairy cattle barns comprising floor scraping and manure acidification resulted in the largest NH_3 reduction, varying between 44% - 49% (table 4). The NH_3 emission reduction effect of acidifying the manure combined with floor scraping is cumulative. If stored manure pH reaches 5.0, its contribution to reducing emissions is at least 27% (see Fig.7), since no emissions would come from the manure pit. The reduction factors calculated from acidification of manure assume that the properties of the manure pit (especially pH) are constant.

Finally, the effect of using solid floors instead of slatted floors combined with scraping and flushing were also modeled (table 4). The obtained reduction factors were rather low, varying between 13 and 27%. The benefit of using solid floors is that emissions from the manure pit level are nearly zero, assuming that the manure pit is perfectly sealed. In the standard dairy cattle barn, as considered in this study, the proportion of NH_3 emissions from floor and manure pit is 70 and 30%, respectively. Significantly lowering manure pit emissions with the use of indoors emission reduction mitigation results in a manure that is richer in N, improving its quality when used for composting and/or direct field application as fertilizer (De Vries et al., 2015a, 2015b).

When it comes to floor emissions, solid floors have the potential to emit much more than slatted floors, simply because the urine puddles will be larger, or in the case when the urine-feces transport to storage is not working properly, then even more feces and urine will be left on the floor, potentially resulting in even more emissions. Hence, use of solid floors is recommended only when combined with hygiene-assuring measures, such as scraping or scraping and flushing, combined with transport of urine and feces to storage.

3.5 Use of the model for regulatory purposes and model limitations

The presented model is currently being used to advise the Flemish government (Belgium), on the performance of certain NH_3 emission reduction systems for dairy barns in Flanders. In view of EU regulations with regard to the NATURA2000 program (Natura 2000, 1992), Flanders' government imposed a Programmatic Approach to Nitrogen (acronym in Dutch 'PAS'). Within this specific regulation, for each dairy farm its contribution is calculated in the N deposition on these sensitive nature protection areas. If such a contribution is overreaching the preset threshold, then the respective dairy farm is obliged to provide measures to reduce its NH_3 emissions significantly (e.g. with 30%). Therefore, the Flemish government asked a scientific committee to certify a list with allowed NH_3 emission reduction techniques and their respective emission reduction efficiencies. This list (VLM, 2015) was first established in 2015, based on a (rather scarce) literature search and expert judgement. The scientific committee used the model presented in this study as a tool to quantify the reduction efficiency of well-defined and general floor-based reduction techniques (e.g. cleaning frequency of manure scrapers and robots installed on both slatted and closed floor systems, frequency and volume of water spraying devices installed at floor level) (see table 4). A safety factor was imposed to deduce a conservative emission reduction efficiency since the model results could not be supported with real measurement data. For more specific low emission floor types (e.g. profiled floors), model results are still being used to support expert judgement if applicable. As previously demonstrated in section 3.3, good comparison with empirical data was found and it is the aim to obtain better uniformity between both assessment methodologies.

The model in principle can also be used to calculate NH_3 emission reduction factors from management-based techniques such as feed manipulation, optimized ventilation, separation of urine and feces and cooling of manure surface in the manure pit. Seasonality effects on the modeled system, such as temperature changes at floor and manure pit, can also be accounted for. However, a description of these techniques and their emission reduction factors was omitted in this study, because of a lack of empirical data for validation.

In this context, the current version of the model neglects the fact that manure and urine pH are rather dynamic (we assume pH to remain constant), while there is increasing amount of evidence suggesting that pH actually decreases in time as observed by Dai and Karring (2014), which can significantly impact emissions. However, we didn't find any study in the literature providing empirical equations of urine and manure pH as a function of time and their resulting impacts of NH_3 emissions.

Furthermore, we would like to highlight that floor cleanliness conditions after scraping events are particularly important, in terms of residual NH_3 emissions. In fig. 8 three cases of floor cleanliness conditions are specified. The case of fig.8-A can be considered as a reference, when the floor hasn't been scraped for a while. The floor looks very wet, which indicates the presence of urine and manure. The case represented in fig.8-B, the floor was cleaned by a pulled scraper, and one notices that a thin layer of manure (mixture of urine and feces) is left behind. In this case, scraping equipment likely needs maintenance. In the case of fig.8-C, the floor has just been scraped by a robot, and looks fairly clean. We recommend that if the proposed model is used to advice the use of floor scraping frequency as an NH_3 emission mitigation means, it be subjected to the proper the choice of a scraping system that is well maintained.

Finally, we stress that the model cannot be applied to barns where litter, such as straw, is used to cover the floors. In these types of floors, an accurate determination of the emission surface and volume is more challenging due to the fact that manure is mixed with the bedding material. Additionally, the complexity of quantifying emissions from littered floors is increased because of the fact that bacteriological decomposition of manure also plays an important role in addition to the enzymatic breakdown of urea.

