



Strategies to mitigate nitrous oxide emissions from land applied manure

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ABSTRACT

Nitrous oxide is an important greenhouse gas primarily produced by microbial nitrification and denitrification processes in soil. Emissions of N_2O also occur indirectly when N is lost through NH_3 volatilization or nitrate leaching and subsequently converted to N_2O in another location. Direct and indirect N_2O emissions represent an unproductive N loss from agricultural systems and therefore reducing emissions has benefits for greenhouse gas mitigation and improving N use efficiency. This paper reviews strategies for mitigating direct and indirect emissions of N_2O from land applied manure. The discussion focuses on cattle and pig manure and includes strategies such as dietary measures, manure treatment, manure application timing, method and rate, tillage, cover crops and nitrification inhibitors. Finally, to illustrate the extent of mitigation potential, two mitigation options (*i.e.*, shifting autumn manure application to spring and incorporating all manure within one day of application) were applied to the swine sector in Ontario, Canada. Emissions calculated for the baseline scenario and mitigation scenarios were compared. Results suggest that if both mitigation strategies were adopted, N_2O emissions from field applied manure could be reduced by 17%. It is clear that opportunity for mitigation exists, but further research is needed to reduce uncertainty about the efficacy of mitigation options and barriers to on farm adoption.

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1. Introduction

Animal manures have historically been considered a valuable resource to restore soil nutrients and improve crop production (Wadman *et al.*, 1987). When crop and animal production systems are integrated on the same farm, crop nutrient removal is partially offset by return of animal manures to fields. With intensification of animal production systems, development of synthetic N fixation, and abundance of cheap inorganic and synthetic fertilizers, agricultural production has

Abbreviations: CP, crude protein; BOD, biological oxygen demand; DCD, dicyandiamide; DE, digestible energy; DM, dry matter; DMPP, 3,4-dimethylpyrazole phosphate; GHG, greenhouse gas; MCF, methane conversion factor; MS, management system distribution factor; NSP, non-starch polysaccharides; PAN, plant available N; PCC, pork–crop–complex; SFN, synthetic fertilizer N; TAN, total ammoniacal N; VS, volatile solids; WFPS, water filled pore space.

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introduced increased amounts of reactive N into the N cycle (Galloway et al., 2003) and manure has often been considered a waste product and environmental burden (Tamminga, 2003). Nitrogen losses from animal manure of global and regional importance to air and water pollution occur in the form of N_2O , NH_3 and nitrate (Petersen et al., 2007).

Nitrous oxide emissions comprise 2.8 Gt CO_2 eq/yr, or about 0.50 of estimated global emissions from agriculture of 5.1–6.1 Gt CO_2 eq/yr in 2005 (Smith et al., 2007). Emissions from soil and associated N inputs, such as synthetic fertilizer, animal manure and crop residue, are the main agricultural N_2O sources contributing 0.90, with emissions from animal manure stores contributing the rest (OECD, 2008). Mosier et al. (1998) estimated that animal manure applied to soils contributed directly 0.3 Gt CO_2 eq/yr (i.e., 0.10) to global N_2O emissions. Leakages from the N cycle as NH_3 volatilization and N loss through leaching or run off also contribute to N_2O emissions as indirect emissions. Although indirect emission estimates are uncertain, they have been estimated to be as large as direct emissions (Mosier et al., 1998). A review by IFA/FAO (2001) estimated the global direct emissions resulting from animal manure application at 0.2 Gt CO_2 eq/yr and indirect emissions at 0.44 Gt CO_2 eq/yr.

Nitrous oxide emissions from soils are often not directly linked to animal production because of difficulties in separating N sources (i.e., synthetic versus manure) and end use (i.e., feed versus food). Hence, in country or global GHG inventories, N_2O emissions from animal manure applied to soils are usually not included in the livestock category (Freibauer, 2003; de Araujo et al., 2007; Vergé et al., 2007a), but rather are apportioned to emissions from croplands as determined by IPCC GHG inventory guidelines (IPCC, 2006; OECD, 2008). Recent analyses have expanded the boundaries of livestock systems to include N_2O emissions from croplands and pasture associated with feed production for animals (Steinfeld et al., 2006; Vergé et al., 2007b, 2009a,b; Beauchemin et al., 2010). Steinfeld et al. (2006) estimated that over 14 t, or 0.20 of total N fertilizer applied worldwide, is used for animal feed production. These studies highlight the importance of considering N_2O emissions from soils when quantifying overall GHG emissions from animal production, as well as mitigation measures.

