AGRICULTURAL MANAGEMENT EFFECTS ON NITROUS OXIDE GAS EMISSIONS

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EXECUTIVE SUMMARY

Nitrous oxide (N_2O) gas is produced by micro-organisms during nitrification and/or denitrification of fertilizer nitrogen in soil. Atmospheric emissions of N_2O can be important from an agronomic standpoint since any escape of N from the soil represents N that cannot be utilized by the crop. Once in the atmosphere, N_2O acts as a greenhouse gas which is 300 times more potent than carbon dioxide. The complexity of the processes controlling N_2O emissions make it difficult to predict how a particular management practice or set of conditions will affect N_2O emissions. This paper summarizes results of ongoing research projects throughout Minnesota which are attempting to quantify the impacts of specific management practices on N_2O emissions. A study conducted in Rosemount in corn planted in a silt loam showed that N_2O emissions can represent a substantial component of the total greenhouse gas budget of the cropping system. Interactions between fertilizer and tillage practices were important in controlling N_2O emissions. A study in Becker in potato planted in a loamy sand showed that soils fertilized with controlled release N fertilized products lower total growing season emissions compared to the conventional urea treatment. A study conducted near Tracy showed that N_2O emissions from soils under conventional drainage tended to emit less N_2O than undrained soils, although the effects were not consistent across the entire field. It is clear from the studies summarized here that N_2O emissions are controlled by a variety of management factors, including tillage, fertilizer, and drainage practices, as well as environmental factors including soil properties and climate. More field studies are required to identify practices that effectively reduce N_2O emissions while maintaining crop production.

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INTRODUCTION

Nitrous oxide (N_2O) gas is produced by micro-organisms (primarily bacteria) during their metabolism of nitrogen (N) in soil (Firestone and Davidson 1989). The source of N can be either added fertilizer or naturally occurring soil N. In agricultural soils the majority of N_2O is derived from fertilizer N. The N_2O produced in the soil can rapidly escape to the atmosphere by diffusing through soil pores. Atmospheric emissions of N_2O can be important from an agronomic standpoint since any escape of N from the soil represents N that cannot be utilized by the crop. Most of the time, annual losses of N_2O account for 1 – 5% of the amount of fertilizer added, although higher amounts have been measured (Mosier et al. 1988). There is substantial uncertainty in many N_2O emissions estimates (Rochette and Eriksen-Hamel 2008). Once in the atmosphere, N_2O acts as a greenhouse gas (GHG) by absorbing infra-red radiation, similar to carbon dioxide (CO_2). Thus, N_2O may cause changes in climate as it accumulates in the atmosphere. Analysis of trapped gases in deep ice cores collected from polar regions indicates that over the past 150 years, atmospheric N_2O levels have increased by 18%. This increase is driven largely by increasing N fertilizer use throughout the world (Solomon et al. 2007). An important characteristic of N_2O is that once emitted to the atmosphere, it has a long lifetime (approximately 120 years), which is much longer that CO_2. For this reason, one pound of N_2O is equivalent to approximately 300 pounds of CO_2 from a greenhouse gas standpoint (Forster et al. 2007). Thus, relatively small changes in emissions of N_2O from an agricultural soil can have a relatively large impact on the total GHG contribution of the cropping system.

There are two basic processes that can generate N_2O: (i) nitrification and (ii) denitrification (Figure 1) (Venterea, 2007). Nitrification occurs when soil bacteria convert fertilizer N from the ammonium form (NH_4^+) to the nitrite (NO_2^-) and nitrate (NO_3^-) forms. In order for nitrification to proceed, fertilizer needs to be added in the form of NH_4^+ or other forms (such as anhydrous ammonia [NH_3] or urea) which are converted to NH_4^+ in the soil. During denitrification, soil bacteria convert NO_3^- to NO_2^-, then to nitric oxide (NO) gas, and then to N_2O in a sequence of reactions. In order for denitrification to proceed, N must be present in the form of NO_3^-. The NO_3^- can be present either because fertilizer NH_4^+ has been converted to NO_3^- via nitrification, or if NO_3^- is added directly, for example as ammonium nitrate (NH_4NO_3). There are three important differences between denitrification and nitrification that affect N_2O production: (1) Denitrification can only proceed in the absence of O_2, while nitrification requires O_2. Thus, denitrification tends to occur under wet conditions and in slowly draining soils that do not allow for rapid replenishment of O_2, while nitrification tends to occur in moderately well-drained and during direr periods. (2) During denitrification, some of the N_2O that is produced can be converted to nitrogen gas (N_2) prior to being emitted to the atmosphere; and (3) Denitrification requires dissolved organic carbon and is therefore enhanced in soils that have higher carbon levels, while nitrification does not require organic carbon. The complexity of the processes controlling N_2O emissions make it difficult to predict how a particular management practice or set of conditions will affect N_2O emissions. This paper will summarize results of ongoing research which is attempting to quantify the impacts of specific management practices on N_2O emissions.