4. Conclusions

A process-based model is proposed, which is able to calculate NH_3 emission reduction factors for dairy cattle barns that feature a single or multiple management-based NH_3 emission mitigation technique(s). The considered alternative 'low emission' management techniques include: (a) scraping the floor; (b) flushing the floor with water; (c) different types of floor and (d) indoor acidification of manure. The NH_3 emission reduction factor is calculated considering an alternative barn, in which at least one of the emission mitigation methods mentioned above is applied, and a standard barn, which has none.

The modeled NH_3 emission of the standard barn and the reduction factors agreed with estimates from empirical studies found in the literature.

A list of NH_3 emission reduction techniques was proposed. In order of efficiency, NH_3 emission reduction technologies were determined: manure acidification, floor scraping and flushing. For combinations of techniques, the order of efficiency was: (a) floor scraping combined with manure acidification (44 - 49%); (b) solid floor combined with scraping and flushing (21 – 27%); (c) floor scraping combined with flushing and (d) floor scraping alone (17 – 22%).

5. Acknowledgements

The authors acknowledge the project financial support provided by the Institute for Agricultural and Fisheries Research. Gratitude is expressed to Dr. Wilfried Winiwarter and Dr. Daisy Brickhill for carefully reviewing the final draft of the manuscript prior to submission. Final thanks go to the anonymous reviewers for their helpful comments on the manuscript.

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Table 1. Equations used in the calculation tool to estimate NH_3 emissions reduction coefficients for adapted dairy cattle barns

Equation	Variable definitions and units	
$CO(NH_2)_2 + H_2O \xrightarrow{urease} CO_2 + 2NH_3$	-	[1]
$\frac{dC_U}{dt} = \frac{-\mu_m \times C_U}{K_m + C_U}$	C_U - urinal urea concentration ($kg \cdot m^{-3}$); μ_m - maximum urinal urea conversion rate ($kg \cdot m^{-3} \cdot s^{-1}$); K_m - Michaelis-Menten constant ($kg \cdot m^{-3}$)	[2]
$NH_4^+ \overset{K_D}{\longleftrightarrow} NH_{3,L} + H^+$	k_D - dissociation constant (dimensionless)	[3]
$NH_{3,L} \overset{H}{\longleftrightarrow} NH_{3,G}$	H – Henry's constant (dimensionless)	[4]
$k_D = 0.81\times10^{-10} 1.07^{\left(T_{liq} - 293.15\right)}$	T_{liq} – urine temperature (K)	[5]
$H = 1384\times1.053^{\left(293 - T_{air}\right)}$	T_{air} – air dry-bulb temperature (K)	[6]
$F = \frac{1}{1+\frac{10^{-pH}}{k_D}}$	F – fraction of ammonia in the urine (F_{floor}) or manure (F_{pit}) (dimensionless)	[7]
$k = 5.317\times10^{-5} + 2.012\times10^{-3}\times1.5686\times v$	k – ammonia mass transfer coefficient ($m \cdot s^{-1}$); v – air speed ($m \cdot s^{-1}$)	[8]
$E_{puddle, floor} = \frac{C_{NH3}\times k_{floor}\times A \times F_{floor}}{H_{floor}}$	$E_{puddle, floor}$ - ammonia emission rate at floor level for a single urine puddle ($kg \cdot s^{-1} \cdot puddle^{-1}$); C_{NH3} – ammonia concentration ($kg \cdot m^{-3}$)	[9]
$\frac{dC_{NH3}}{dt} = 2\times\frac{dC_U}{dt} - \frac{E_{puddle,floor}}{A\times d}$	A – urine puddle area (m^2); d – urine puddle depth (m)	[10]
$n = \frac{f\times A}{A_{cow, floor}}$	n – total number of times per day in which one urination puddle will be reloaded in a certain time period (d^{-1}); f – urination frequency ($cow^{-1} \cdot day^{-1}$); $A_{cow,floor}$ - walking area per cow allocated at floor level ($m^2 \cdot cow^{-1}$)	[11]
$E_{cow, floor} = \frac{E_{puddle, floor}\times A_{cow, floor}}{60\times10^6\times A}$	$E_{cow,floor}$ – ammonia emission rate in a 'per-cow' basis at floor level ($kg \cdot s^{-1} \cdot animal\text{-}place^{-1}$)	[12]
$E_{cow,pit} = \frac{17}{14}\times\frac{TAN\times k_{pit}\times A_{cow, pit}\times F_{pit}}{60\times H_{pit}}$	$E_{cow,pit}$ – ammonia emission rate in a 'per-cow' basis at manure pit level ($kg \cdot s^{-1} \cdot animal\text{-}place^{-1}$); TAN – total ammoniac nitrogen ($g \cdot kg^{-1}$). The ratio 17/14 converts N-NH_3 into NH_3.	[13]
$E_{cow} = E_{cow,floor} + E_{cow,pit}$	E_{cow} – ammonia emission rate in a 'per-cow' basis ($kg \cdot s^{-1} \cdot animal\text{-}place^{-1}$)	[14]
$R = \left(\frac{E_{cow, std} - E_{cow, alt}}{E_{cow, std}}\right)\times100$	R – ammonia emission reduction factor of the alternative barn in relation to the standard barn (%);$E_{cow,std}$ and $E_{cow,alt}$ – ammonia emission rate in a 'per-cow' basis for the standard and alternative barns, respectively ($kg \cdot s^{-1} \cdot animal\text{-}place^{-1}$)	[15]
$\eta = \begin{cases} \eta_{min} & \text{during a scraping event} \\ \frac{t_{ac}}{t_{ac} - 0.5} & \text{between scraping events} \end{cases}$	η – floor scraping inefficiency (dimensionless); η_{min} – minimum floor scraping inefficiency (dimensionless); t_{ac} – elapsed time after a scraping event (s). The constant 0.5 s was determined via calibration with the data presented by Dai and Karring, (2014).	[16]
$t_{dc} = \frac{L_{alley}\times n_{alley}}{30\times S\times n_{cow}}$	t_{dc} – duration of a scraping event (s); L_{alley} – length of the walking alley barn (m); n_{alley} – number of walking alleys in the barn (dimensionless); S – traveling speed of the scraping robot across the barn (m•s-1); ncow – total number of cows in the barn (dimensionless)	[17]

