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An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices

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HIGHLIGHTS

- The Canadian-specific NH_3 emission model was revised and improved for dairy farming.
- NH_3 emissions inventory of Ontario dairy cattle was quantified.
- Manure land application has greater emission potential than other stages in Ontario.
- Effects of mitigating practices on NH_3 emissions were evaluated with the model.

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ABSTRACT

The Canadian ammonia (NH_3) emissions model and a survey of dairy farm practices were used to quantify effects of management on emissions from dairy farms in Ontario Canada. Total NH_3 emissions from dairy farming were 21 Gg NH_3–N yr^{-1} for the four ecoregions of the province. Annual emission rates ranged from 12.8 (for calves in ecoregions of Manitoulin-Lake Simcoe-Frontenac) to 50 kg NH_3–N $animal^{-1}$ yr^{-1} (for lactating cows in ecoregions of St. Lawrence Lowlands) (mean of 27 kg NH_3–N $animal^{-1}$ yr^{-1}). The St. Lawrence Lowlands ecoregion had the highest emission rate because more dairy manure was managed as solid manure in that ecoregion. Total dairy cattle N intake (diet-N) was 81 Gg N yr^{-1}, 23% of which was retained in animal products (e.g., milk, meat, and fetus), 47% was returned to the land, and 30% was emitted as gas (i.e., NH_3–N, N_2O–N, NO–N, and N_2–N) and nitrate-N leaching/runoff. Ammonia volatilization constituted the largest loss of diet-N (26%), as well as manure-N (34%). Reducing the fraction of solid manure by 50% has the potential to mitigate NH_3 emissions by 18% in Ontario ecoregions.

1. Introduction

Ammonia (NH_3) is an important agricultural air pollutant (e.g., fine particulate matter precursor) and impacts the health of humans and animals that are in confined animal housing systems (NRC, 2003; Ni, 2015). Furthermore, it results in nutrient losses from agricultural ecosystems (Drury et al., 2012; Yang et al., 2011; Sheppard and Bittman, 2013), contributes to indirect greenhouse gas (GHG) emissions, and causes environmental problems through surface water eutrophication and acidification of terrestrial ecosystems (Renard et al., 2004; Hristov et al., 2011; McClean et al., 2011). Quantifying NH_3 emissions and identifying primary emission sources are important steps in developing country- and region-specific strategies and policies for mitigating emissions and improving manure-N use efficiency (Janzen et al., 2006; Ndegwa et al., 2008).

Animal feeding operations are identified as the dominant

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sources of anthropogenic NH_3 emissions and dairy farming is one of the major contributors in North America and Europe (Webb, 2001; Powell et al., 2008a, b; Flesch et al., 2009; Sheppard and Bittman, 2010). About 85% of atmospheric NH_3 was contributed by agricultural activities (78% from animal manure and 22% from fertilizer) in Canada (Sheppard and Bittman, 2010). National and regional NH_3 emissions from dairy farming usually are quantified with mathematical emission models (Pinder et al., 2004; Sheppard et al., 2011a) such as a mass balance approach based on total ammoniacal nitrogen (TAN) content in animal manure (Webb and Misselbrook, 2004; Reidy et al., 2008, 2009).

Most existing mass balance models/approaches (Webb and Misselbrook, 2004; Velthof et al., 2012) start from N excretion instead of N intake when quantifying dairy farming NH_3 emissions inventory, which does not consider N intake and utilization by of the animals. The current Canadian NH_3 model considered N intake but not diet compositions (Sheppard et al., 2011a). For those models the fraction of urinary-N excretion (initial source of NH_3 volatilization) in dairy cattle manure is an assumed fixed value (e.g., 0.6 or 0.5), which fails to respond to variation in diet composition for the various animal subcategories and production stages. It is well known that the urinary-N fraction (TAN fraction) for cattle manure varies with crude protein (CP) content of the animal's diet (Fisher et al., 2000; Waldrip et al., 2013; Dong et al., 2014). In addition, manure-N transformations between organic N and inorganic N (e.g., immobilization, mineralization, nitrification and denitrification of N compounds), N leaching/runoff, as well as emissions of N_2O, NO, and N_2 are not considered or are extremely simplified in most existing models/approaches. We argue that to reflect country- or region-specific production practices and conditions reliably in NH_3 emission inventories, TAN fractions and manure-N transformation factors need to be refined and used.

Impacts of animal feeding and manure management practices on NH_3 emissions vary regionally because climate conditions, cropping, and other factors are not uniform across most countries (Webb and Misselbrook, 2004; Sheppard et al., 2011a). Canadian agricultural land is grouped into 12 ecoregions based on attributes of soil and climate (Sheppard et al., 2009). Dairy farming management practices including diet management and manure handling differs across ecoregions with varying climate conditions (Sheppard et al., 2011b).

