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Modeling ammonia emissions from dairy production systems in the United States

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HIGHLIGHTS

- We tested a process-based model against NH_3 emission from the U.S. dairy systems.
- Impacts of management practices on farm-scale NH_3 emission has been assessed.
- An optimized strategy could reduce the farm-scale NH_3 emission by up to 50%.

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ABSTRACT

Dairy production systems are hot spots of ammonia (NH_3) emission. However, there remains large uncertainty in quantifying and mitigating NH_3 emissions from dairy farms due to the lack of both long-term field measurements and reliable methods for extrapolating these measurements. In this study, a process-based biogeochemical model, Manure-DNDC, was tested against measurements of NH_3 fluxes from five barns and one lagoon in four dairy farms over a range of environmental conditions and management practices in the United States. Results from the validation tests indicate that the magnitudes and seasonal patterns of NH_3 fluxes simulated by Manure-DNDC were in agreement with the observations across the sites. The model was then applied to assess impacts of alternative management practices on NH_3 emissions at the farm scale. The alternatives included reduction of crude protein content in feed, replacement of scraping with flushing for removal of manure from barn, lagoon coverage, increase in frequency for removal of slurry from lagoon, and replacement of surface spreading with incorporation for manure land application. The simulations demonstrate that: (a) all the tested alternative management practices decreased the NH_3 emissions although the efficiency of mitigation varied; (b) a change of management in an upstream facility affected the NH_3 emissions from all downstream facilities; and (c) an optimized strategy by combining the alternative practices on feed, manure removal, manure storage, and land application could reduce the farm-scale NH_3 emission by up to 50%. The results from this study may provide useful information for mitigating NH_3 emissions from dairy production systems and emphasize the necessity of whole-farm perspectives on the assessment of potential technical options for NH_3 mitigation. This study also demonstrates the potential of utilizing process-based models, such as Manure-DNDC, to quantify and mitigate NH_3 emissions from dairy farms.

1. Introduction

Driven by the growth of human population and rising income, global livestock production has expanded dramatically over the past several decades (FAO, 2006). For example, the global cattle number increased from 942 to 1430 million heads during the period from 1960 to 2010 (FAO, 2012). The expansion of livestock production results in a large amount of nitrogen (N) excreted as manure waste (Oenema et al., 2005). A significant portion of the excreted N is often lost into the atmosphere or water bodies, and subsequently leads to a series of environmental problems (e.g., Davidson, 2009; Galloway et al., 2003; Pitesky et al., 2009). Ammonia (NH_3) gas is an important pollutant and directly contributes to the formation of fine particulate matter and deterioration of atmospheric environment (Pinder et al., 2007). When NH_3

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deposits into terrestrial or aquatic ecosystems, it can cause acidification, over-fertilization, eutrophication, and/or emission of nitrous oxide in these systems (e.g., Galloway et al., 2003; Krupa, 2003).

Globally, NH_3 emissions from the excreta of domestic animals could be as high as 21.6 Tg (10^{12} g) N yr^{-1}, an amount that comprises about 50 percent of total NH_3 emissions from terrestrial systems (Bouwman et al., 1997; Van Aardenne et al., 2001). In the U.S., the excreta of domestic animals are the most important source of NH_3 emission as well. NH_3 fluxes from the U.S. animal husbandry are approximately 2.4 Tg yr^{-1} (USEPA, 2004). There is a high demand for the quantification and mitigation of NH_3 emissions from livestock operations (Petersen and Sommer, 2011). However, the complex mechanisms related to the NH_3 emissions from livestock systems have been being a barrier for the quantification or mitigation. In livestock farms, NH_3 emission can begin soon after excretion and continue through all the manure handling processes (Sommer and Hutchings, 1997; Rotz, 2004). The processes involved in NH_3 emission include hydrolysis of urea or uric acid, decomposition of organic N, ammonium (NH_4^+) dissociation, and NH_3 volatilization (Arogo et al., 2006; Montes et al., 2009; Ni, 1999). A number of factors, such as animal type, feed quantity and quality, housing conditions, manure treatment and storage, and manure land application, jointly with the local weather and soil properties, can regulate the processes (Arogo et al., 2006; Bouwman et al., 2002; NRC, 2003). The variability of these controlling factors results in temporal and spatial heterogeneity of NH_3 emissions from the animal husbandry (e.g., Arogo et al., 2006; Bussink and Oenema, 1998; Rotz, 2004). In addition, the losses of various forms of N during one stage of manure treatments may influence the N losses during subsequent stages, and the intricate transfer and transformation of N within the manure life cycle have further complicated the quantification and mitigation of NH_3 emissions at the farm scale (NRC, 2003; Reidy et al., 2008; Rotz and Oenema, 2006).

Emission factor (EF) methods have long been utilized for quantifying NH_3 emissions from individual category of livestock (e.g., dairy cow, beef cow, and swine) (Anderson et al., 2003; Battye et al., 1994) or specific manure handling processes (e.g., Misselbrook et al., 2000; Reidy et al., 2008; USEPA, 2004). The EFs are usually generated based on field measurements. However, the measurements are usually limited by their temporal or spatial coverage (Harper et al., 2009). At present, the measured NH_3 flux data are still scarce and the EF approaches based on the measurements are hard to capture the complex combinations of climate, soil, farm types, and manure management practices (e.g., NRC, 2003; Pinder et al., 2004a; USEPA, 2004). Modeling approaches ranging from statistical regression to processes-based models have been developed to fill the gap. Regression models are developed by relating NH_3 fluxes to some regulating factors, such as animal type, feed quantity and quality, and climate, among others (NRC, 2003). This kind of models are relatively easy to perform, but may be constrained to the conditions under which the models have been developed (De Visscher et al., 2002). In addition, the regression models often lack mechanisms to include some management practices that could potentially reduce NH_3 emission (Pinder et al., 2004b). In order to improve the quantification and mitigation of NH_3 emission, process-based models have drawn more attentions recently (e.g., Pinder et al., 2004b; Rotz and Oenema, 2006). Equipped with detailed processes regarding NH_3 production and emission and specifications of farm facilities, these models are able to simulate NH_3 emissions from various farm components (e.g., housing facility, manure storage, and field with manure application) (NRC, 2003; Rotz, 2004). However, few validation tests, especially against long-term or farm-scale NH_3 observations, have been reported for the process-based models yet (e.g., NRC, 2003; Pinder et al., 2004b; Rotz and Oenema, 2006).

A process-based biogeochemical model, Manure-DNDC, was recently developed to predict carbon (C), N, and phosphorus (P) dynamics by linking a biogeochemical model, Denitrification–Decomposition (DNDC), to the manure life cycle across major facilities in livestock farms (Li et al., 2012). As a newly developed model, Manure-DNDC has been tested against very limited number of field records. Assisted by the innvoation center for U.S. dairy, we obtained a dataset of NH_3 emissions collected from four dairy farms across the country. The extensive data have provided an opportunity to evaluate the applicability of Manure-DNDC for predicting NH_3 emissions from dairy production systems in the U.S. and for investigating the mitigation options. In this study, we tested Manure-DNDC against NH_3 emissions from dairy production systems with different environmental conditions and management practices, and then applied the model to assess impacts of alternative management practices on NH_3 emissions at the farm scale.