Table 2. List of input variables table for the standard dairy cattle barn

Variable	**Value at floor**	**Value at manure pit**	**Reference***
Number of cows in the barn (n_{cow})	60	-	-
Walking area per cow (A_{cow}, m^2)	3.9	8.0	-
Urine puddle area (A, m^2)	0.77	-	Monteny et al., (1998)
Urine puddle depth (d, m)	4.8×10^{-3}	-	Monteny et al., (1998)
Urination frequency (f, $cow^{-1}\cdot day^{-1}$)	10	-	-
Starting urea concentration ($C_U(t=0)$, $kg\cdot m^{-3}$)	4.75	-	Dai & Karring, (2014)
Manure TAN concentration ($g\cdot kg^{-1}$)	-	3.5	Dai & Karring, (2014)
Temperature of urine puddle (T_{liq}, ^oC)	10	10	Ogink et al., (2014)
Urine pH (dimensionless)	9.4	-	Ogink et al., (2014)
Air velocity near urine puddle (v, $m\cdot s^{-1}$)	0.15	0.05	Ogink et al., (2014)
Manure pH (dimensionless)	-	8.4	Ogink et al., (2014)
Starting NH_3 concentrations ($C_{NH3}(t=0)$, kg $\cdot m^{-3}$)	0	-	-

*The values that are not referenced were implemented into the model by the authors based on expert judgement.

Table 3. Comparison of NH_3 emission reduction factors for different cases, obtained via modeling and empirically determined from studies found in the literature

Scenario	**Cited study**	**Description of reference barn**	**Description of alternative barn**	**NH_3 emission reduction factor (%)**	
				Cited study	**This study**
1	Braam et al., (1997)	Slatted floor, no scraping mentioned	Solid (sloped) floor, and scraping frequency of 12 d^{-1}	42 - 59	43 (42, 44)
2	Braam et al., (1997)	Slatted floor, no scraping mentioned	Solid (sloped) floor, scraping frequency of 12 d^{-1} and spraying of water at a rate of 6 L d^{-1} cow^{-1}	53 - 67	54 (52, 55)
3	Ogink & Kroodsma, (1996)	Slatted floor, no scraping mentioned	Slatted floor scraped 12 d^{-1}, flushing with water at a rate of 20 L d^{-1} cow^{-1}	9 -19	21 (19, 21)
4	Bleijenberg et al., (1995)	Slatted floor scraped 12 d^{-1}	Slatted floor scraped 12 d^{-1}, flushing with water at a rate of 19 L d^{-1} cow^{-1}	10 - 23	10 (8, 10)
5	Bleijenberg et al., (1995)	Slatted floor scraped 12 d^{-1}	Slatted floor scraped 12 d^{-1}, flushing with water at a rate of 47 L d^{-1} cow^{-1}	23 - 33	17 (16, 18)
6	Bleijenberg et al., (1995)	Slatted floor scraped 12 d^{-1}	Acidification of manure	33 - 42	27 (24, 27)
7	Bleijenberg et al., (1995)	Slatted floor scraped 12 d^{-1}	Acidification of manure and flushing with water at a rate of 26 L d^{-1} cow^{-1}	44 - 55	39 (37, 40)

Table 4. List of alternative low ammonia emission dairy cattle barns and their reduction factors

