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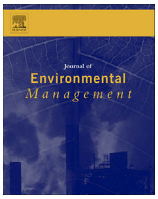

Review

A review of nitrous oxide mitigation by farm nitrogen management in temperate grassland-based agriculture

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ABSTRACT

Nitrous oxide (N_2O) emission from grassland-based agriculture is an important source of atmospheric N_2O. It is hence crucial to explore various solutions including farm nitrogen (N) management to mitigate N_2O emissions without sacrificing farm profitability and food supply. This paper reviews major N management practices to lower N_2O emission from grassland-based agriculture. Restricted grazing by reducing grazing time is an effective way to decrease N_2O emissions from excreta patches. Balancing the protein-to-energy ratios in the diets of ruminants can also decrease N_2O emissions from excreta patches. Among the managements of synthetic fertilizer N application, only adjusting fertilizer N rate and slow-released fertilizers are proven to be effective in lowering N_2O emissions. Use of bedding materials may increase N_2O emissions from animal houses. Manure storage as slurry, manipulating slurry pH to values lower than 6 and storage as solid manure under anaerobic conditions help to reduce N_2O emissions during manure storage stage. For manure land application, N_2O emissions can be mitigated by reducing manure N inputs to levels that satisfy grass needs. Use of nitrification inhibitors can substantially lower N_2O emissions associated with applications of fertilizers and manures and from urine patches. N_2O emissions from legume based grasslands are generally lower than fertilizer-based systems. In conclusion, effective measures should be taken at each step during N flow or combined options should be used in order to mitigate N_2O emission at the farm level.

1. Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) with a global warming potential 298 times higher than carbon dioxide (CO_2) over a 100-year time horizon (Solomon et al., 2007). It is the third most important anthropogenic GHG and contributed about 6.0% to the overall global radiative forcing in 2011 (WMO, 2012). In addition, N_2O currently is the single most important stratospheric ozone-depleting substance and is expected to remain the largest throughout the 21st century (Ravishankara et al., 2009). Global average mixing ratio of N_2O has been increasing with a rate of 0.78 ppb yr^{-1} over the past 10 years (WMO, 2012). The mitigation of N_2O emissions has been regarded as one of the major choices to combat climate change and has received much attention (Reay et al., 2012; Smith et al., 2012).

The challenges for mitigating N_2O emissions are substantially different from those for CO_2 and methane (CH_4) because on one hand about 90% of anthropogenic N_2O emissions are from the agricultural sector while on the other hand nitrogen (N) is essential

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for food production (IPCC, 2007; Davidson, 2012). The increase in N_2O emissions from agriculture is largely induced by the elevated N inputs via synthetic fertilizer N or manure (Davidson, 2009). However, to meet the nutritional needs of a growing human population more N inputs to agriculture are likely needed (Davidson, 2012). N_2O is produced mainly by two biological processes during N cycling, i.e., nitrification and denitrification, which is stimulated by N surplus between N input and crop demand (Smith et al., 2008). N_2O emissions are supposed to be reduced by increasing N use efficiency (NUE, percentage of applied N taken up by the crop), which seldom exceeds 50% (Davidson, 2012). N management to increase NUE has been recognized as an effective way to mitigate N_2O emissions from agriculture (Smith et al., 2008).

Globally, grassland-based agriculture is the major part in agriculture sector with permanent pastures responsible for 68% of all the agricultural land (FAO, 2009). Synthetic fertilizer N and manure are widely used to sustain farm productivity in intensively or semi-intensively managed grassland systems. In extensively managed grasslands a large proportion of N_2O emissions are from excreta deposited by grazing livestock, mostly from urine patches. In New Zealand and Australia, for example, where extensive grassland management is characterised as year-round grazing of grass-clover pastures and very low input of fertilizer N, direct N_2O emissions from excreta recycled to the soil surface by grazing livestock contributed between 50% and 60% of the direct N_2O emissions and up to 80% when indirect emissions (from NH_3 volatilization and NO_3^- leaching) are included (de Klein et al., 2001; de Klein and Ledgard, 2005). The second largest source, fertilizer N, contributed no more than 15% (de Klein et al., 2008). In more intensive managed systems with greater reliance on inputs of fertilizer N, the contribution of excreta recycled by grazing livestock can also be considerable. For example, in the Netherlands, Schils et al. (2005) reported that N recycled by grazing livestock accounted for 44% of total N_2O emissions compared to 22% from fertilizer N, 14% from soil and 11% from manure management in an intensive grassland-based dairy production system receiving total annual inorganic N inputs of 275 kg ha^{-1}. Indirect emissions of N_2O from leached nitrate and from volatilized NH_3 accounted for 9% of total emissions (Schils et al., 2005).