METHODS

Site Descriptions

Tillage/fertilizer study

Plots were located at the University of Minnesota's field station in Rosemount, MN (www.umorepark. umn.edu/Research_and_Outreach_Center.html). Soil at the site was a Waukegan silt loam underlain by outwash sands. Since 1990, the following tillage treatments have been maintained in a corn/soybean rotation: (i) "Conventional" tillage (CT) employing fall moldboard plowing following corn, disk-ripping following soybean, with spring pre-plant cultivation prior to both corn and soybean, (ii) "Conservation" tillage (CsT) employing disk-ripping following corn, no fall plowing following soybean, with spring cultivation prior to soybean only, and (iii) no-till (NT). In 2003 and 2004, we made measurements in nine plots (three replicates of each tillage treatment). In 2003, 120 kg N ha^{-1} as broadcast urea (BU) was applied to all plots when corn seedlings were approximately 20-cm high (23 June) in keeping with historical fertilizer practices at the site. In spring 2004, each of the nine main plots were divided into three subplots, which received 120 kg N ha^{-1} either as (i) pre-plant, injected anhydrous ammonia (AA), (ii) pre-plant, surface applied urea ammonium nitrate (UAN) or (iii) BU applied uniformly 6 wks after planting. Additional details are available in Venterea et al. (2005 and 2006).

Controlled release fertilizer study

This ongoing study is being conducted at the Sand Plain Research Farm (http://sprf.cfans.umn.edu/) operated by the University of Minnesota in Becker, MN. The loamy sand at this site is representative of soils used for potato and corn production in various parts of Minnesota. During the 2007 growing season, N_2O fluxes were measured in plots planted in potato that compared conventional urea (with split applications at planting, emergence, and 5 after hilling) to three different controlled release fertilizer products: (i) Environmentally Smart Nitrogen (ESN) (Agrium, Inc.), (ii) Polymer-coated urea (PCU) (Kingenta), and (iii) Sulfur-coated urea (SCU). All treatments received a total of 240 lbs N per acre. The controlled release treatments all used 200 lbs of product N applied prior to planting and an additional 40 lbs of diammonium phosphate at planting. All treatments were managed under irrigation.

Drainage management study

This ongoing study is being conducted on a family-owned farm operated by Mr. Brian Hicks near Tracy, MN. Due to the depth and clay content of sub-soils, many fields in this area have been artificially drained by installation of perforated plastic pipe ("tile drains"). Subsurface tile drainage was installed on a 37-ha site during fall 2005 at approximately 4-ft deep with 50-foot spacing. This field was divided into two drainage zones, west (22 ha) and east (15 ha), both of which are managed by separate control structures. During 2006, both sides were managed under "conventional" drainage, with the outlet level of the system is maintained at the tile drain depth (~4 ft). Starting in the spring of 2007, both sides were managed under "controlled drainage", where the control structures were used to elevate the outlet level of the system to within 2 ft of the surface.

This practice reduces the total amount of water and therefore nutrients entering surface waters. However, while the amount of NO_3^- entering the stream or ditch may be reduced, it is possible that higher soil moisture and more anaerobic conditions may increase denitrification and N_2O emissions from the field. It should be noted that during April 2007, the outlet level was lowered to ~4 ft to improve trafficability during field operations. An adjacent field located to the south of the drained fields was farmed without artificial drainage in 2006-2007. All fields were planted in corn and fertilizer applied in the spring prior to planting. Urea was surface applied and incorporated at 155 and 160 lbs N acre^{-1} in 2006 and 2007, respectively. N_2O emissions were measured 1-2 times per week during the growing season at three locations with each of the east and west zones of the drained field. In both years, N_2O emissions were measured at three locations in the northwest quadrant of the undrained field. In 2007 and 2008, three locations in the southwest quadrant of the undrained field were also monitored.

