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Soil nitrous oxide emissions in forage systems fertilized with liquid dairy manure and inorganic fertilizers

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ABSTRACT

Intensive dairy production generates large amounts of manure, which is typically reused as fertilizer for the production of forage. In the Central Valley of California, application of manure often results in high inputs of N and labile organic C, a combination that can lead to large nitrous oxide (N_2O) emissions. The present study included dairy forage production fields at three dairies with a range of soil textures. Liquid manure from lagoons was applied in surface irrigation water in addition to inorganic N fertilizers. Nitrogen inputs, N_2O emissions, crop N removal, soil inorganic N, moisture, and temperature were assessed over two summer corn and one winter forage seasons at each dairy. Between 0.76 and 1.30% of the applied total N was emitted as N_2O annually. A significant portion of the N_2O emissions was explained by high soil moisture, soil inorganic N, and soil temperature, as shown by multiple regression analysis. Variability in total N_2O emissions and emission patterns was likely due to differences in N management and soil texture. Large single applications of N when crop N uptake potential was low were responsible for the largest N_2O emissions, whereas distributing N additions, applied with the irrigation water, over the cropping season resulted in lower emissions. The field study was complemented with laboratory incubations of soil amended with liquid manure and ^{15}N-labeled urea-ammonium-nitrate (UAN) to determine the proportion of liquid manure and fertilizer N emitted as N_2O. The incubation results showed that liquid manure stimulated the release of N_2O originating from fertilizer N. Therefore, liquid manure should not be added to irrigation water following side dress fertilizer N applications. To reduce the risks of N_2O emissions and other N losses to the environment, manure and fertilizer N inputs, as well as soil N mineralization, must be accounted for and N supplied in increments according to crop demand.

1. Introduction

Agricultural management constitutes the largest source of anthropogenic nitrous oxide (N_2O) emissions (Metz et al., 2007). Management practices that affect water and available N largely influence the production and release of N_2O to the atmosphere. The dilemma for intensive agriculture production practices is to supply sufficient amounts of N to meet crop yield potential without resulting in residual N that will stimulate N_2O emissions (Van Groenigen et al., 2010). In addition to fertilizer application amounts, the form of N applied to the soil has a strong influence on the amount N_2O that can be potentially emitted (Bouwman et al., 2002b; Asgedom et al., 2014). Nitrous oxide in soil can be produced through nitrification, which requires ammonium (NH_4^+) as a substrate, and denitrification, which requires nitrate (NO_3^-). Therefore fertilization that increases the concentration of either inorganic N form can influence N_2O emissions. Also, N_2O production is further stimulated by the addition of labile C sources typically added with organic based fertilizers such as manure (Paul and Beauchamp, 1989). Consequently several studies have reported larger N_2O emissions with organic than with inorganic fertilizers (Bouwman et al., 2002b). In addition, throughout the literature it is observed that organic and inorganic fertilizers applied concurrently result in higher N_2O emissions per unit of N applied than if applied alone, suggesting interactive effects that stimulate N_2O release (Bouwman et al., 2002a). Irrigation strategies also have a strong influence on N_2O emissions through

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the modification of the prevalent edaphic conditions such as water content and oxygen availability (Burger et al., 2005; Trost et al., 2013). Under low oxygen concentrations, which are likely to occur with flood irrigation and carbon additions in the liquid manure, the contribution of nitrification pathways, in addition to denitrification, can be a substantial source of N_2O (Zhu et al., 2013a).

Recent airborne measurements in the Central Valley of California report large N_2O emissions that are directly attributed to use of inorganic and organic N fertilizers (Xiang et al., 2013). Identification of the main sources and driving factors is therefore essential to reduce N_2O emissions. More than 1.5 million dairy cows are concentrated in the Central Valley (CDFA, 2013), as milk production is one of the top ten agricultural commodities in the State (CDFA, 2013). Intensive dairy production generates large amounts of manure which is typically reused as fertilizer for forage production (Pettygrove et al., 2009a; National Agricultural Statistics Service, 2012). Usually two crops are grown per year, including silage corn in summer and other forage crops (oat, alfalfa, sudan grass, wheat, triticale, and forage mixes) during fall and/or winter. Typical manure management in these dairies involves flushing of feed lanes and free stalls. The remaining manure slurry is first passed through a screen to separate larger particles from the liquid fraction. The larger fraction (separator manure), consists mainly of coarse fibrous particles, spent bedding, and spilt forage and feed, and is stockpiled with or without a composting process. The resulting liquid manure fraction, consisting mainly of NH_4-N^+, dissolved and some suspended solid organic N, is stored in anaerobic basins or lagoons (Pettygrove et al., 2009a). Stockpiling of solid manure scraped from dirt-floored corrals is also common. Solid manure is sometimes applied to the fields in spring, prior to corn planting, whereas liquid manure is applied multiple times through furrow or flood irrigation, almost always mixed with fresh water. Manure N inputs to the forage crops are usually supplemented with commercial inorganic fertilizers to ensure sufficient available N. Therefore these systems receive higher annual N inputs than typical agricultural systems. Previous studies describing N dynamics in these forage production systems showed that annual N inputs ranged between 500 and 1200 kg N ha^{-1} whereas crop outputs were only 350–600 kg N ha^{-1} (Geisseler et al., 2012). Yet currently, according to the General Order for dairies under the authority of the Central Valley Regional Water Quality Control Board, the dairies are not allowed to apply more than 140% of the N harvested annually in crop removal. Flood irrigation systems used in these forage production systems have a great potential for large losses of N to the environment, through ammonia volatilization, NO_3 leaching and N_2O emissions (Van der Schans et al., 2009; Geisseler et al., 2012). The dissolved organic carbon, particularly the volatile fatty acids contained in liquid manure, stimulates N_2O production through denitrification (Paul and Beauchamp, 1989; Heinrich and Pettygrove, 2012). Modeling has been used to determine the influence of soil factors and management outcomes on N loss through NO_3^- leaching and denitrification (Geisseler et al., 2012), however little data is available to quantify N_2O emissions from these systems.