Scenario name	**Description**	**Floor / Pit ratio (%)**	**Reduction factor (%)***
Scraping 1	Scraping frequency^1: 6 d^{-1}	67/33	17 (17, 19)
Scraping 2	Scraping frequency^1: 10 d^{-1}	66/34	22 (21, 22)
Scraping comb. w/ acidification of manure 1	Scraping frequency^1: 6 d^{-1}; manure pH 5.0	100/0	44 (43, 45)
Scraping comb. w/ acidification of manure 2	Scraping frequency^1: 10 d^{-1}; manure pH 5.0	100/0	49 (48, 50)
Scraping comb. w/ flushing 1	Scraping frequency: 6 d^{-1}; flushing w/ water at 10 L animal-place^{-1} d^{-1}	67/33	20 (17, 20)
Scraping comb. w/ flushing 2	Scraping frequency: 10 d^{-1}; flushing w/ water at 10 L animal-place^{-1} d^{-1}	64/36	25 (22, 25)
Solid floor comb. w/ scraping 1	Scraping frequency: 6 d^{-1}	100/0	13 (12, 14)
Solid floor comb. w/ scraping 2	Scraping frequency: 10 d^{-1}	100/0	20 (20, 21)
Solid floor comb. w/ scraping & flushing 1	Scraping frequency: 6 d^{-1}; flushing w/ water at 10 L animal-place^{-1} d^{-1}	100/0	21 (20, 23)
Solid floor comb. w/ scraping & flushing 2	Scraping frequency: 10 d^{-1}; flushing w/ water at 10 L animal-place^{-1} d^{-1}	100/0	27 (27, 30)

*The number outside brackets represent the average of 100 simulations in which the urination events were randomly selected and the numbers between brackets represent minimum and maximum occurring values.