de Klein and Eckard (2008) published an overview of technologies for abatement of N_2O emissions from ruminant agriculture. They identified a 50% reduction potential for animal housing systems and 15% for grazing systems. Snyder et al. (2009) provided a comprehensive review of GHG emissions from crop production systems and synthetic N fertilizer best management practices that have the potential to reduce N_2O emissions. Here we review soil processes that lead to N_2O emissions, highlighting effects of field manure application, followed by a synopsis of proposed mitigation strategies and identification of the most promising strategies from a technical perspective. Two selected mitigation options were applied in a model to quantify their potential impacts on overall GHG emissions in the province of Ontario, Canada, in a case study of the swine sector.

2. Nitrogen cycling and nitrous oxide production

Nitrogen, an essential element for life, is present and transferred between the atmosphere, terrestrial and aquatic ecosystems in reactive (i.e., organic, oxidized, reduced) and non-reactive (i.e., N_2) forms (Galloway et al., 2003). Most feed N consumed by animals is excreted in urine or feces, with a proportion retained in animal product (e.g., milk, meat, eggs) of 10–40% (Rotz, 2004). Hence, animal manure, a mixture of feces, urine, wash water and bedding materials rich in reactive N is re-introduced to the environment from animal housing, manure storage, in grazing lands and during land application (Petersen et al., 2007).

Nitrous oxide is produced in soils by microorganisms and, to a lesser extent, by chemodenitrification and soil fungi (Firestone and Davidson, 1989). Nitrifying bacteria oxidize NH_4^+ to NO_3^- under aerobic conditions, and denitrifying bacteria reduce NO_3^- to N_2 under anaerobic conditions, usually with organic C as a reductant. Most denitrifiers are aerobes capable of reducing N oxides when O_2 is limited (Firestone and Davidson, 1989). These N transformations consist of multiple intermediate steps in which NO_2^- , NO and N_2O are produced and subsequently consumed. However the processes are 'leaky' in the sense that intermediate products can escape if production and consumption rates are unequal. A conceptual 'hole-in-the-pipe' model described by Firestone and Davidson (1989) explains that environmental factors regulate production of N_2O by controlling the overall rate of N-transformation (i.e., the flow rate through the 'pipe'), and by partitioning N species into more oxidized or reduced products (i.e., controlling the size of the 'holes' in the 'pipe').

Many factors affect nitrification rate, with fine scale factors including pH, temperature, allelopathic compounds, availability of NH_4^+ , NO_2^- , PO_4^{3-} and O_2 . Each of these is affected by large scale factors such as soil texture, precipitation and climate (Firestone and Davidson, 1989). The proportion of N_2O produced by nitrification appears to be regulated by the partial pressure of O_2 , where more N_2O is produced if O_2 is limiting. Similarly, increasing acidity increases the ratio of N_2O/NO_3^- , which is usually below 1%, although ratios of 20% have been reported. Overall, production of N_2O is complicated by the rate of nitrification being decreased by acidity and O_2 limitation, thereby offsetting the increased N_2O/NO_3^- ratio to some extent (Beauchamp, 1997).

Denitrification requires oxides of N (NO_3^- , NO_2^-) and suitable reductants, usually C, with limited O_2 . Denitrification usually occurs when these conditions exist because denitrifying bacteria are ubiquitous in most soils (Firestone and Davidson, 1989). The end products of denitrification have proven to be difficult to predict. In some cases denitrifiers reduce NO_3^- to N_2 without producing any N_2O , but in other cases large amounts of N_2O are produced. Numerous factors affect the ratio of end products of denitrification, and interactions among these factors in the environment complicate N_2O flux prediction. Overall, the relative amount of reductant versus oxidant is a key factor that regulates the N_2O/N_2 ratio. For example, increasing the amount of available oxidant (i.e., NO_3^- or NO_2^-) while holding C availability constant will tend to cause N_2O production.

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