N_2O flux determination

At all sites, static chambers were used to measure soil-to-atmosphere N_2O fluxes. At the Rosemount and Tracy sites, rectangular stainless steel chamber anchors measuring 53 cm X 32 cm X 8.6 cm deep with a 1.9 cm-wide horizontal flange on the top end were inserted into the soil, so that the top was nearly flush with the soil surface. Anchors remained in the soil for the entire season, except when removal and reinsertion were required by field operations. During measurement, flanged stainless steel chamber tops (50 cm X 29 cm X 10.2 cm high) lined with EPDM rubber gasket material were secured to bases with metal clamps. At the Becker site, cylindrical stainless steel chamber tops (22 cm ID X 15 cm deep) with sharp bottom ends were inserted directly into the soil to a depth of 2 cm prior to each measurement. Chamber gas samples were collected at regular intervals of 0, 30, and 60 min by inserting the needle of a 12-mL polypropylene syringe through a septum in the chamber top and slowly withdrawing 12 mL. Samples were immediately transferred to 9-mL glass vials sealed with butyl rubber septa, which were taken to the laboratory for analysis. Fluxes were generally measured between 1100 and 1400 local time when soil temperatures were expected to be close to their daily mean values. Gas samples were analyzed within 3 d of collection by gas chromatography (GC) using a headspace autosampler (Teledyne Tekmar, Mason, Ohio) connected to a Hewlett-Packard 5890 GC equipped with an electron capture detector (ECD). The ECD was calibrated using analytical grade standards (Scott Specialty Gases, MI). Gas fluxes were calculated from the rate of change in chamber concentration, chamber volume, and soil surface area. Chamber gas concentrations were converted from molar mixing ratio units (e.g., parts per million) determined by GC analysis to mass per volume units (e.g., ng N m^{-3}) assuming ideal gas relations using air temperatures during sampling. Total growing season N_2O emissions were estimated by integration of the flux versus time data.

RESULTS AND DISCUSSION

Tillage/fertilizer study

At the Rosemount site in 2003 – 2004, tillage effects on N_2O emissions varied, in both magnitude and direction, depending on fertilizer practices (Fig. 2). Emissions of N_2O following BU application were higher under NT and CsT compared to CT. In contrast, following AA injection, N_2O emissions were higher under CT and CsT compared to NT. Emissions following surface UAN application did not vary with tillage. Emissions of N_2O from AA-amended plots were two to four times greater than UAN- and BU-amended plots. These data indicate that N_2O emissions can represent a substantial component of the total GHG budget of RT systems, and that interactions between fertilizer and tillage practices can be important in controlling N_2O emissions. Further work by Venterea and Stanenas (2008) showed that the patterns found here can be largely explained by differences in vertical distributions of denitrifying microbial populations as affected by tillage combined with the vertical placement of fertilizer N. Consistent with results of Linn and Doran (1984a) and Groffman (1985), Venterea and Stanenas found higher denitrification activity under NT compared to CT in the top 5 cm the reverse pattern at greater depth. Higher water content and bulk density under NT in the upper 0–10 cm may have further reduced net N_2O emissions by enhancing reducing conditions, thereby promoting the reduction of N_2O to N_2 during transport toward the soil surface (Linn and Doran, 1984b). Conversely, surface applied urea would be expected to stimulate more denitrifying activity in the upper soil layers, thereby favoring more denitrification under NT compared to CT.

Total growing season N_2O emissions were equivalent to CO_2 emissions of 0.02 to 0.24 tons soil C acre^{-1} yr^{-1} (Fig. 2). In a recent survey, soil C storage rates under reduced tillage in the central USA were found to average 0.18 ± 0.27 tone soil-C acre^{-1} yr^{-1} in 44 treatment pairs (Johnson et al., 2005). Differences in N_2O emissions due to tillage in the current study are therefore substantial (12–58%) when compared to potential rates of soil C sequestration.