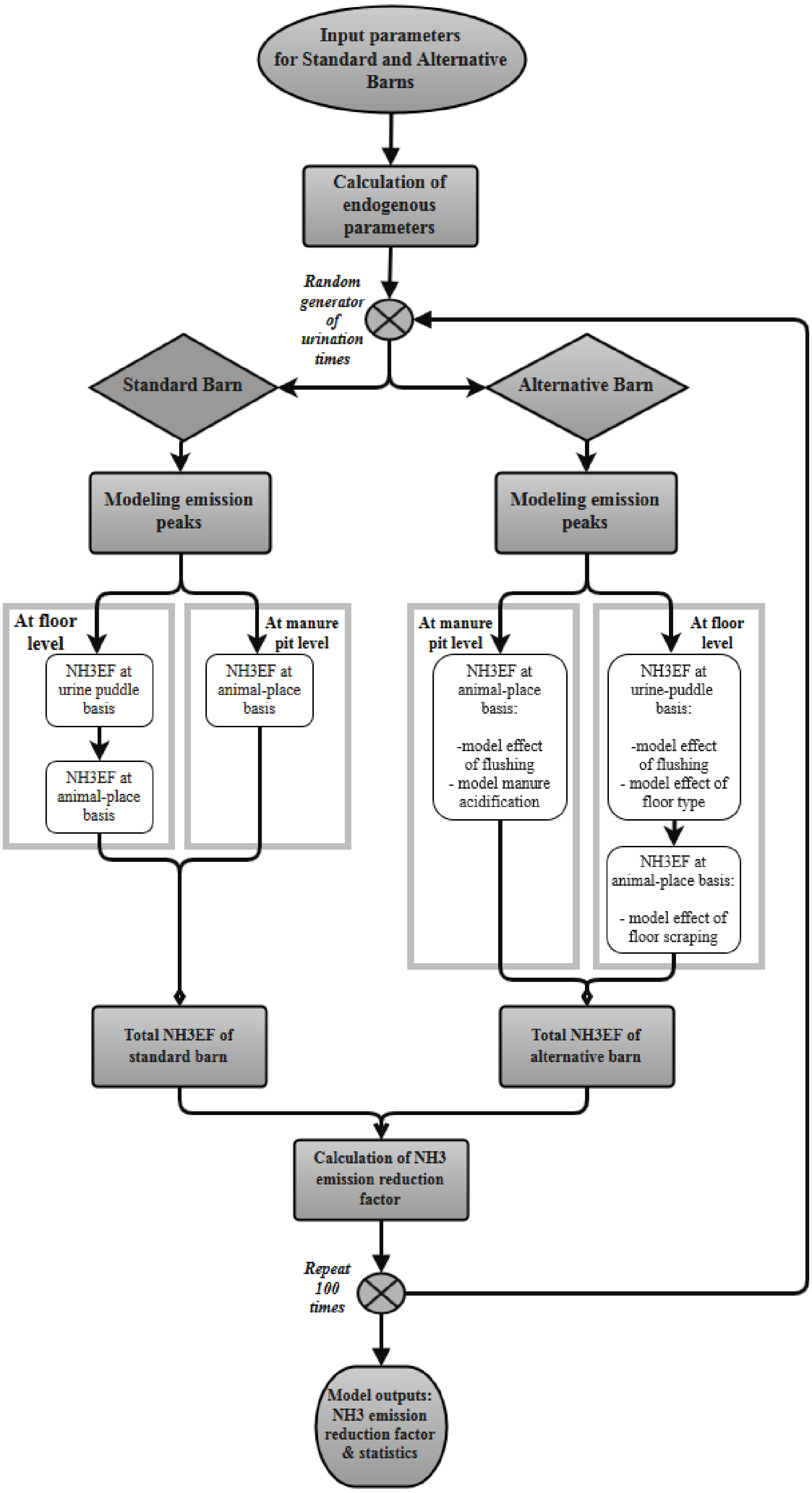

Figure 1. General setup of the flow of calculations in the model for the determination of total NH_3 emission reduction factor of an alternative barn in relation to the standard barn. NH_3EF stands for NH_3 emission factor (g·animal-place^{-1}·year^{-1}).

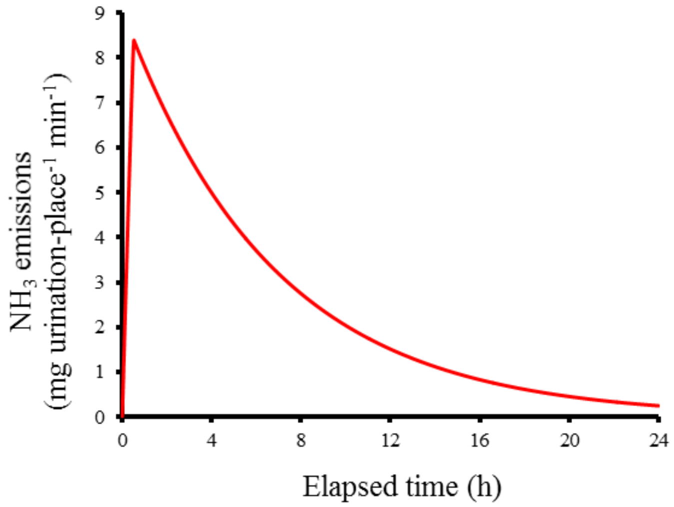

Figure 2. Sample of the dynamics of NH_3 emissions from a single urine puddle after being loaded with fresh urine.

