

Cover Crop Effects on Nitrous Oxide Emissions: Role of Mineralizable Carbon

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Nitrous oxide (N_2O) emission from denitrification in agricultural soils often increases with N fertilizer and soil nitrate (NO_3) concentrations. Overwintering cover crops in cereal rotations can decrease soil NO_3 concentrations and may decrease N_2O emissions. However, mineralizable C availability can be a more important control on N_2O emission than NO_3 concentration in fertilized soils, and cover crop residue provides mineralizable C input. We measured the effect of a winter rye (*Secale cereale* L.) cover crop on soil N_2O emissions from a maize (*Zea mays* L.) cropping system treated with banded N fertilizer at three rates (0, 135, and 225 kg N ha⁻¹) in Iowa. In addition, we conducted laboratory incubations to determine if potential N_2O emissions were limited by mineralizable C or NO_3 at these N rates. The rye cover crop decreased soil NO_3 concentrations at all N rates. Although the cover crop decreased N_2O emissions when no N fertilizer was applied, it increased N_2O emissions at an N rate near the economic optimum. In laboratory incubations, N_2O emissions from soils from fertilizer bands did not increase with added NO_3 , but did increase with added glucose. These results show that mineralizable C availability can control N_2O emissions, indicating that C from cover crop residue increased N_2O emissions from fertilizer band soils in the field. Mineralizable C availability should be considered in future evaluations of cover crop effects on N_2O emissions, especially as cover crops are evaluated as a strategy to mitigate agricultural greenhouse gas emissions.

Abbreviations: N0, 0 kg fertilizer N ha⁻¹; N135, 135 kg fertilizer N ha⁻¹; N225, 225 kg fertilizer N ha⁻¹; WFPS, water-filled pore space.

The atmospheric concentration of the potent greenhouse gas N_2O has increased 40 to 50% since pre-industrial times as a consequence of human activity (Forster et al., 2007). Agricultural soils are the largest anthropogenic source of N_2O (Smith et al., 2007; Reay et al., 2012). The microbial processes nitrification and denitrification, as well as abiotic processes, produce N_2O in soils (Venterea et al., 2012). In cultivated soils, denitrification tends to be the dominant process producing N_2O (Azam et al., 2002; Ostrom et al., 2010). In denitrification, NO_3 is reduced to N_2O during organic C oxidation in the absence of oxygen (O_2). Nitrous oxide can then be used as an electron acceptor and reduced to N_2 before diffusing from the soil; however, high NO_3 availability inhibits N_2O reduction (Blackmer and Bremner, 1978; Senbayram et al., 2012). Physical soil conditions such as temperature, texture, and bulk density also influence denitrification and N_2O emission from the soil surface (Venterea et al., 2012). When these conditions are constant, emission of denitrification-derived N_2O is controlled by anaerobicity, the availability of NO_3 and mineralizable C substrates, and the amount of N_2O reduced to N_2 before leaving the soil (Firestone and Davidson, 1989).

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Laboratory studies of denitrification (Myrold and Tiedje, 1985; Lalisse-Grundmann et al., 1988) and field studies of N₂O emissions (Sehy et al., 2003; van Groenigen et al., 2004; Adviento-Borbe et al., 2007) have shown that these processes are not necessarily limited by NO₃ concentrations in fertilized soils. In soils with high NO₃ concentrations and low O₂ availability, availability of mineralizable C substrate can control denitrification rates (Burford and Bremner, 1975; Bijay-Singh et al., 1988). Under field conditions, increased C availability can also increase N₂O emissions by promoting O₂ consumption, which creates anaerobic microsites in the soil that support activity of denitrifying microorganisms (Tiedje et al., 1983; Myrold and Tiedje, 1985; Azam et al., 2002). Mineralizable C availability has been shown to limit N₂O emission from NO₃-rich (30–100 mg NO₃-N kg⁻¹ soil) cultivated soils (e.g., Weier et al., 1993; Huang et al., 2004; Gillam et al., 2008), even with high total organic C contents (Sainz Rozas et al., 2001; Sánchez-Martín et al., 2008).