2. Materials and methods

2.1. Description of field measurements

Field measurements used for the model validation were performed at four confined dairy farms in New York (NY), Indiana (IN), and Wisconsin (WI) states during the period from September 2007 to December 2009 under the program of National Air Emissions Monitoring Study (Bogan et al., 2010; Lim et al., 2010; Cortus et al., 2010; Grant and Boehm, 2010). Five free stall barns and a lagoon used for manure storage were monitored for NH_3 emission. These dairy farms possessed different environmental conditions and management practices (e.g., feeding, housing, and manure storage and treatment practices), and therefore could represent a range of dairy production systems in the U.S.

The five free stall barns (denoted as barn 1 through barn 5, respectively; Table 1) were located at the three confined dairy farms in Onondaga County, NY (barn 1), Jasper County, IN (barns 2 and 3), and Saint Croix County, WI (barns 4 and 5). All management practices at the test farms were performed following the local conventional practices. During the study period, concentrations of NH_3 in air entering and exiting the facilities as well as the ventilation rates were monitored for each barn. Gas fluxes were calculated based on the measured NH_3 concentrations and ventilation rates. Table 1 summarizes the primary characteristics of the test barns, including animal inventory, housing area, feed intake rate, concentration of crude protein (CP) in forage, milk production, bedding material, methods and frequency of manure removal, coordinate, and annual mean air temperature during the study period. The technical details regarding the field measurements have been described by Bogan et al. (2010), Lim et al. (2010) and Cortus et al. (2010).

The lagoon used for manure storage was located in Jasper County, IN (40°52′ N 86°12′ W, hereinafter denoted as lagoon IN) but at a different confined dairy farm than the barns 2 and 3 site. The farm held approximately 2600 dairy cows. The monitored lagoon had a surface area of 9884 m^2 and a maximum storage capacity of 48,212 m^3, and received manure slurries from the milking parlor and holding area (Grant and Boehm, 2010). The manure stored in the lagoon was not removed during the study period from September 2008 to August 2009. NH_3 measurements were continuously performed for approximately one year at this lagoon by using open-path techniques (Grant and Boehm, 2010). During the study period, concentrations of NH_3 in the upwind and downwind air were measured using tunable diode laser

Table 1
General characteristics of the test dairy barns.

Sites	Barns	AI[a]	Area (m^2)	DMI[b]	CP[c]	MP[d]	Bedding material	MRM[e]	AMT[f]	Coordinate
NY	1	470	3332	21.5	13	35.4	Manure solid	Scrape	11.5	42°52′ N 76°27′ W
IN[g]	2	1650	13,688	23.7	16	32.9	Manure solid	Scrape	10.7	41°6′ N 87°15′ W
	3	1750	13,688	24.7	16	33.9	Manure solid	Scrape	10.7	41°6′ N 87°15′ W
WI	4	211	2604	26.3	12	32.2	Sand	Flushing or scrape	7.5	44°54′ N 92°23′ W
	5	355	3210	26.3	12	32.2	Wood shaving or sand	Flushing or scrape	7.5	44°54′ N 92°23′ W

[a] AI, animal inventory (head).
[b] DMI, average daily intake rate of dry matter (kg $head^{-1}$).
[c] CP, concentration of crude protein in forage (%).
[d] MP, average daily milk production (kg $head^{-1}$).
[e] MRM, manure removal method. The method of removing manure in the barns 4 and 5 was converted from flushing the barns into scraping since 19 September 2008. Manure was removed on a daily basis in each barn.
[f] AMT, annual mean air temperature during study periods (°C).
[g] Field measurements were conducted for the west side of barns 2 and 3, which held 836 and 865 cows, respectively (Lim et al., 2010).

spectrometers. Gas fluxes were determined based on the measurements of NH_3 concentration and meteorological parameters by using Radial Plume Mapping (RPM) and Backward Lagrangian Stochastic (BLS) models on a half hour basis (Grant et al., 2013a). Daily NH_3 fluxes were then calculated as average values of half-hour measurements, and a valid daily flux required at least 25 valid half-hour measurements throughout the day (Grant et al., 2013b). The technical details of the field measurements can be found in the report by Grant and Boehm (2010).

Daily NH_3 fluxes were generally available for two entire years for all the free stall barns except some short periods when the instruments were down. For the Lagoon IN, we combined the measurements calculated by using the RPM and BLS models to get the maximum number of valid daily measurements, considering that the measurements determined by these two methods were similar (Grant et al., 2013a). During September 2008 to August 2009, valid daily measurements were available for 71 days using the RPM method and for 144 days using the BLS method, giving a total of 166 valid daily fluxes. In order to calculate annual total NH_3 emissions, NH_3 fluxes for the days lacking measurements were determined using the arithmetic mean fluxes of the two closest days when observations were performed. Annual total NH_3 emissions were then calculated by summing up the daily fluxes from either the direct measurements or gap-filling for each barn and lagoon IN. In general, the field measurements provided rich datasets, including both NH_3 fluxes and input information, to support the Manure-DNDC validation.

2.2. The Manure-DNDC model

The Manure-DNDC model (Li et al., 2012) used in this study was developed to simulate biogeochemical cycles of C, N, and phosphorus (P) in livestock farms. The model contains fundamental processes describing turnover of manure organic matter, which were originally developed for simulating dynamics of soil organic matter in the DNDC model (Li et al., 1992a, 1992b; Li, 2000). A relatively complete suite of biogeochemical processes, including decomposition, urea hydrolysis, ammonia volatilization, fermentation, methanogenesis, nitrification, and denitrification, have been embedded in Manure-DNDC, which allows the model to compute the complex transfer and transformations of C, N, and P in livestock production systems. In Manure-DNDC, two bridges have been built to link three basic components, i.e., farm facilities (e.g., barn, compost, lagoon, anaerobic digester, and cropping field), environmental factors, and biogeochemical processes. The first bridge predicts environmental factors of the farm facilities, such as temperature, moisture, air velocity, pH, redox potential, and substrates concentration, based on primary drivers, such as climate, farm structure, characteristics of the facilities, animal type, vegetation, soil properties, and farming management practices. The second bridge links the predicted environmental factors to the biogeochemical reactions that simulate dynamics of C, N, and P in each single farm facility. Within the framework of Manure-DNDC, the primary drivers, environmental factors, and biogeochemical processes exchange information at an hourly or daily time step. Losses of C, N, and P through gas emission, runoff, or leaching are calculated as part of the biogeochemical cycles of the three elements across the facilities within livestock farms (Li et al., 2012).