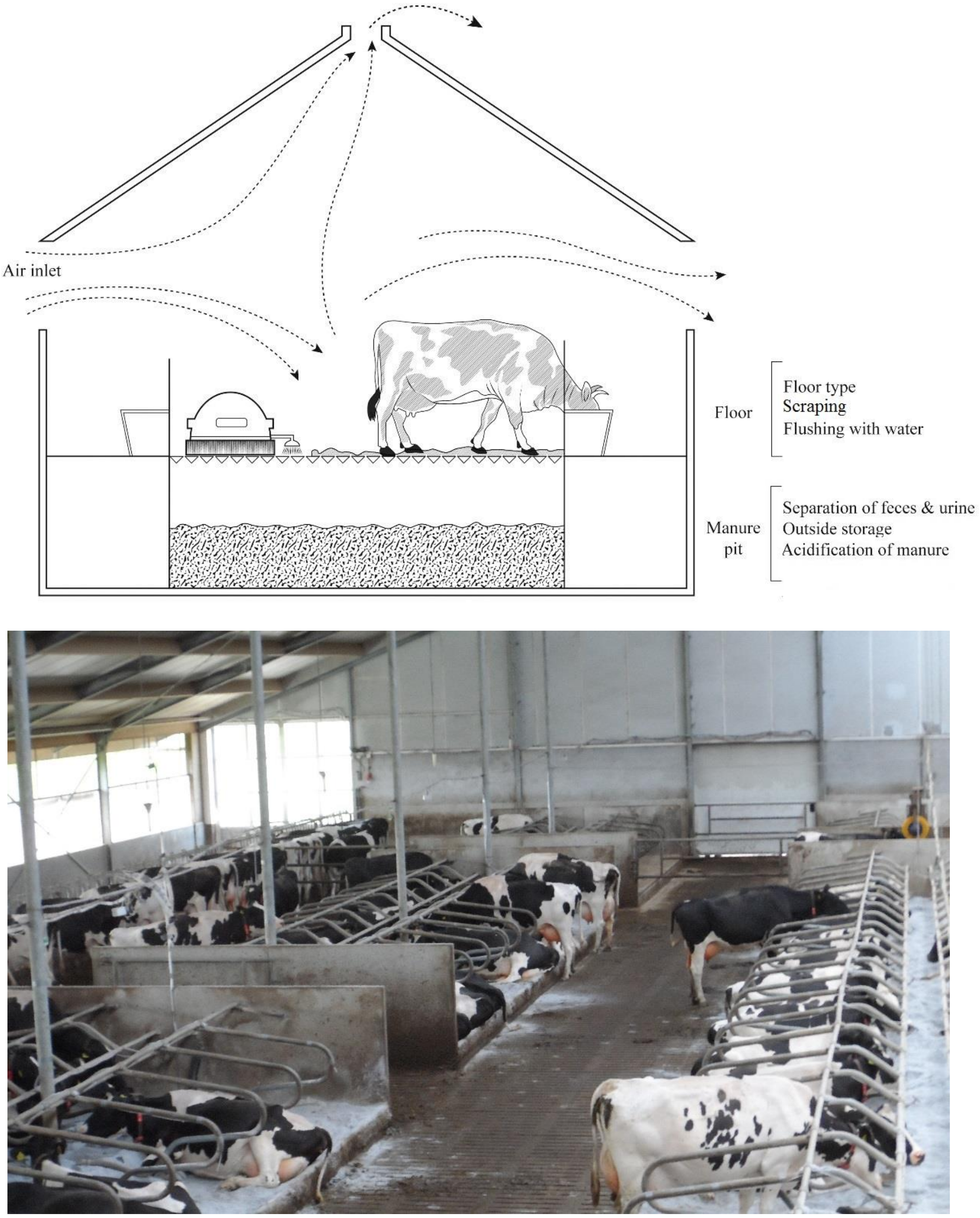

Figure 3. (A) Disaggregation of NH_3 emissions from a dairy cattle barn, and *loci* where mitigation strategies can be applied. Although all management-based NH_3 emission mitigation techniques in this figure are taken into account in the model, focus was given to floor type, floor scraping and flushing with water, and acidification of manure; (B) Picture of a typical dairy cattle cubicle barn where the cubicles and walking alleys are shown.

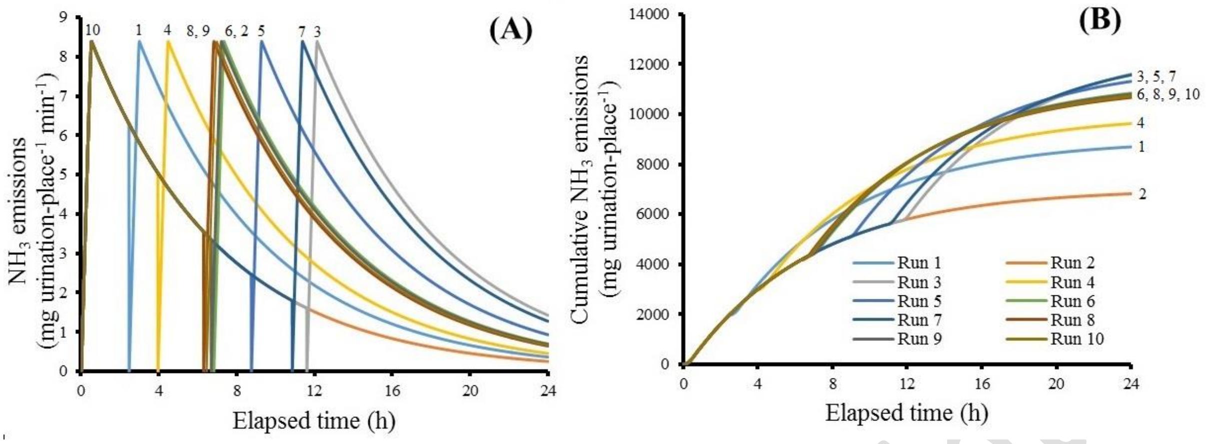

Figure 4. Dynamics of NH$_3$ emissions rates (A) and cumulative NH$_3$ emissions (B) in 10 different runs. In each run, the urine puddle was loaded twice with fresh urine at random times.

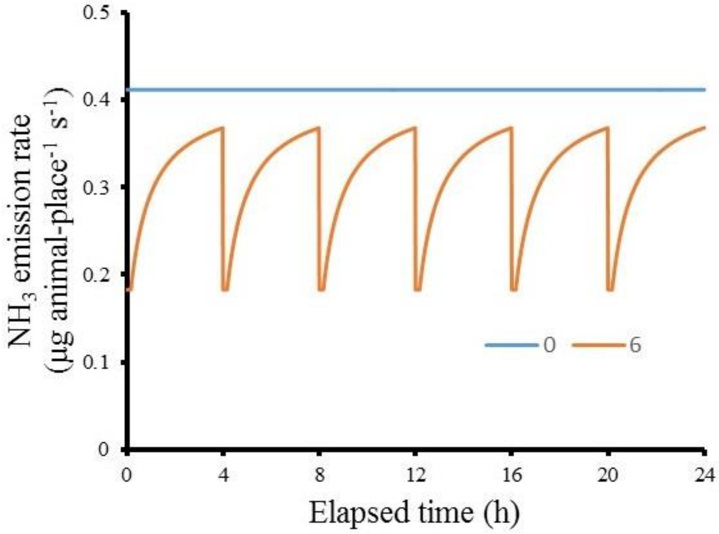

Figure 5. Dynamics of the effect of scraping the floor with a scraper 6 times over a period of 24h (orange line), as opposed to no scraping (blue line). The valleys in the orange curve represent the occurrence of a scraping event, after which the emission is restored following the Michaellis-Menten Kinetics until a new scraping event takes place.