Controlled release fertilizer study

As shown in Figure 3, the conventional urea treatment displayed a gradual increase in N_2O flux starting on approximately May 20 that continued until reaching a maximum on June 15. This response appears to have been the result of the 100-lb urea application at hilling on May 15. None of the controlled release treatments displayed such a sustained increase in N_2O flux, and all had lower total growing season emissions compared to the conventional urea treatment (as shown in legend in Figure 3). The lower N_2O emissions in the controlled fertilizer treatments was likely due to slower release of NH_4^+ into the soil, and therefore lower rates of nitrification and denitrification (although this was not measured directly). With slower release of NH_4^+ into the soil, there is a greater likelihood that root uptake of nitrogen will keep levels of NH_4^+ low enough so that nitrification rates will also be low. With less nitrification, there is also less production of NO_3^- and therefore less denitrification. Potato yields were similar across treatments, although the SCU treatment had slightly higher yields than the other controlled release products (Figure 3).

Drainage management study

During the 2006 growing season, the tile-drained field managed under conventional drainage emitted on average approximately 50% of the N_2O emitted from the undrained field (Figure 4a). The higher soil moisture levels in the undrained field apparently promoted increased denitrification and soil N_2O production. In 2007, with the tile-drained field managed under controlled drainage, a different pattern was found (Figure 4b). The west side of the drained field and the north side of the undrained fields emitted similar amounts of N_2O (1.64–1.75 lbs N per acre). In contrast, the east side of the drained field emitted 0.58 lbs per acre, while the south side of the undrained field emitted only 0.13 lbs per acre. It is not immediately clear what factors were responsible for these trends. Apparently the west side of the field under controlled drainage in 2007 responded to the elevated drainage outlet by emitting more N_2O than during 2006 while under conventional drainage. The south side of the undrained field, which emitted the least N_2O of all, tends to also be the most poorly-drained section of the undrained field. It is therefore possible that the very high moisture contents in this area of the field may have inhibited nitrification and NO_3^- production. It is also possible that any N_2O produced in the soil in this area was converted to N_2 due to the high moisture levels, so that very little N_2O escaped to the atmosphere. In both 2006 and 2007, the temporal patterns of N_2O emissions were consistent, in that large pulses of N_2O emissions occurred in the days immediately following fertilizer applications. Because the undrained field was fertilized later than the drained field, the peak in N_2O emissions from the undrained field also occurred later (Figure 4a-b).

CONCLUSIONS

It is clear from the studies summarized here that N_2O emissions are controlled by a variety of management factors, including tillage, fertilizer, and drainage practices, as well as environmental factors including soil properties and climate. These data indicate that in reduced tillage systems, sub-surface application of N fertilizer may minimize N_2O emissions. Controlled release fertilizer products may also hold some promise for minimizing emissions. Impacts of drainage management on N_2O emissions so far have proven to be complicated, since increased water content may either increase or decrease net N_2O emissions. More field studies are required to identify practices that effectively reduce N_2O emissions.

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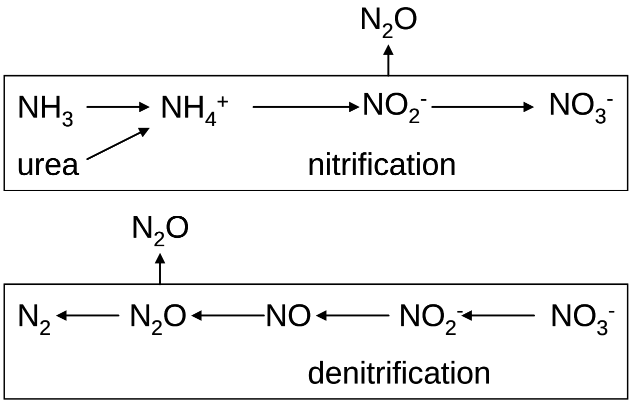

Figure 1. Pathways of nitrous oxide (N_2O) production.