Fig. 1 illustrates N transfer and transformations simulated by Manure-DNDC for livestock farms. The model tracks N flows across the farm components following the manure life cycle. In Manure-DNDC, manure is excreted either at the housing facilities or in the grazing pastures, and N excretion is calculated as the difference between feed N intake and N secreated in milk and meat. The manure accumulated in the housing facilities can be removed into the facilities used for manure storage/treatment or directly applied to the fields with the user-defined method and removal frequency. During the stage of storage or treatment, manure can be transferred among different storage facilities. The residue manure released from the storage/treatment facilities is usually applied to the cropping fields (Fig. 1). In the manure life cycle, the biology or biogeochemical processes related to N dynamics include decomposition, microbial assimilation, urea hydrolysis, ammonium adsorption, ammonia volatilization, nitrification, denitrification, plant uptake, and nitrate leaching. The N mass is conserved although the chemical forms of N are continually changing over the simulation of the manure life cycle. All the N outputs, including productions of livestock and plant as well as the N losses through gas emission, runoff, or leaching are quantified and reported by the model at daily and annual steps. Further details regarding the model structure and the physical, chemical, and biogeochemical processes incorporated into Manure-DNDC were described by Li et al. (2012).

2.3. Model application

2.3.1. Model validation

Field data from the test dairy production systems, including the measured NH_3 fluxes as well as the local climate and farm characteristics, were collected for validation of Manure-DNDC. The

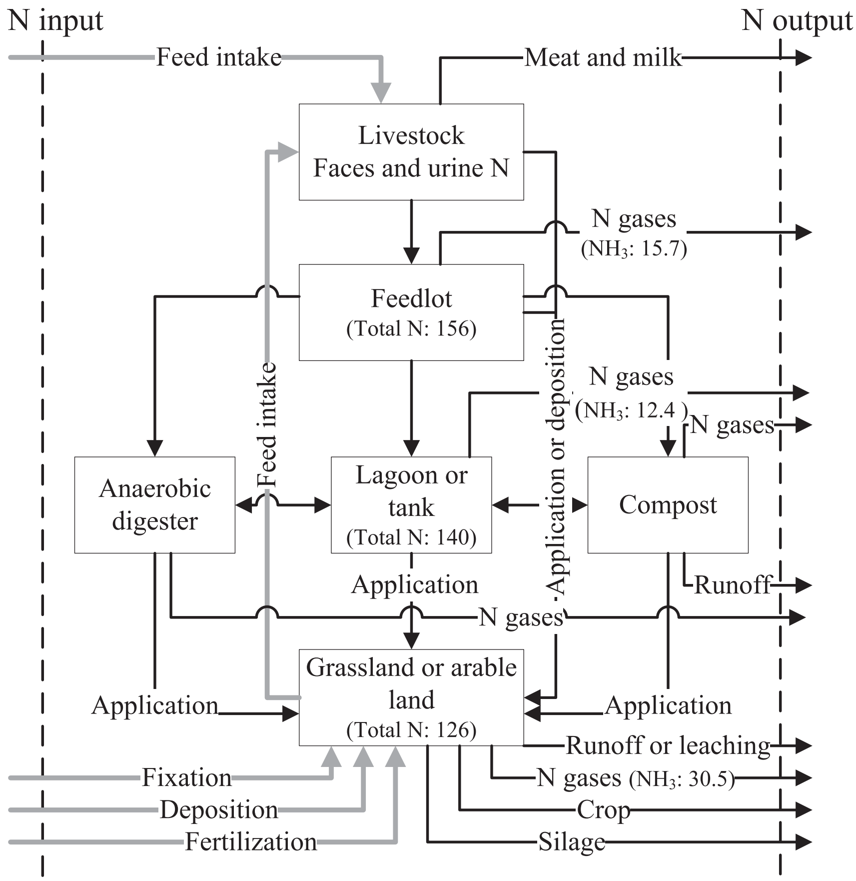

Fig. 1. Nitrogen (N) dynamics simulated by Manure-DNDC. The model tracks N inputs, outputs, and transfers among different facilities within a livestock farm based on manure life cycle. In Manure-DNDC, model inputs include climate, farm characteristics, soil properties, N inputs (gray lines), and farming management practices. The model calculates manure production and then tracks manure transfers among facilities. All N outputs (dark lines) are simulated by the model and can be compared against field data for model testing. In a dairy farm, NH_3 emission may occur in all facilities, and the N flows and NH_3 emission rates (in kg N head^{-1} yr^{-1}) shown are the simulations for a slurry-based dairy farm (the baseline scenario in Table 4). The detailed settings for the baseline management practices are described in the text.

input information included daily meteorological data (i.e., maximum and minimum air temperatures, precipitation, and wind speed) from 2007 to 2009, conditions of the farm facilities (i.e., animal inventory, housing area, floor type, bedding material, ventilation, and surface area and storage volume of the lagoon), feeding practices (i.e., intake rate of feed and CP in forage), and manure management practices (i.e., method and frequency of manure removal from the free stall barns, and residing time of manure stored in the lagoon). Because the manure slurries stored in the lagoon IN were came from the milk parlor and holding area during the experimental period (Grant and Boehm, 2010), we assumed that 15% of the excreted manure was transferred into the lagoon based on the study reported by USEPA (2004).

The field studies didn't perform on-site measurements of N excretion, although which this is an important factor regulating NH_3 emissions from barn. We estimated the N excretion rates for the barns using Equation (1), which was developed by Nennich et al. (2005) based on 550 samples.

$$NE = 84.1 \times DMI \times CP + 0.196 \times BW \quad (1)$$

Where NE is the rate of N excretion (g N head^{-1} day^{-1}), DMI is the intake rate of dry matter (kg head^{-1} day^{-1}), CP is the concentration of crude protein in forage (%), and BW is the body weight of cow (kg head^{-1}).

Driven by the input parameters set for the free stall barns and lagoon, Manure-DNDC was run from 2007 to 2009 and 2008 to 2009 for the barns and lagoon, respectively. The measured NH_3 emissions and the estimated N excretion rates were utilized for comparison to the modeled results. We used zero-intercept linear regression between simulations and observations to evaluate the model performance. The slope of the regression can examine the consistency between simulations and observations (Moriasi et al., 2007). In addition, two statistical indices, the normalized root mean squared error (RMSE) and the coefficient of correlation (R), were used for quantitative comparisons between the simulations and observations. The RMSE (Equation (2)) and R (Equation (3)) can examine the accordance and correlation between model predictions and field measurements, respectively (Moriasi et al., 2007).

$$RMSE = \frac{100}{\overline{o}}\sqrt{\frac{\sum_{i=1}^{n}(p_i - o_i)^2}{n}} \quad (2)$$

$$R = \frac{\sum_{i=1}^{n}(o_i - \overline{o})(p_i - \overline{p})}{\sqrt{\sum_{i=1}^{n}(o_i - \overline{o})^2 \sum_{i=1}^{n}(p_i - \overline{p})^2}} \quad (3)$$

Where o_i and p_i are the observed and simulated values, respectively, $\overline{o}$ and $\overline{p}$ are their averages, and n is the number of values.

