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

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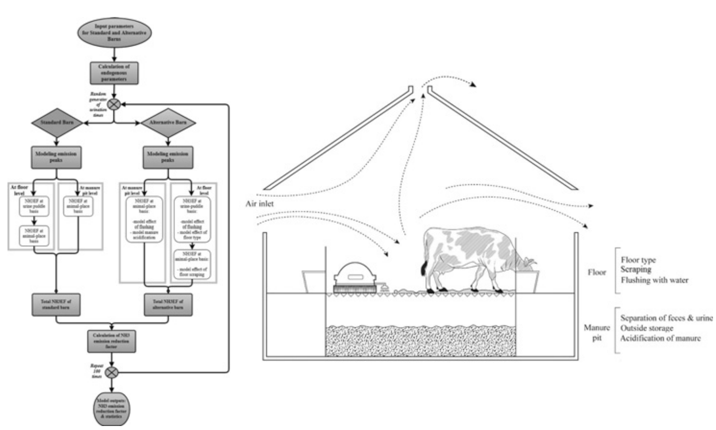
HIGHLIGHTS

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

GRAPHICAL ABSTRACT



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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

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currently being used to advise the Flemish Government (Belgium), on the performance of certain NH_3 emission reduction systems for dairy barns in Flanders.

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, 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 management 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,b), 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,b) 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 and 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 and 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., 1997a; Ogink and Kroodsma, 1996), flushing the floor with water (Bleijenberg et al., 1995; Braam et al., 1997b; 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., 2014a, 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 urine and manure.

Three main physico-chemical mechanisms are responsible for the emission of NH_3 from cattle urine or manure: (1) Enzymatic conversion