Overwintering non-legume cover crops can decrease NO₃ concentrations in agricultural soils through N uptake during growth and immobilization during residue decomposition (Thorup-Kristensen et al., 2003). By decreasing the soil NO₃ pool, these cover crops can also decrease soil N₂O emissions (Baggs et al., 2000). However, the effects of cover crops on N₂O emissions have been mixed (Cavigelli et al., 2012); some studies have found cover crops to increase (Petersen et al., 2011) or have no consistent effect on N₂O emissions (Jarecki et al., 2009; Smith et al., 2011). When cover crops are killed shortly before N application, mineralizable C from their residue may stimulate denitrification and N₂O emissions (Sarkodie-Addo et al., 2003; Petersen et al., 2011).

Together, inconsistent effects of cover crops on N₂O emissions and evidence for C limitation of agricultural N₂O emissions indicate that cover crop effects on the availability of C, as well as NO₃, can affect N₂O emissions. An improved understanding of the relationship between cover crops and N₂O emissions is particularly important as cover crops are increasingly promoted as a greenhouse gas mitigation strategy (Eagle and Olander, 2012). The goal of this study was to determine how cover crop C inputs can interact with soil NO₃ to affect N₂O emissions in a maize–soybean [*Glycine max* (L.) Merr.] crop rotation. We used a coupled field and laboratory experimental approach. In the field, we measured the effects of three N fertilizer rates and a rye cover crop on soil N₂O emissions in the maize phase of the rotation. In the laboratory, we incubated soils sampled from the fertilizer bands from the field experiment with glucose and NO₃ additions to determine if potential N₂O emissions in these soils were limited by NO₃ or mineralizable C availability. The inference of the field experiment is limited to one growing season; further data from the field site would be needed to evaluate the effects of the treatments on N₂O emissions over multiple years. However, the purpose of this study was to use a lab experiment to examine the soil biogeochemical mechanisms responsible for the 1 yr of field observations, with the goal of understanding some of the variability of N₂O responses to cover crops reported in the literature.

MATERIALS AND METHODS

Field Study

A field study was conducted at the Iowa State University Agricultural Engineering and Agronomy Ames Research Farm in Boone County, Iowa (42.02 N, 93.77 W). Long-term mean annual temperature and precipitation at this location are 9.4°C and 872 mm yr⁻¹. The soil at this site is predominantly Clarion loam series (fine-loamy, mixed, superactive, mesic Typic Hapludolls), with pH 6.4 in water (1:1 soil/water ratio), 2.4% total C, and 0.2% total N (0–15-cm depth). The site for this study was managed as a no-till maize–soybean rotation.

The experimental design of the field experiment was a split-plot with four replicates. Within each replicate, presence or absence of a winter rye cover crop was the main plot treatment, and N fertilizer rate for maize was the subplot treatment. No N was applied to soybean. This site was established primarily to better determine the economical optimum nitrogen rate (EONR) for maize following soybean with and without a rye cover crop. The long-term optimal N rate for this rotation in Iowa is 152 kg N ha⁻¹ at a fertilizer/grain price ratio of 0.1, according to the Corn Nitrogen Rate Calculator (Iowa State University Agronomy Extension, 2012), a widely-used resource for N fertilizer recommendations in the United States (Sawyer et al., 2006; Robertson and Vitousek, 2009).

Of the six N rate treatments at this site, those included in this study were 0, 135, and 225 kg N ha⁻¹ (hereafter N0, N135, and N225), for a total of 24 experimental plots (four replicates × two cover crop treatments × three N fertilizer rates). Individual plot size was 6.1 (eight maize rows) by 15.2 m length. Cover crop treatments were begun in fall 2008 and N rate treatments in spring 2009. Rye was drill-seeded after soybean harvest on 5 Oct. 2010 at 70 kg seed ha⁻¹ and killed with glyphosate [*N*-(phosphonomethyl)glycine] on 2 May 2011. Rye aboveground biomass was sampled before glyphosate application using a 0.09 m² frame at six random locations per replicate. Since soil NO₃ concentrations following 2010 soybean harvest did not differ between N rates, rye biomass was pooled from all N rates per replicate. Samples were dried at 60°C, ground to pass a 2-mm sieve, and subsampled for total C analysis by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI). Maize was planted on 10 May 2011 at 76-cm row spacing with the planter equipped with residue cleaners and no-till coulters. The N fertilizer was urea ammonium nitrate (UAN, 32% N), side-dressed in bands to 15-cm depth between every other crop row on 19 May 2011. Nitrogen fertilizer was therefore highly concentrated in a small soil zone, as is typical for injected N applied to maize, and concentrations of mineral N within these bands were very high relative to the surrounding soil.