Table 2
The settings of baseline and alternative scenarios.

Scenarios	Farming management practices
Baseline	Feeding rate: 24.2 kg head^{-1} day^{-1}; CP: 16%; MRM: scrape; open lagoon; the manure in lagoon was removed one time per year; manure application: surface spreading.
AS1	Baseline + CP: 13%.
AS2	Baseline + flushing with recycled liquid urine to remove manure in barn.
AS3	Baseline + covered lagoon.
AS4	Baseline + the manure in lagoon was removed two times per year.
AS5	Baseline + the manure in lagoon was incorporated into crop fields.
AS6	Feeding rate: 24.2 kg head^{-1} day^{-1}; CP: 13%; MRM: flushing; covered lagoon; the manure in lagoon was removed two times per year; manure application: incorporation.

CP: the concentration of crude protein in forage; MRM: manure removal method.

2.3.2. *Investigating impacts of management practices on NH_3 emission*

A scenario analysis was performed to investigate impacts of alternative management practices on NH_3 emissions at the farm scale. A group of management scenarios were designed to represent conventional and alternative farming management practices. A slurry-based dairy farm located in Indianan was selected as the target farm. Model inputs were set to represent the farm facilities and management practices commonly used in this region. The farm consisted of two free stall barns, a lagoon used for manure storage, and crop fields where manure was applied. The barns totally held 3400 dairy cows. The average feeding rate was 24.2 kg dry matter head^{-1} day^{-1} with CP of 16%. Both barns were naturally ventilated and each had a concrete floor with a surface area of 3850 m^2. The manure accumulated on the two floors was scraped and then transferred into the lagoon on a daily basis. The lagoon was uncovered, and had a surface area of 34,400 m^2 and a maximum storage capacity of 172,000 m^3. The manure stored in the lagoon was removed one time annually and applied to the surface of the crop fields (2700 ha) before planting (May 1). The crop fields were planted with corn (1800 ha) and alfalfa (900 ha). The portions of the manure applied to the corn and alfalfa fields were 70% and 30%, respectively. The local soil properties were determined based on the SSURGO database from the Natural Resources Conservation Service, U. S. Department of Agriculture (available online at http://websoilsurvey.nrcs.usda.gov/). The soil was a loamy sand with pH (H_2O) 6.7, bulk density 1.14 g cm^{-3}, and content of soil organic carbon 0.017 kg C kg^{-1} soil dry weight. The actual farming management practices in the dairy farm were set as baseline scenario.

Five alternative scenarios were set by exclusively modifying a farming management practice applied under the baseline scenario, including the feed quality, manure removal method, lagoon coverage, frequency of lagoon manure removal, or method of applying manure into the fields, to investigate impacts of each management practice on NH_3 emission. The five alternative scenarios were as follows (Table 2): (1) reducing the CP in forage from the baseline level of 16%–13% (AS1); (2) changing the method of scraping into flushing with recycled manure liquid for barn manure removal (AS2); (3) covering the open lagoon (AS3); (4) increasing manure removal frequency from one to two times per year for the lagoon and the manure was applied to the surface of the fields on May 1 and October 15 (AS4); and (5) changing the method of field manure application from surface spreading to incorporation (AS5). In addition, we set another scenario (AS6) by combining all the changes made from AS1 to AS5. In AS6, a series of farming management practices were modified in comparison with the baseline (Table 4). The Manure-DNDC was run for 2007 and 2008 with the baseline and six alternative scenarios. Climate, soil, and other management practices were kept the same for the simulations under different scenarios. The modeled NH_3 emissions from each farm facility and the whole farm in 2008 were collected for analysis.

3. Results and analyses

3.1. *Model validation*

3.1.1. *Rates of N excretion*

By using the Equation (1), the rates of N excretion were calculated as 334, 443, 457, 403, and 403 g N head^{-1} day^{-1}, respectively, for the barn 1 to barn 5. The corresponding rates simulated by Manure-DNDC were 308, 418, 436, 348, and 348 g N head^{-1} day^{-1}, respectively. The modeled N excretion rates were comparable with the calculated rates, with the RMSE values ranged from 5% to 14% (mean: 9%) across the five barns. These results indicate that Manure-DNDC was capable of quantifying N excretion rates for the test barns.

3.1.2. *NH_3 emissions from free stall barns*

Figs. 2–4 illustrate seasonal variations of the measured and simulated daily NH_3 fluxes from the barns. The daily measurements showed similar seasonal patterns across the barns 1–5 when the manure accumulated on floors was removed with the scraping method. However, the magnitudes of daily NH_3 fluxes highly varied across the barns due to the differences in animal inventory, climate, housing conditions, and feeding practices (Figs. 2–4). When the manure was removed by flushing the floors with recycled liquid urine (i.e., during September 2007 to September 2008 in the barns

Table 3
Comparison of the simulated and measured annual total ammonia (NH_3) emissions.

	Periods	NH_3 emissions (kg N head^{-1} yr^{-1})			NH_3 emissions (kg N yr^{-1})		
		Simulated	Measured	RMSE[a]	Simulated	Measured	RMSE
Barn 1	Dec. 2007–Nov. 2008	13.8	14.6	6	6473	6857	6
	Dec.2008–Nov. 2009	13.5	12.1	11	6276	5651	11
Barn 2	Nov. 2007–Oct. 2008	15.6	15.0	4	13,202	12,688	4
	Nov. 2008–Oct. 2009	14.2	16.8	15	11,783	13,962	15
Barn 3	Nov. 2007–Oct. 2008	16.2	14.3	14	14,180	12,475	14
	Nov. 2008–Oct. 2009	14.8	13.9	7	12,768	11,954	7
Barn 4	Nov. 2007–Oct. 2008	10.6	11.0	4	2232	2317	4
	Nov. 2008–Oct. 2009	12.2	13.4	9	2547	2779	9
Barn 5	Nov. 2007–Oct. 2008	10.6	8.8	21	3754	3109	21
	Nov. 2008–Oct. 2009	12.2	10.2	20	4386	3651	20
Lagoon	Sep. 2008–Aug. 2009				6282	7090	11

[a] RMSE, normalized root mean squared error (%).

Table 4
The simulated nitrogen (N) flows and annual ammonia (NH_3) emissions for a dairy farm under baseline (B) and alternative scenarios (AS1 to AS6).