Ontario produces about one-third of the Canada's annual milk production and is an ideal starting location for developing an ecoregion dairy farming NH_3 emissions inventory to build a region-specific national emissions inventory and beneficial management practices (BMPs) in Canada (Environment Canada, 2013; Jayasundara and Wagner-Riddle, 2014).

The objectives of this study were to (1) refine the NH_3 emissions inventory from dairy farming with an improved Canadian agricultural NH_3 mass flow model based on changes in dairy cattle dietary CP and manure TAN content; (2) identify the primary influential factors affecting emission rates; and (3) evaluate the effect of potential options for mitigation of NH_3 emissions from dairy farming in Ontario's four ecoregions.

2. Materials and methods

2.1. Emission model

A Canadian NH_3 emissions model (Holos-NH_3, Fig. 1) was refined based on the model used in Sheppard et al. (2011a) by including a relationship that modifies TAN in animal manure based on animal crude protein (CP) intake. The Holos-NH_3 model was used to process Canadian-specific information of dairy cattle feed based on the Livestock Farm Practices Survey (LFPS) of dairy management practice and Ontario dairy farm operations (Dairy Farmers of Ontario, 2007; Sheppard et al., 2011a, b), and provide manure N excretion rates and TAN fractions that were subsequently distributed to manure management systems identified in the LFPS. From these feed and manure handling information, estimates of NH_3 emissions from lactating cows, dry cows, heifers for replacement, calves (<1 year), and breeding bulls were developed.

The Holos-NH_3 model utilized some concepts from the model used by Sheppard et al. (2011a) including NH_3 emission fractions and manure management information. However, the Holos-NH_3 model includes some new algorithms and approaches for estimating animal N intake and excretions, manure TAN fractions, N-transformations (mineralization, immobilization, nitrification and denitrification), and calculations of N_2O, NO, and N_2 emissions and NO_3–N leaching/runoff during manure storage. In addition, some model parameters were refined (e.g., updated emission factors for liquid manure scraping and flushing) based on U.S. National Air Emissions Monitoring Study (NAEMS) (Bogan et al., 2010; Ramirez-Dorronsoro et al., 2010).

Unlike the beef cattle NH_3 emissions model for Alberta Canada (Chai et al., 2014), the Holos-NH_3 model for dairy farming includes different manure management and housing systems as well as application systems that impact emission rates, specifically slurry/liquid manure systems of collection (manure scraping and flushing from barns and milking parlors), storage (tank, slurry pit, and lagoon/earthen storage), and land application (e.g., slurry spreading, drop hose banding, and shallow and deep injection), using TAN-based emission factors [EFs, kg (NH_3–N) (kg TAN)$^{-1}$] developed for each manure handling system.

2.2. Weather and animal information (housing and grazing)

The agricultural land of Ontario is located in four ecoregions: Boreal Shield (BSD), St. Lawrence Lowlands (SLL), Manitoulin-Lake Simcoe-Frontenac (MLSF), and Lake Erie Lowland (LEL) (from north to south; Sheppard et al., 2011a). The BSD has a lower monthly air temperature and LEL has a higher air temperature than the other two ecoregions throughout the year (Vincent et al., 2012). As air temperature is an important factor affecting NH_3 volatilization (Sheppard et al., 2011a), ecoregion 30-year (1981–2010) monthly normal temperatures (Fig. 2) were derived by averaging 30-year monthly normal temperatures by ecodistrict (a further subdivision of ecoregion with relatively homogeneous biophysical and climatic conditions) within each ecoregion (Vincent et al., 2012).

Animal activity data (e.g., housing and grazing time, milk production, and diet composition) and manure management information in Ontario ecoregions were derived from the LFPS data (Sheppard et al., 2011a, b). There were 782,077 dairy cattle in Ontario in 2006 (Statistics Canada, 2012), distributed in the four ecoregions (Table 1). Most dairy cattle (58%) were located in the MLSF. About 42% of Ontario dairy cattle were mature cows, of which at any one time 84% were lactating (Sheppard et al., 2011a). General animal information of live body weight, average daily gain, and milk production were estimated based on default values recommended in the Holos model (Little et al., 2013) that were derived from Ontario dairy farm operations (Dairy Farmers of Ontario, 2007). The information agrees well with the National Greenhouse Gases Reports for Ontario (Liang and MacDonald, 2014).

Dairy cattle in Ontario are mainly held in barns and standing yards, with some time (about four hours per day for lactating cows and 10 h per day for dry cows on average across Canada) spent on pasture in summer (Sheppard et al., 2011b). Two main types of housing are used: free-stall barns and tie-stall barns. The free-stall barns are generally equipped with holding areas and milking