Soil surface N₂O fluxes were measured in the 24 experimental plots approximately fortnightly from 11 Apr. to 3 Oct. 2011 using the static chamber method (Parkin and Venterea, 2010), with increased frequency following N fertilizer application. Polyvinyl chloride (PVC) rings (25 cm diam. by 10 cm height) were placed in the plots to 5-cm depth. Two rings were

placed in each plot in the following configuration: one ring directly over the N fertilizer band (or equivalent position in N0 plots), the second ring overlapping the adjacent crop row and the next inter-row space (which received no N fertilizer). Rings were removed during fertilizer application and replaced immediately afterward, to ensure that the rings were placed correctly relative to the bands. A vented PVC lid (25 cm diam. by 5 cm height) was used for a total chamber volume of 0.0049 m³. The lid was covered in reflective tape to minimize temperature change within the chamber during measurement. Change in N₂O concentration inside the chambers was analyzed in situ with a 1412 Infrared Photoacoustic Gas Monitoring System (Innova Air Tech Instruments, Ballerup, Denmark) (Iqbal et al., 2013). Fluxes were measured between 0800 and 1400 h to obtain flux rates proximate to the 24-h period (Adviento-Borbe et al., 2007, 2010). During each week of measurement, the four replicates were measured on different days; all six treatments were measured in one replicate on each day of measurement, with the treatment order randomized each day. Gas fluxes in all four replicates were measured a total of 13 times over the study period.

During each measurement, N₂O concentration in the chamber was determined every 2 min over 14 min, for a total of eight values including time zero. Since N₂O concentrations were observed to increase linearly over the 14 min of measurement, all eight values were used to calculate flux rates with a linear model. Flux rates with $R^2 < 0.65$ (due to non-increasing concentration inside the chamber) were considered zero. Flux rates from the two rings were weighted proportional to the area of the plot they represented. Cumulative N₂O emissions from the period of measurement were calculated by linear interpolation and numerical integration between sample times.

During each gas flux measurement, soil temperature at 5-cm depth was measured with a thermometer and volumetric water content to 5-cm depth was measured with a TH300 theta probe (Dynamax Inc., Houston, TX) within a meter of the rings. Since soil bulk density was observed not to vary with time or treatment over the period of measurement, soil volumetric water data were converted to water-filled pore space (WFPS) using the average bulk density (1.09 g cm⁻³) for the site. Soil samples (2 cm diam. to 10-cm depth) were collected during each gas flux measurement from the fertilizer band and crop row, corresponding to (but outside of) the two gas flux chambers in each plot. Soil samples were extracted in 2 M KCl (5:1 solution/soil ratio) by shaking for 1 h at 180 rpm. Extracts were filtered through pre-leached Whatman 1 filter paper and frozen until analysis. Extract (NO₃ + NO₂)-N (hereafter NO₃-N) and NH₄-N concentrations were measured in microplates using the Griess-Ilosvay reaction with vanadium(III) chloride as a reducing agent and the Berthelot reaction, respectively (Hood-Nowotny et al., 2010).

Incubation Study

In conjunction with the field study, we conducted a laboratory assay of soils from the fertilizer bands of the field site to determine if NO₃ or mineralizable C availability limited N₂O emissions at the three N rates under conditions favorable for denitrification.

Soil samples (2 cm diam. to 10-cm depth) were collected from the 24 field plots between 13 and 16 June 2011, before soil NO₃ concentrations in the bands had decreased substantially. These samples were taken directly from the fertilizer bands in N135 and N225 plots and the equivalent locations in N0 plots. Three soil samples were collected per plot and were immediately combined and homogenized. Soils were air-dried (~25°C) on returning to the lab and sieved to 4 mm. Initial NO₃-N and NH₄-N concentrations were determined in a subsample of air-dried soil from each plot using the methods described above. Soils from the two cover crop treatments were not analyzed separately since soils were air-dried before incubation. Instead, the cover crop treatments were pooled by N rate within each replicate and comparisons were made between incubating soils from the three N fertilizer rate treatments, to determine the effects of additional NO₃ and labile C additions to soils with varying concentrations of mineral N.