During the past two decades, a few reviews about N_2O mitigation or N losses related to grassland-based agriculture systems have been conducted, including N_2O mitigation from herbivore production systems (Schils et al., 2011), GHG and NH_3 emissions from organic mixed crop-dairy systems (Novak and Fiorelli, 2011), GHG emissions from manure management (Chadwick et al., 2011), NH_3 and N_2O emissions with different manure application methods (Webb et al., 2010). In this review, major choices of N management on grassland farms were evaluated with respect to their effectiveness to mitigate N_2O emissions. The knowledge synthesized in the review will be useful for identifying potential cost-effective and sustainable ways to mitigate N_2O emissions from grassland-based agriculture under temperate conditions.

2. Mechanisms underlying nitrous oxide emissions from grassland

The emission of N_2O arises from microbial nitrification and denitrification of inorganic N in the soil, which in turn is derived from excreta deposited by grazing livestock, application of synthetic fertilizers and manures, and biological N fixation (BNF) (Fig. 1). Nitrification consists of two steps, NH_4^+ oxidation to NO_2^- and NO_2^- oxidation to NO_3^-, carried out by ammonium-oxidizers and nitrite-oxidizers, respectively (Ward, 2000). Denitrification is the anaerobic microbial reduction of NO_3^- to dinitrogen (N_2). During the denitrification process, NO_3^- is successively reduced to NO_2^-, NO, N_2O and finally dinitrogen (N_2). Since N_2O is an intermediate during denitrification, it can be both produced and consumed. Nitrification and denitrification are tightly coupled since NO_2^- or NO_3^- produced during nitrification can be utilized by denitrifiers and this coupling can take place in soils where favourable conditions for both nitrification and denitrification are present in neighbouring microhabitats (Wrage et al., 2001). However, under oxygen (O_2) limiting conditions, NH_4^+ may be oxidized to NO_2^- and then sequentially reduced to NO, N_2O and N_2. This process, which is carried out by autotrophic ammonium-oxidizers is termed nitrifier denitrification (Wrage et al., 2001). The relationships between nitrification, denitrification and nitrifier denitrification are shown in Fig. 1. In addition to the above micro-organism mediated processes, some abiotic processes (mostly chemodenitrification) may also contribute to the production of N_2O under certain conditions (Williams et al., 1992). Current evidence indicates that most of the N_2O evolved from soils is produced by biological processes and that little is produced by chemodenitrification (Bremner, 1997).

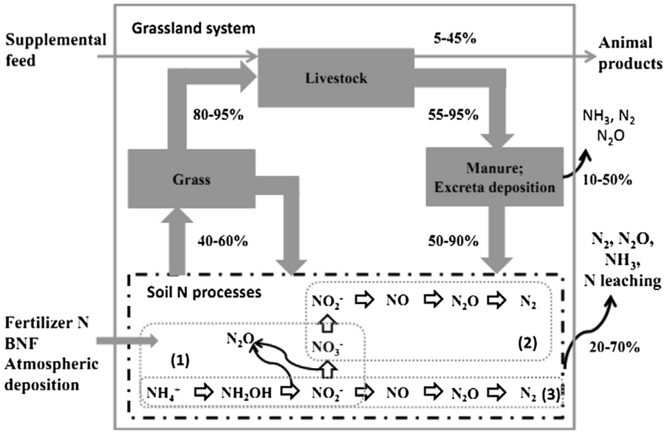

Fig. 1. Nitrogen cycling in grassland based systems showing N_2O production. Open arrows represent soil N cycling processes (nitrification (1), denitrification (2) and nitrifier denitrification (3)). Solid arrows denote the relative size and direction of the N flows. Percentages indicate the estimated transfer of N from one compartment to the other compartment (modified from Oenema et al. (2005) and Wrage et al. (2001)). N_2O production in soil also applies to the manure environment. N losses other than N_2O are not shown. BNF – Biological N fixation.

3. Potential N_2O mitigation options by farm N management

3.1. *Options to lower N_2O emissions from excreta patches*

Urine and dung patches on grasslands represent high (up to more than 1000 kg N ha^{-1}), random and very local additions of N and readily available carbon (C) that can create optimal conditions for N_2O production (van Groenigen et al., 2005). It was estimated that between 0.1 and 3.8% of urine-N and between 0.1 and 0.7% of the dung-N is emitted to the atmosphere as N_2O (Oenema et al., 1997). In countries that depend economically to a large extent on livestock farming, these fluxes are major contribution to the national GHG budget. It is therefore imperative to seek measures lower N_2O emissions from excreta patches.

3.1.1. *Restricted grazing*

Restricting grazing has been proposed as an option to reduce N_2O and other GHG emissions (Oenema et al., 2001; Schils et al., 2006; de Klein et al. 2006; Luo et al. 2008a,b). This management tactic involves a reduction in grazing time or livestock number, each of which results in decreased dung and urine deposition. Therefore there is a great potential to lower N_2O emissions via