	B[a]	AS1	AS2	AS3	AS4	AS5	AS6
Cow number	3400	3400	3400	3400	3400	3400	3400
CP (%)[b]	16	13	16	16	16	16	13
N intake rate (kg N head^{-1} yr^{-1})	226	184	226	226	226	226	184
N excretion rate (kg N head^{-1} yr^{-1})	156	127	156	156	156	156	127
NH_3 emissions from barns (kg N head^{-1} yr^{-1})	15.7	12.8	13.2	15.7	15.7	15.7	10.8
N imported into lagoon (kg N head^{-1} yr^{-1})	140	114	143	140	140	140	116
NH_3 emissions from lagoon (kg N head^{-1} yr^{-1})	12.4	11.3	8.4	2.8	12.7	12.4	1.5
N applied into crop fields (kg N ha^{-1} yr^{-1})	159	127	168	171	160	159	144
NH_3 emissions from crop fields (kg N ha^{-1} yr^{-1})	38.4	29.5	42.2	43.5	33.9	23.8	21.6
NH_3 emissions from crop fields (kg N head^{-1} yr^{-1})	30.5	23.4	33.5	34.6	26.9	18.9	17.2
NH_3 emissions from whole farm (kg N head^{-1} yr^{-1})	58.6	47.5	55.2	53.1	55.4	47.0	29.5
NH_3 emissions from farm/Manure-N (%)	38%	37%	35%	34%	35%	30%	23%

[a] The detailed settings for baseline and alternative management practices are described in the text and Table 2.
[b] CP, the concentration of crude protein in forage.

4 and 5), the seasonal pattern of daily NH_3 fluxes changed, with relative lower rates in summer as compared to the scraping method (Fig. 4). In comparison with the measurements, Manure-DNDC successfully captured the seasonal characteristics and magnitudes of daily NH_3 fluxes, although a few discrepancies existed (Figs. 2–4). The R values ranged between 0.72 and 0.90 across these five barns and were statistically significant ($P < 0.001$) for all cases (Figs. 2–4), indicating that the simulated daily NH_3 fluxes were highly correlated to the observations for all the barns. Fig. 5a–e shows significant zero-intercept linear regressions of the simulated daily NH_3 fluxes against the measurements, with the slopes ranged between 0.92 and 1.23 across the barns. If the daily NH_3 fluxes from all the test barns were included for analysis, the slope of the linear regression equaled to 1.03 (Fig. 5f). These results indicate that Manure-DNDC successfully predicted the daily NH_3 fluxes although the accuracies varied across the barns.

The Manure-DNDC results indicate that the variations of daily NH_3 fluxes closely related to air temperature. For example, low temperature showed a restricting effect on the modeled NH_3 fluxes as temperature is a determinate factor affecting urea hydrolysis, NH_3 volatilization, and other relevant processes embedded in Manure-DNDC. As a result, the model predicted obvious decrease of NH_3 fluxes during the winter season (Figs. 2–4).

We calculated annual total NH_3 emissions for each barn (totally 10 years for 5 barns). Of the 10 studied years, the measured annual NH_3 emissions varied from 2317 to 13,962 kg N yr^{-1} with a mean of 7977 kg N yr^{-1}. The corresponding simulations ranged from 2232 to 14,180 kg N yr^{-1} with a mean of 8135 kg N yr^{-1} (Table 3). The values of RMSE between the simulated and observed annual emissions ranged between 4% and 21% with a mean of 11%. The results suggest that the model reliably predicted the annual total NH_3 emissions for the test barns.

As Table 3 lists, both the simulations and field measurements showed a great variation in annual total NH_3 emissions across the barns that were apparently related to the difference in herd size. However, other factors could also contribute to the variation in annual NH_3 emissions, which can be testified by the different emission rates per head cow across the studied years (Table 3). The model results indicate that the rates of NH_3 emission were jointly affected by climate, feeding practice, and manure removal method, in addition to the herd size. For example, of the 10 studied years, Manure-DNDC predicted the lowest rate of annual NH_3 emission (10.6 kg N head^{-1} yr^{-1}) in the barn 5 during 2007–2008 (Table 3); which was primarily due to the low air temperature (Table 1) and the decreased emission rates during the summer when the barn was flushed with recycled liquid urine.

3.1.3. NH_3 emissions from lagoon

Fig. 6a illustrates the simulated and observed daily NH_3 fluxes from the lagoon IN. Manure-DNDC generally captured the seasonal pattern of the NH_3 emissions from the lagoon IN, although

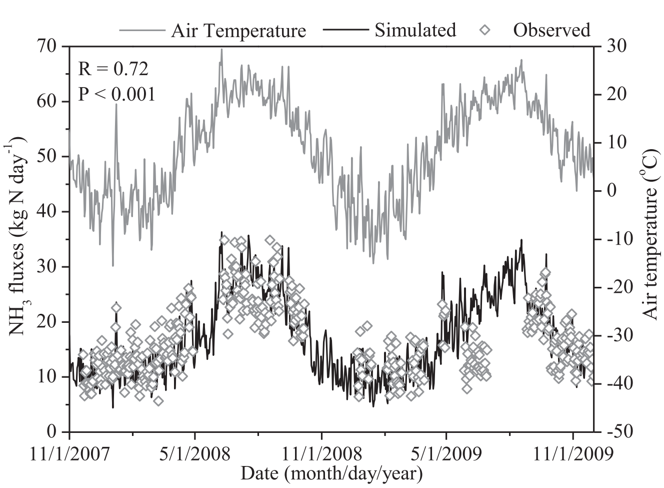

Fig. 2. Daily air temperatures, and simulated and measured daily NH_3 fluxes at the barn in NY. Note that Manure-DNDC simulates NH_3 fluxes at a daily step, and the measurements are the daily means with substantial diurnal variations (not shown for reasons of clarity).

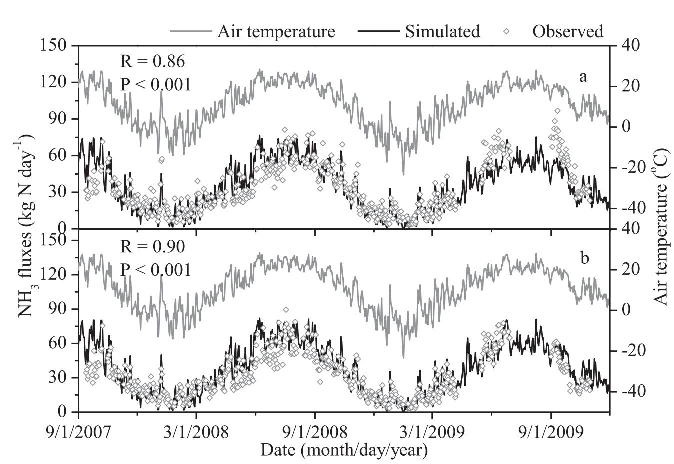

Fig. 3. Daily air temperature, and simulated and measured daily NH_3 fluxes at the (a) barn 2 and (b) barn 3 in IN. Note that Manure-DNDC simulates NH_3 fluxes at a daily step, and the measurements are the daily means with substantial diurnal variations (not shown for reasons of clarity).