Soils were incubated in a fully-factorial design with four replicates, corresponding to the four replicates of each treatment in the field. Subsamples of 15 g air-dried soil were placed in 120-mL bottles for incubation. In a pilot study, soil water content of 90% water-holding capacity (WHC), or ~0.80 cm³ cm⁻³ WFPS, had been observed to maximize N₂O emissions from these soils (data not shown). Soils were brought to this water content with one of four treatment solutions: deionized water, 1 mM KNO₃ in water, 1 mM glucose (C₆H₁₂O₆) in water, or 1 mM of both KNO₃ and glucose in water. Concentrations of KNO₃ and glucose in treatment solutions were based on the denitrification enzyme assay protocol (Tiedje, 1994). Treatment solutions were applied fully factorially to soils for a total of 12 treatment combinations (3 N fertilizer rates × with or without NO₃ addition × with or without glucose addition) within each of the four replicates. Soils were then incubated in the dark at ~22°C with bottles open to laboratory air. Soils were maintained at 90% WHC by periodic re-application of the treatment solutions, though initial application accounted for 91% of water, KNO₃, and glucose added. Total additions over the 10 d incubation were 7.8 mg NO₃-N and 40.3 mg glucose-C kg⁻¹ soil.

Nitrous oxide emissions from the incubating soils were measured 1, 4, and 10 d after initial treatment solution application. Air samples were collected from the bottle headspaces at 0 and 30 min after sealing the bottles with rubber septa and stored in pre-evacuated Exetainer vials (Labco Ltd., Lampeter, Ceredigion, UK). An equal volume of laboratory air was added to each bottle immediately after removing the 0 min samples to maintain headspace pressure. Concentrations of N₂O in the vials were measured with a gas chromatograph (Agilent 7890, Santa Clara, CA) operated with an electron capture detector at 350°C. Gas species separation was accomplished with stainless steel columns packed with Porapak Q, 80/100 mesh and maintained at 85°C. Carrier gas was 10% CH₄ and 90% Ar. Carbon dioxide production in the incubating soils was measured more frequently over the 10 d of incubation using a LI-7000 infrared gas analyzer (LI-COR, Omaha, NE). Cumulative N₂O and CO₂ emissions were calculated by linear interpolation and numerical integration between sample times.

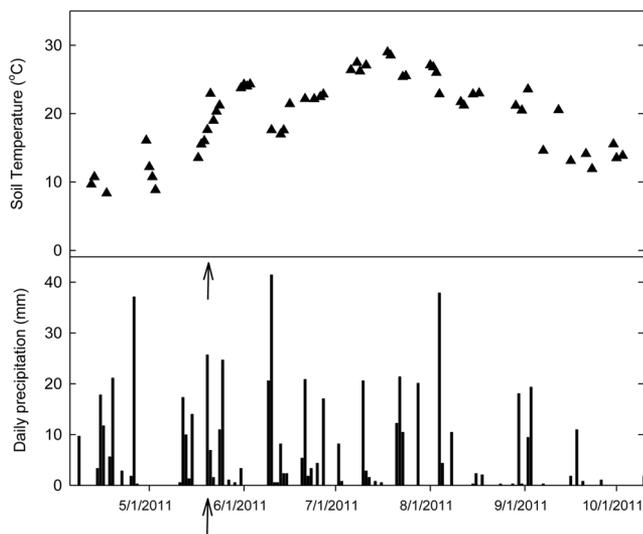


Fig. 1. Daily mean soil temperature at 5-cm depth and precipitation at the research site during the period of gas flux measurements (11 Apr.–3 Oct. 2011). The arrows below the x axes show the date of fertilizer application (19 May 2011).