The objective of this study was to determine the impacts of N fertilizer source and irrigation management on N_2O production in dairy forage production in the Central Valley of California. We selected three dairy farms with contrasting soil texture to assess total N inputs and N_2O emissions over three cropping seasons (two summer corn and one winter forage). The dairies used similar management practices, including the use of liquid manure, inorganic fertilizers and flood irrigation, but different irrigation schedules, inorganic N inputs and timing of manure and fertilizer applications. We hypothesized that combining manure with inorganic fertilizers would stimulate N_2O emissions from soil, as compared to equivalent N doses from both sources alone. To test this hypothesis, field data was supplemented with laboratory incubations of soils from the three farms using various combinations of inorganic N fertilizer and liquid manure. Overall, the aim of this study was to better understand the N_2O emission dynamics in order to improve fertilizer management and the sustainability of dairy production systems.

2. Material and methods

2.1. Field site description and agricultural management

The study was carried out on three dairy farms located in the California Central Valley, in San Joaquin (Farms A and B) and Sacramento (Farm C) counties, between April 2011 and October 2012. The climate is Mediterranean, with hot, rainless summers and relatively mild rainy winters. The average annual temperature is 16.3 °C with average rainfall of 310 and 470 mm for San Joaquin and Sacramento County, respectively (Western Regional Climate Center, http://www.wrcc.dri.edu). The three farms were representative of California Central Valley dairy farms, using dairy manure combined with synthetic N to produce forage crops. However, the timing and frequency of N fertilizer and manure applications, as well as the composition of the manures and types of synthetic fertilizer N sources were different on each farm.

On Farm A, the soil, classified as coarse-loamy, mixed, active, thermic Typic Haploxeralf (http://casoilresource.lawr.ucdavis.edu/soilweb/) with a high sand content (Table 1), has been under no-till management since 2005. Silage corn was grown in summer and a forage mixture of grasses and legumes from fall to spring. Fertility management consisted of a 27-0-6 liquid starter (34 and 40 kg N ha^{-1} in 2011 and 2012, respectively) applied at planting followed by liquid manure and inorganic fertilizer in the form of urea ammonium-nitrate (UAN-28) applied in flood irrigation water (approx. 7:1 freshwater:liquid manure) at almost every irrigation event once the corn reached the two leaf (V2) stage. An average of 56 and 54 kg ha^{-1} total N, including 45 and 40 kg inorganic N + urea-N ha^{-1}, were applied in each irrigation for a total of 10 and 11 irrigation events, in 2011 and 2012, respectively (Fig. 2). Nitrogen contents and forms of the liquid manures applied over the course of this study are shown in Fig. 1. Including synthetic fertilizer and manure, a total of 546 and 457 kg N ha^{-1} were applied to the corn crop in 2011 and 2012 (Table 2). The fields were irrigated three times during fall and winter (i.e. at the end of October 2011, in mid January 2012, and at the end of March 2012) with additional N inputs of 186 kg N ha^{-1}.

The soil at Farm B was classified as a mixed, thermic Typic Xeropsamment, also with a high sand content (Table 1). Conventional tillage practices were used on this farm. Silage corn was grown in summer and wheat for silage from fall to spring. Corral manure (not composted, 17.1 g N kg^{-1}), composted (24.8 g N kg^{-1}), and non-composted separator manure (18.1 g N kg^{-1}) were incorporated into the soil in spring 2011 two weeks before corn planting at rates of 142, 159, and 283 kg total N ha^{-1}, respectively. No solid manure was applied in 2012. Side-dress N as UAN-32 was injected

Table 1
Soil characteristics (0–30 cm) of the three dairy forage systems.

	Farm A	Farm B	Farm C
Sand (%)	77.6	84.0	30.6
Silt (%)	15.8	11.5	27.9
Clay (%)	6.6	4.5	41.5
pH (H_2O 1:1)	6.7	6.8	7.5
Bulk density 5–15 cm (g cm^{-3})	1.67	1.37	1.51
Total C (g kg^{-1})	10.4	11.8	12.4
Total N (g kg^{-1})	1	1.1	1.3