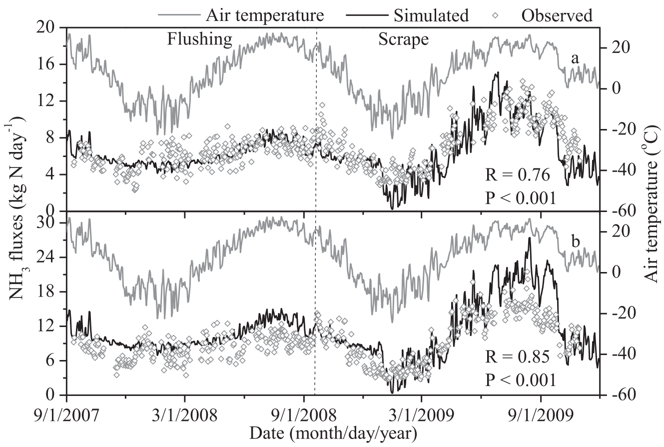

Fig. 4. Daily air temperature, and simulated and measured daily NH_3 fluxes at the (a) barn 4 and (b) barn 5 in WI. Note that Manure-DNDC simulates NH_3 fluxes at a daily step, and the measurements are the daily means with substantial diurnal variations (not shown for reasons of clarity).

discrepancies existed. The R value between the simulated and observed daily NH_3 fluxes was 0.82, indicating that a significant correlation ($P < 0.001$; Fig. 6a) remained between the simulations and observations for this case. As Fig. 6b shows, a significant zero-intercept linear regression was obtained to relate the simulations to the observations of the daily NH_3 fluxes. The slope of the regression was 0.79.

The simulation of the annual total NH_3 emission was 6282 kg N yr^{-1} for the lagoon IN, which was comparable with the corresponding measurement (7090 kg N yr^{-1}, Table 3). The comparison between the modeled and observed results indicates that the model reliably predicted the annual total NH_3 emission from the lagoon IN (RMSE: 11%).

3.2. Impacts of management practices on NH_3 emissions at the farm scale

Table 4 lists the simulated NH_3 emissions under the baseline and alternative scenarios. For the baseline, the rates of annual total N intake and N excretion were 226 and 156 kg N head^{-1} yr^{-1}, respectively. The rates of annual total NH_3 emissions from the barns, lagoon, and crop fields were 15.7, 12.4, and 30.5 kg N head^{-1} yr^{-1}, respectively. At the farm scale, the rate of NH_3 loss was 58.6 kg N head^{-1} yr^{-1}, an amount that comprises 38% of the excreted N.

All the changes in farming management practices under the alternative scenarios can mitigate NH_3 emissions from one or more components within the dairy farm (Table 4). Reducing CP from 16% to 13% (AS1, Table 2) decreased the rate of N intake (184 vs. 226 kg N head^{-1} yr^{-1}). This option can reduce the rate of N excretion and thereby can mitigate the NH_3 emissions from all the facilities within the dairy farm. The rates of NH_3 emission were

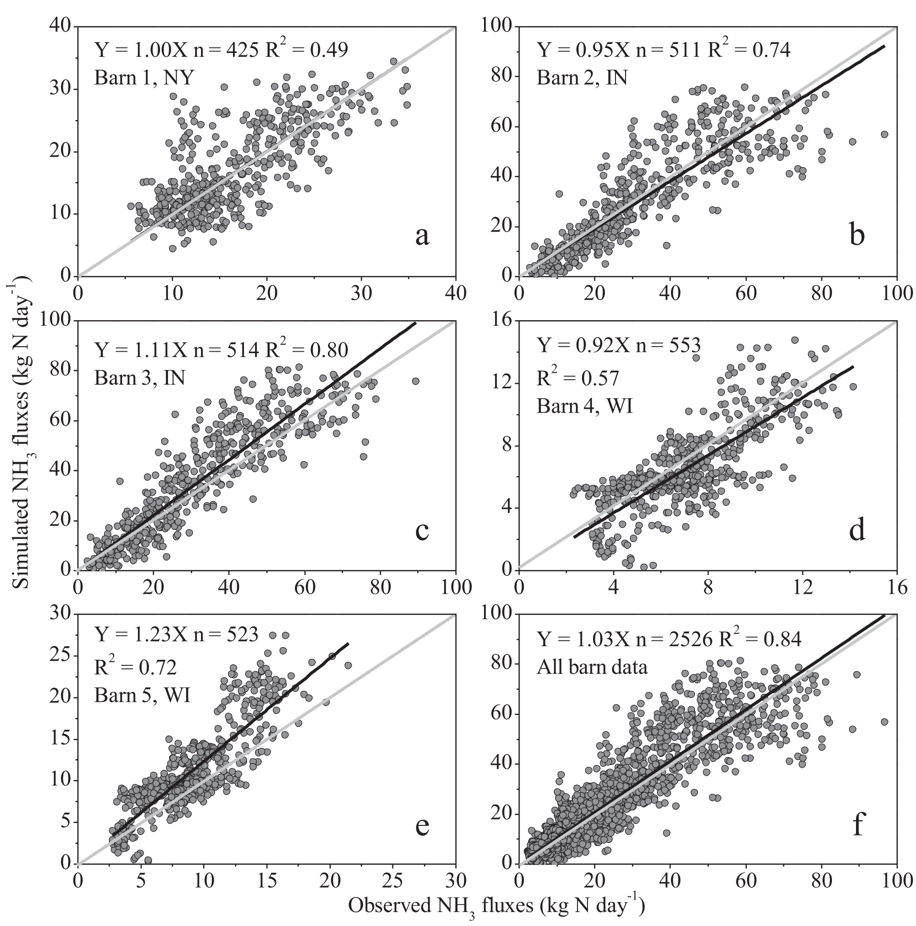

Fig. 5. Comparisons between the simulated and measured daily NH_3 fluxes from the barns. The black and gray lines represent the zero-intercept linear regression and 1:1 lines, respectively. The regressions of the simulated daily NH_3 fluxes against the measurements were significant ($P < 0.001$) for all cases. The functions shown describe the regression lines.