Statistical Analyses

Soil $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentration data from the two soil sampling locations in the field plots (fertilizer band and crop

row) were analyzed separately. Soil $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentration data from the fertilizer bands and cumulative N_2O emission data from both the field and the incubation studies were log-transformed before analysis to meet the assumptions of normality and homogeneity of residuals. Soil temperature, moisture, and $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ concentration data from the field study were analyzed as repeated measures. All data were analyzed by analysis of variance using PROC GLM in Statistical Analysis Software package (SAS Institute Inc., Cary, NC).

RESULTS

Field Study

Rye produced 160 to 345 kg C ha^{-1} in aboveground biomass before herbicide application. Nitrogen fertilizer was applied during a period of relatively frequent precipitation and soil temperatures above 20°C (Fig. 1), and thus during conditions conducive to denitrification. Over the period of measurement, soil temperatures were highest in N0 but did not differ between the other N rates or cover crop treatments. Soil WFPS did not differ between cover crop treatments or N rates. The rye cover crop had no effect on soil NH_4 concentrations at all N rates (data not shown), but decreased NO_3 concentrations in the crop rows and fertilizer bands over all N rates (Fig. 2). Soil NO_3 concentrations in the fertilizer bands were greater at N225 than N135 (Fig. 2).

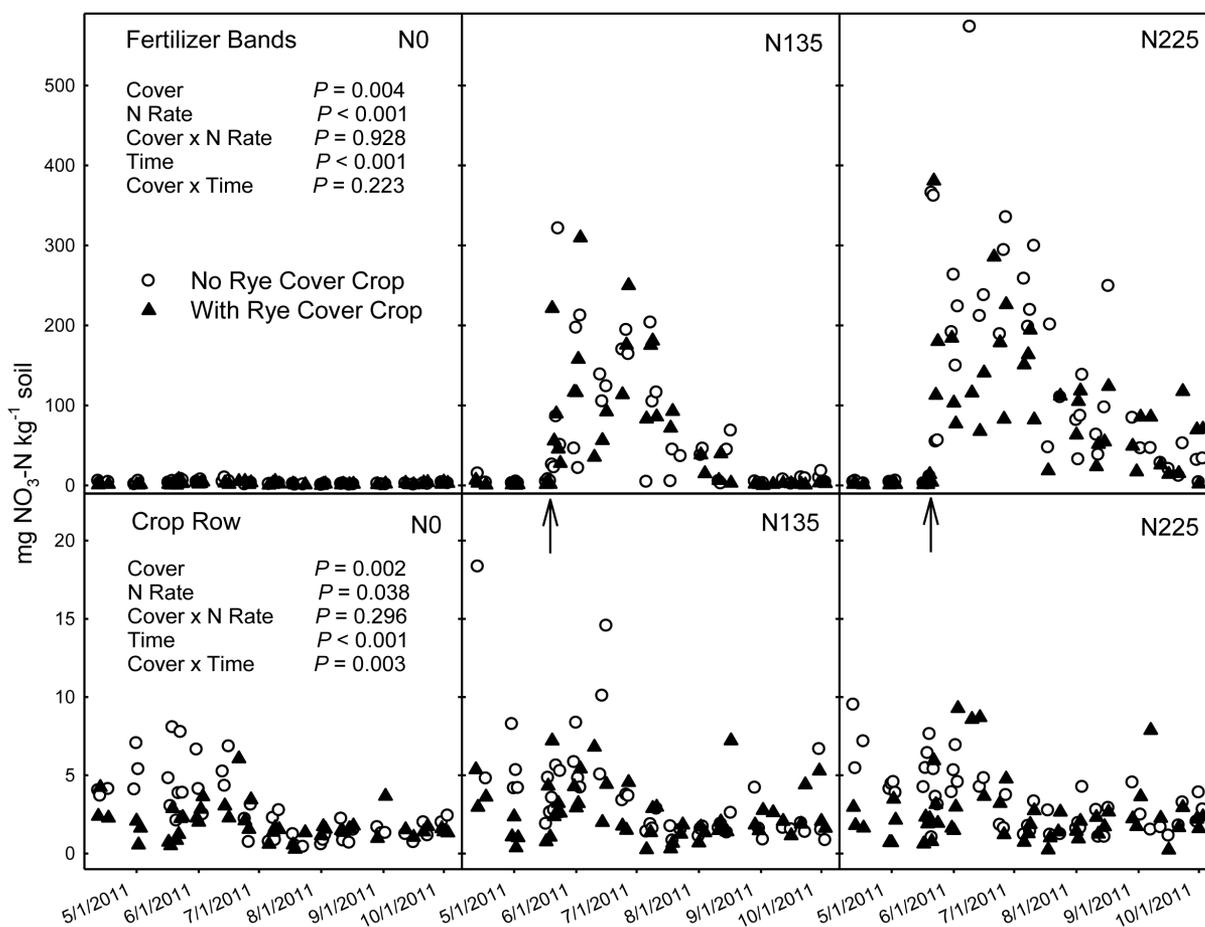


Fig. 2. Soil $\text{NO}_3\text{-N}$ concentrations at 0 (N0, left), 135 (N135, center), and 225 $\text{kg fertilizer N ha}^{-1}$ (N225, right) over the period of field gas flux measurements (11 Apr.–3 Oct. 2011) in the (top panels) fertilizer bands and (bottom panels) crop rows, with one-way analysis of variance results for each position. Note difference in y axis scaling between top and bottom panels. Fertilizer band data were log-transformed for statistical analysis. Arrows show date of fertilizer application in bands receiving fertilizer (19 May 2011).