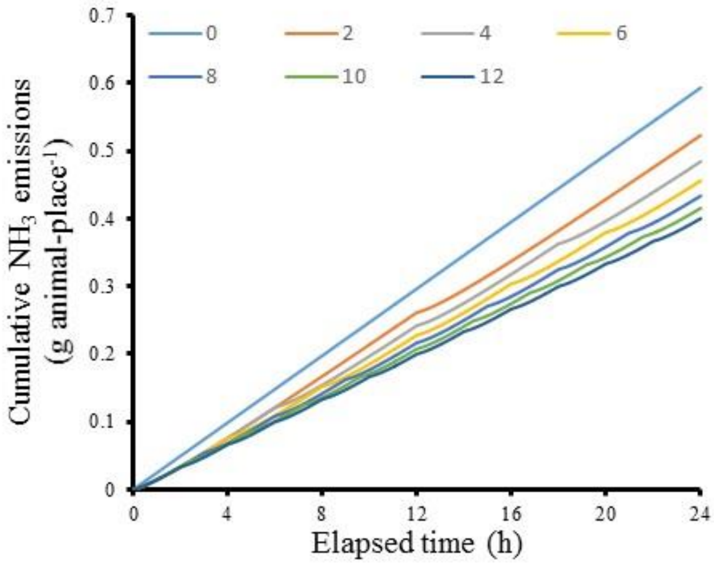

Figure 6. Cumulative NH_3 emissions from floor at different scraping frequencies.