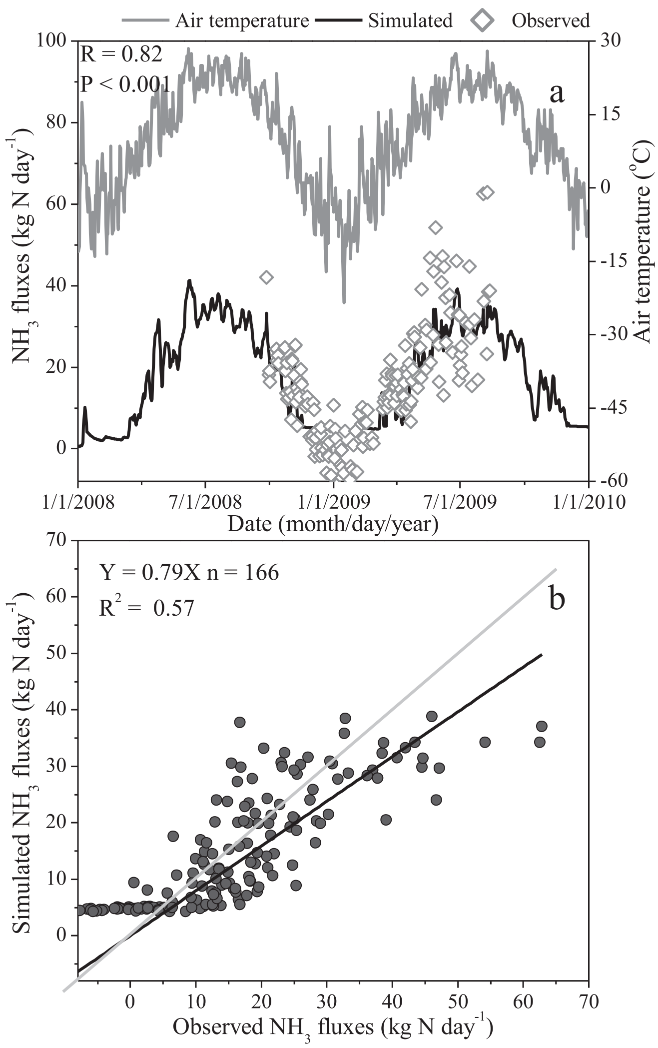

Fig. 6. Daily air temperature, and simulated and measured daily NH_3 fluxes (a) and comparisons between the simulations and measurements (b) at the lagoon IN. Manure-DNDC simulates NH_3 fluxes at a daily step, and the measurements were calculated as means of half-hour measurements when there were at least 25 valid half-hour values throughout the day. Diurnal variations of NH_3 fluxes are not shown for reasons of clarity. Note that the observed negative emissions during the winter were likely a result of the observed near-minimum-detectable NH_3 concentrations in combination with NH_3 transported to the lagoon from surrounding barns (Grant and Boehm, 2010), and were responsible for constantly higher simulations during the winter season. The black and gray lines represent the zero-intercept linear regression and 1:1 lines, respectively. The regressions of the simulated daily NH_3 fluxes against the measurements were significant ($P < 0.001$). The function shown describes the regression line.

decreased by 19%, 8%, 23%, and 19%, respectively, for the barns, lagoon, crop fields, and whole farm. Compared to the baseline, removing the manure by flushing the barns with recycled liquid urine (AS2, Table 2) decreased the NH_3 losses from the barns and lagoon by 16% (13.2 vs. 15.7 kg N head^{-1} yr^{-1}) and 32% (8.4 vs. 12.4 kg N head^{-1} yr^{-1}), respectively; but increased the NH_3 losses from the crop fields by 10% (33.5 vs. 30.5 kg N head^{-1} yr^{-1}) because more manure-N was applied to the fields (Table 4). The rate of NH_3 emissions from the whole farm was mitigated by 6% (55.2 vs. 58.6 kg N head^{-1} yr^{-1}) under this scenario. Covering the lagoon (AS3, Table 2) substantially reduced the NH_3 emissions from the lagoon by 77% (2.8 vs. 12.4 kg N head^{-1} yr^{-1}). However, because of the increase in the N transferred from the lagoon into the crop fields, the NH_3 losses from the crop fields were increased by 13% (34.6 vs. 30.5 kg N head^{-1} yr^{-1}, Table 4); which greatly offset the mitigation of NH_3 losses from the lagoon. Compared to the baseline, the NH_3 emissions from the whole farm were reduced by 10% (53.1 vs. 58.6 kg N head^{-1} yr^{-1}) under AS3. In AS4, the manure stored in the lagoon was removed two times per year and was applied to the surface of the crop fields on May 1 and October 15. As compare to the baseline, this strategy slightly reduced the rate of NH_3 emissions from the farm by 5% (55.4 vs. 58.6 kg N head^{-1} yr^{-1}) through mitigating the field NH_3 emission (26.9 vs. 30.5 kg N head^{-1} yr^{-1}). Changing the method of field manure application from the surface spreading into manure incorporation (AS5, Table 2) mitigated the NH_3 emissions by 38% (18.9 vs. 28.1 kg N head^{-1} yr^{-1}) for the crop fields and by 20% (47.0 vs. 58.6 kg N head^{-1} yr^{-1}) for the whole farm. In this study, AS6 was set to represent the improvements of farming management practices from feeding to manure application (Table 2). AS6 can mitigate the NH_3 emissions from all the facilities within the dairy farm (Table 4). Compared to the baseline, the rate of NH_3 emissions from the whole farm under AS6 were mitigated by 50% (29.5 vs. 58.6 kg N head^{-1} yr^{-1}).

4. Discussions

4.1. Validation of Manure-DNDC

For most dairy farms in the U.S., the feed N use efficiencies are only approximately 15–35% (e.g., Gourley et al., 2012; Haynes and Williams, 1993; Powell et al., 2006). Along with large amounts of N excretion, dairy production systems have been regarded as hot-spots of NH_3 emission (Place and Mitloehner, 2010). In this study, we tested a process-based biogeochemical model, Manure-DNDC, against NH_3 emissions from a number of dairy production systems. Given the large variability of the NH_3 emissions across the tested facilities, we are encouraged by the model performance because the simulations of annual total NH_3 emission were consistent with the observations across the facilities (Table 3). The simulated annual NH_3 emissions from the barns (ranged between 10.6 and 16.2 kg N head^{-1} yr^{-1}) and lagoon IN (10% of the N entering the lagoon) were also within the reported ranges of NH_3 emissions from dairy barns (4.0–25.6 kg N head^{-1} yr^{-1}) and manure storage lagoons (6%–42% of the N entering lagoons) in Europe (Groot Koerkamp et al., 1998; Misselbrook et al., 2000; Snell et al., 2003; Webb and Misselbrook, 2004). In addition, the model generally captured both the magnitudes and seasonal patterns of daily NH_3 fluxes for the barns and lagoon IN (Figs. 2–6). These results suggest the potential of utilizing Manure-DNDC to serve the quantification of NH_3 emissions, which are usually highly variable across different seasons and dairy production systems (Harper et al., 2009; Place and Mitloehner, 2010).