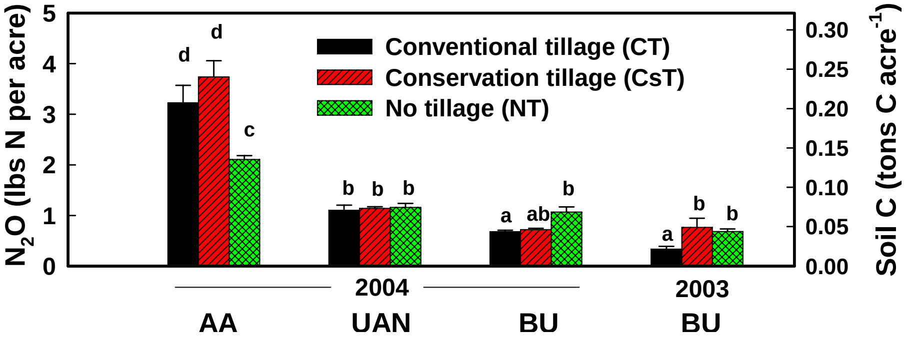

Figure 2. Total growing season N_2O emissions under three tillage treatments receiving anhydrous ammonia (AA), urea ammonium nitrate (UAN), or broadcast urea. The right-hand axis shows N_2O emissions expressed as soil C equivalents.

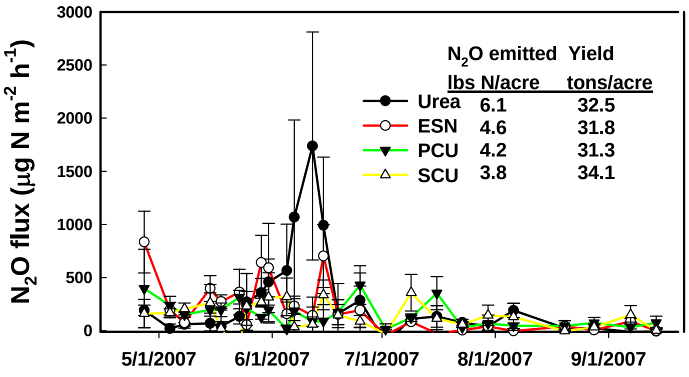

Figure 3. N_2O fluxes versus time from loamy sand soil planted in potatoes and fertilized with conventional urea, Environmental Smart Nitrogen (ESN), polymer coated urea (PCU) and sulfur-coated urea (SCU) during 2007. Also shown in legend are total estimated growing season emissions in lbs per acre for each treatment.

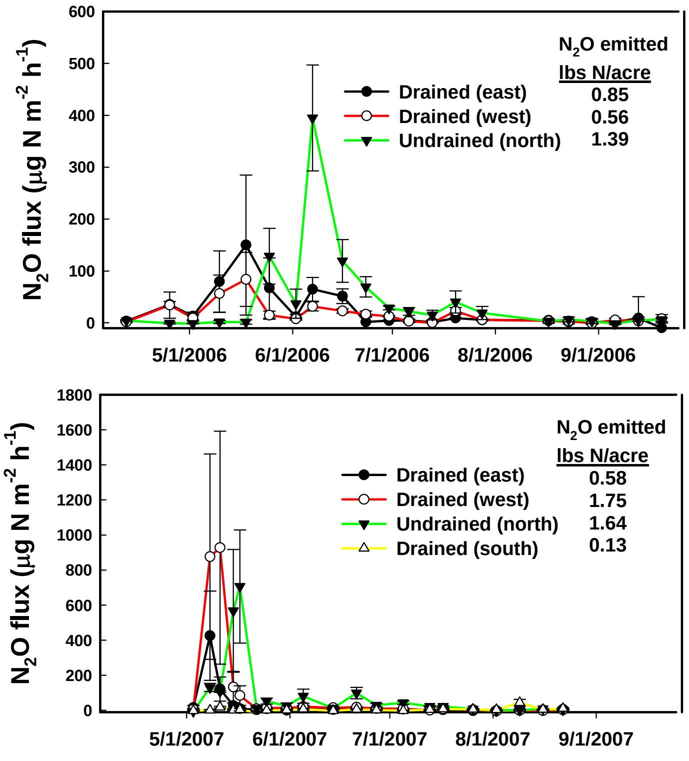

Figure 4. N_2O fluxes versus time from Drained and Undrained fields in Tracy, MN planted in corn during 2006 (upper graph) and 2007 (lower graph). Also shown in legend are total estimated growing season emissions in lbs per acre for each treatment.