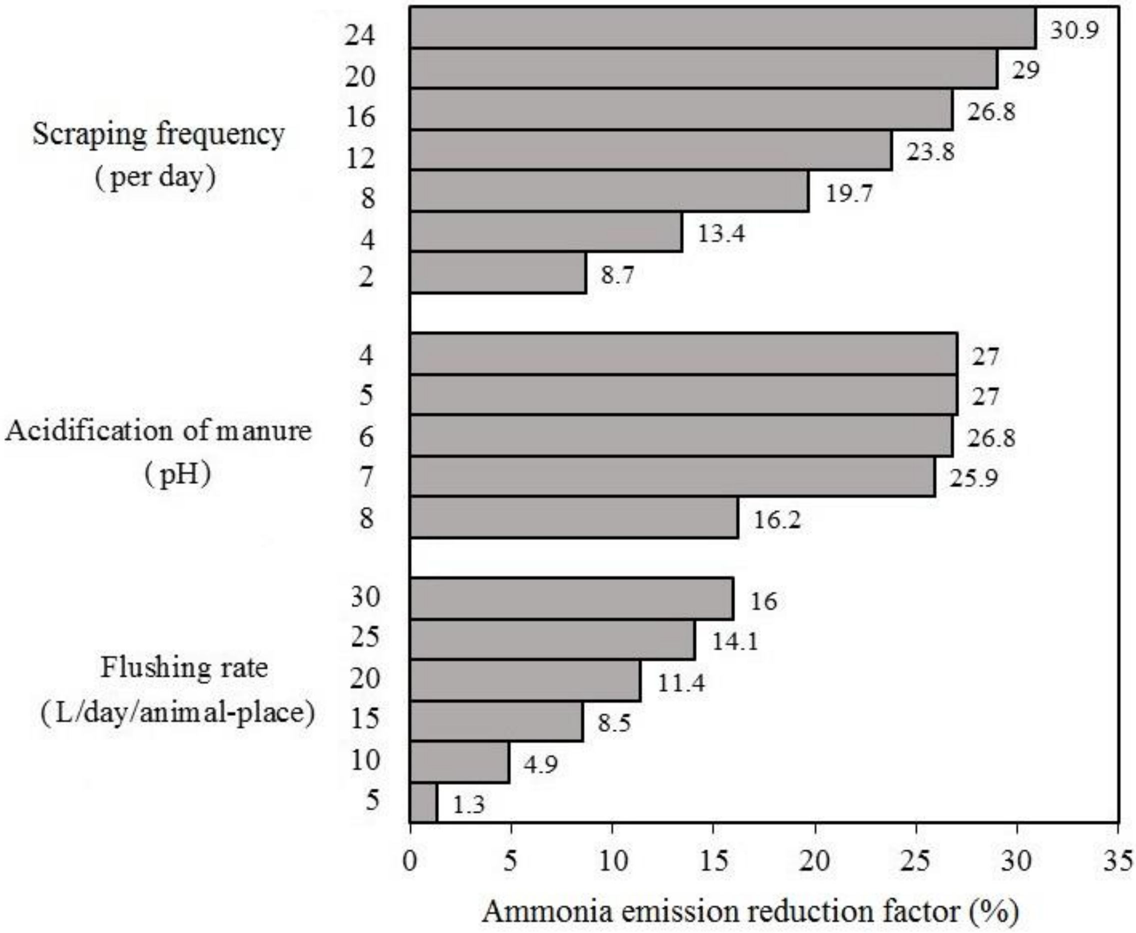

Figure 7. Ammonia emissions reduction efficiencies obtained from the model after a sensitivity analysis for the management-based emission reduction techniques.

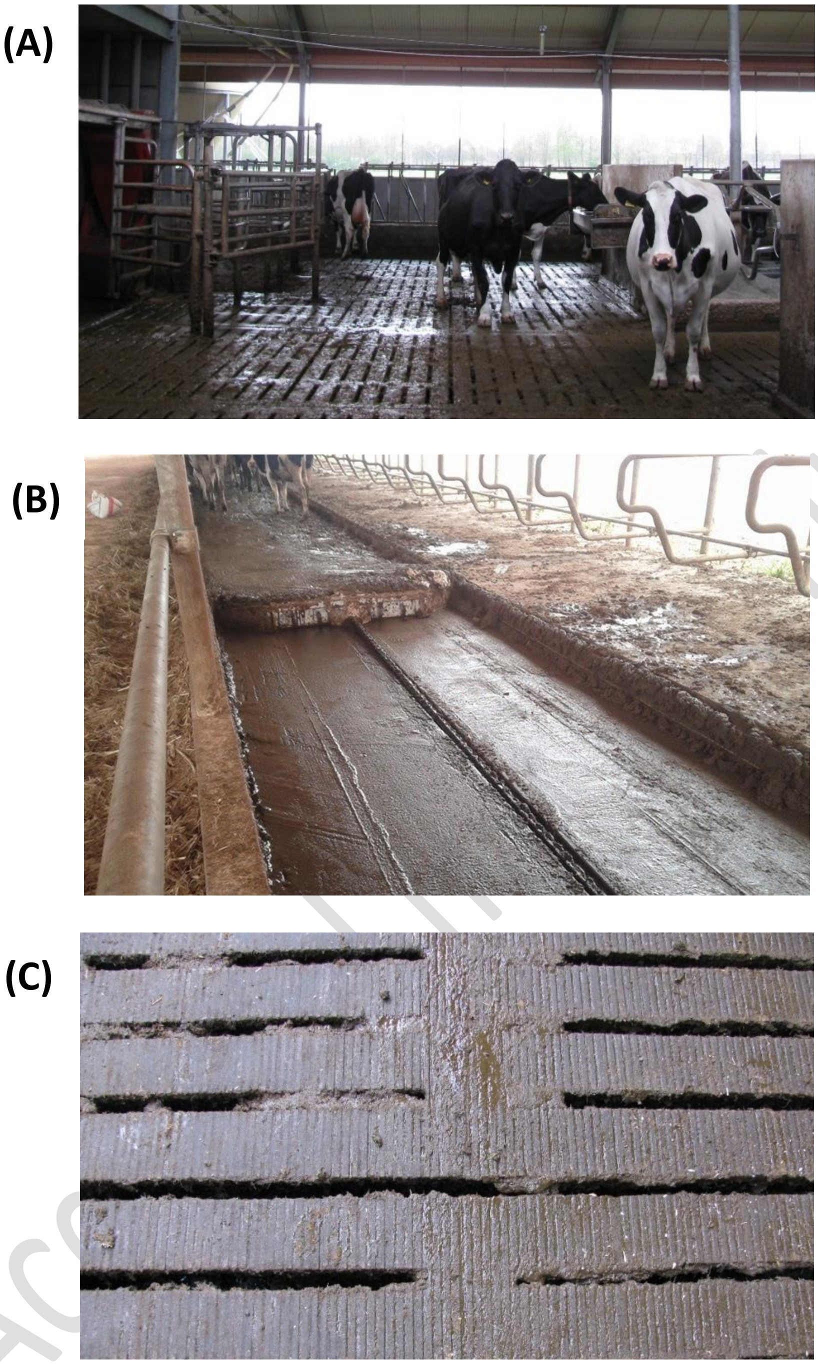

Figure 8. Pictures of dairy cattle barn floors at different cleanliness levels. (A) Hasn't been scraped in a while; (B) After being cleaned by a pulled scraper, a thin film of manure is left behind; (C) After being cleaned by a robot scraper, fairly clean.