However, we also noticed a few discrepancies between the modeled and measured results. For example, Manure-DNDC overestimated the NH_3 fluxes in June 2009 for the barn 1 (Fig. 2) and during July to September 2009 for the barn 5 (Fig. 4b), and underestimated the fluxes from the lagoon on a few days during May to early August 2009 (Fig. 6a). These discrepancies between the simulations and field measurements could be partially explained by the uncertainties in the field records of NH_3 emission, which varied from 6.6% to 11.6% across the tested barns (Bogan et al., 2010; Lim et al., 2010; Cortus et al., 2010) and were around 20% for the lagoon (Grant and Boehm, 2010). In addition, there are uncertainties in model inputs. For example, daily animal inventory and feeding practices were set as constants throughout the simulation periods for each farm, although minor variations occurred under the actual conditions. Because daily animal inventory and feeding practices have influences on N excretion, potential biases in these inputs could affect the simulated NH_3 fluxes. We also set that

15% of the excreted manure was transferred from the milk parlor and holding area into the lagoon IN as the farm-specific value was unavailable. Because the amount of manure come from an upstream facility, such as milk parlor and holding area, can affect concentration of N in lagoon, potential biases in this setting could affect the simulated NH_3 fluxes from the lagoon IN. Discrepancies may also have resulted from model deficiency or over-simplification. For example, Manure-DNDC simulated average environmental conditions for the lagoon IN by assuming the lagoon was relatively well mixed, and therefore did not consider the impacts of stratification on lagoon conditions. Because the temperature at the lagoon surface is usually higher than the average temperature or the temperature at the bottom for relatively deep lagoons during warm periods (e.g., Lovanh et al., 2009; VanderZaag et al., 2010), this simplified approach may underestimated the surface temperature of the lagoon IN, and therefore should be partially responsible for the under-prediction of the NH_3 fluxes during May to early August 2009 and the slope of 0.79 (Fig. 6). Further studies reducing uncertainties in both the measured gas fluxes and basic input information and improving over-simplified processes could reduce the discrepancies between the simulations and measurements. In addition, there remained a few discrepancies that can hardly be explained by existing field information. At the WI farm, the model generally captured the daily NH_3 fluxes from the barn 4 (Fig. 4a), but overestimated the fluxes from the barn 5 during certain periods (Fig. 4b), even though these two barns had similar climate, barn design, and management practices (Table 1), causing Manure-DNDC predicted same emission rates (in per cow, Table 3). Further studies are needed to clarify the differences in NH_3 fluxes between the two barns at the WI farm, as well as the inconsistencies between the predictions and observations for the barn 5.

It may be noteworthy that the modeled NH_3 emissions from the manure applied to crop fields have not been validated in this study due to that we lacked field measurements, including both NH_3 data and input information, to support the Manure-DNDC validation. Therefore, the modeled NH_3 fluxes from crop fields remain uncertain. However, under the baseline scenario, the simulated annual NH_3 emission from the crop fields was 24% of the manure-N (or 64% of the NH_4–N) applied (Table 4), which was close to a world average value of 23% (ranged from 19 to 29%) of the manure-N applied (Bouwman et al., 2002) and was also comparable with the reported field NH_3 emissions from the dairy manure application in the U.S. (ranged between 40% and 100% of the NH_4–N applied) (Meisinger and Jokela, 2000) and in Europe (ranged between 32% and 83% of the NH_4–N applied) (Misselbrook et al., 2002; Reidy et al., 2008). The modeled impact of manure incorporation on reducing NH_3 emissions from the crop fields (mitigated the NH_3 emissions by 38%) was also in agreement with the studies (e.g., Bouwman et al., 2002; Misselbrook et al., 2002; Sommer and Hutchings, 2001; Webb et al., 2009), which reported approximately 20%–50% reduction by incorporating manure in comparison with surface spreading. These results may suggest that Manure-DNDC reasonably predicted NH_3 emissions from the manure applied to crop fields. However, further tests directly comparing the modeled and measured NH_3 fluxes are necessary to verify the model's capacity on predicting field losses of NH_3 from manure.

4.2. *Impacts of management alternatives on NH_3 emission*

In this study, simulations were performed to investigate impacts of alternative management practices on NH_3 emissions at the farm scale. Compared to the baseline, a 50% reduction can be achieved for the NH_3 emissions from manure under AS6, in which a series of farming management practices have been improved (Table 2). Given that the N bound in manure can be recycled into crop fields to replace synthetic fertilizers, the efforts to mitigate NH_3 emissions from manure can further alleviate the detrimental environmental consequences induced by applying synthetic N (Smith et al., 2008). The model results also demonstrate that a specific management practice could simultaneously affect NH_3 released from several facilities within a dairy farm due to interactions among facilities. For instance, the Manure-DNDC simulations indicate that adding a cover (AS3, Table 2) may substantially reduce the NH_3 emissions from lagoon (2.8 vs. 12.4 kg N head^{-1} yr^{-1}). While this conclusion is consistent with a number of studies (e.g., Hornig et al., 1999; Petersen and Sommer, 2011; VanderZaag et al., 2010), the AS3 also increased the NH_3 emissions from crop fields as compare to the baseline (43.5 vs. 38.4 kg N head^{-1} yr^{-1}, Table 4), which would no doubt offset some of the gains resulted from mitigating the NH_3 emissions from lagoon. The simulations emphasize the necessity of a whole-farm approach, such as Manure-DNDC, on the assessment of potential strategies for NH_3 mitigation. Interactions may also exist between losses of NH_3 and other forms of N. For example, incorporation of manure may increases N leaching and/or N_2O emissions (e.g., Webb et al., 2010) from crop fields, although this technique usually decreases NH_3 emission in comparison with surface spreading. The tradeoffs between losses of NH_3 and other forms of N should be considered on evaluating the mitigation of NH_3 emission.

In addition to the farming management practices investigated in this study, other practices, such as cooling feedlots and facilities used for manure storage, manure dilution, manure acidification, and adding urease inhibitor, among others, may provide opportunities to further mitigate NH_3 emissions from dairy farms (e.g., Arogo et al., 2006; Ndegwa et al., 2008). The impacts of these practices should be further investigated through both field studies and modeling efforts.

To mitigate the increasing detriments to environments from food productions (e.g., FAO, 2006), researchers, land managers, and policy makers are looking for tools that are capable of assessing impacts of agricultural activities on both food production and environmental sustainability. The majority of livestock farms are complex systems in which livestock and cropping systems are managed comprehensively. Therefore it is necessary to integrate livestock facilities and cropping systems when assessing the impacts of alternative practices on environmental issues in livestock production (Petersen and Sommer, 2011). The farm-scale simulations shown in this study illustrate the potential of utilizing process-based models, such as Manure-DNDC, to serve the mitigation of detrimental environmental consequences in livestock production, such as the mitigation of NH_3 emission.

5. Conclusions

In this study, a process-based biogeochemical model, Manure-DNDC, was tested against measurements of NH_3 fluxes from five barns and one lagoon in four dairy farms over a range of environmental conditions and management practices in the United States. Results from the validation tests indicate that the magnitudes and seasonal patterns of the simulated NH_3 fluxes were in agreement with the observations. The model was then applied to assess impacts of alternative management practices on NH_3 emission at the farm scale. The simulations under the alternative management practices demonstrate that: (a) all the tested alternative management practices decreased the NH_3 emissions although the efficiency of mitigation varied; (b) a change of management in an upstream facility affected the NH_3 emissions from all downstream facilities; and (c) an optimized strategy by combining the alternative practices on feed, manure removal, manure storage, and land application could reduce the farm-scale NH_3 emission by up to 50%. The results from this study may provide useful information for mitigating NH_3 emissions from dairy production systems and emphasize the necessity of whole-farm perspectives on the assessment of potential technical options for NH_3 mitigation.

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