Soils adjacent to the fertilizer bands were the dominant source of N_2O from the fertilized treatments at this site (Fig. 3). On average, fertilizer band soils accounted for 18, 65, and 70% of cumulative N_2O emissions at N0, N135, and N225, respectively. High ($>600 \text{ g } N_2O\text{-N ha}^{-1} \text{ d}^{-1}$) N_2O emission rates from the fertilizer band soils were only observed at WFPS $> 0.55 \text{ cm}^3 \text{ cm}^{-3}$ (relationship not shown). Cover crop and N rate treatments interacted to affect cumulative N_2O emissions (Fig. 4, Table 1). The rye cover crop decreased cumulative N_2O emissions at N0 (though this effect was only significant at $P = 0.1$), increased emissions at N135, and had no effect at N225 (Table 1). Without the cover crop, N_2O emissions were greater at N225 than N135. However, with the cover crop, emissions did not differ between these N rates (Fig. 4, Table 1).

Incubation

Initial NO_3^- and NH_4^+ concentrations in incubated soils were greater in soils from N225 than N135 and lowest in soils from N0 (Table 2). Across NO_3^- addition and glucose addition treatments, cumulative CO_2 emission from incubating soils did not differ between N fertilizer rates (Table 2). In contrast, N fertilizer rate (field treatment) had a main effect on cumulative N_2O emissions from the incubated soils (Table 3). Nitrate addition did not have a main effect on N_2O emissions from incubating soils; however, there was an interaction between N fertilizer rate

and NO_3^- addition (Table 3). Nitrate addition increased N_2O emissions from N0 soils but not N135 and N225 soils (Fig. 5). In contrast, there was a main effect of glucose addition on N_2O emissions (Table 3); glucose addition increased cumulative N_2O emission at all N rates (Fig. 6).

DISCUSSION

Field Nitrous Oxide Emissions

Nitrogen fertilizer is a major control on N_2O emissions from cultivated soils (Stehfest and Bouwman, 2006), and emissions of N_2O have been found to increase with N fertilizer rate, both linearly and nonlinearly (Kim et al., 2012). However, some studies have not found consistent increases in N_2O emissions with N fertilizer rate (e.g., Sehy et al., 2003; van Groenigen et al., 2004; Adviento-Borbe et al., 2007). In this study, N_2O emissions were greater in fertilized treatments than N0, but the relationship between N_2O emission and N rate was not consistent between cover crop treatments. Cumulative N_2O emissions were greater at N225 than N135 without the rye cover crop, but did not differ with the rye cover crop (Fig. 4 and Table 1), despite greater soil NO_3^- concentrations in N225 than N135 across cover crop treatments (Fig. 2).

Because N_2O emissions in the fertilizer band soils peaked under wet conditions (WFPS $> 0.55 \text{ cm}^3 \text{ cm}^{-3}$) conducive to denitrification, denitrification was likely the dominant N_2O -producing process in these soils. Since non-legume cover crops

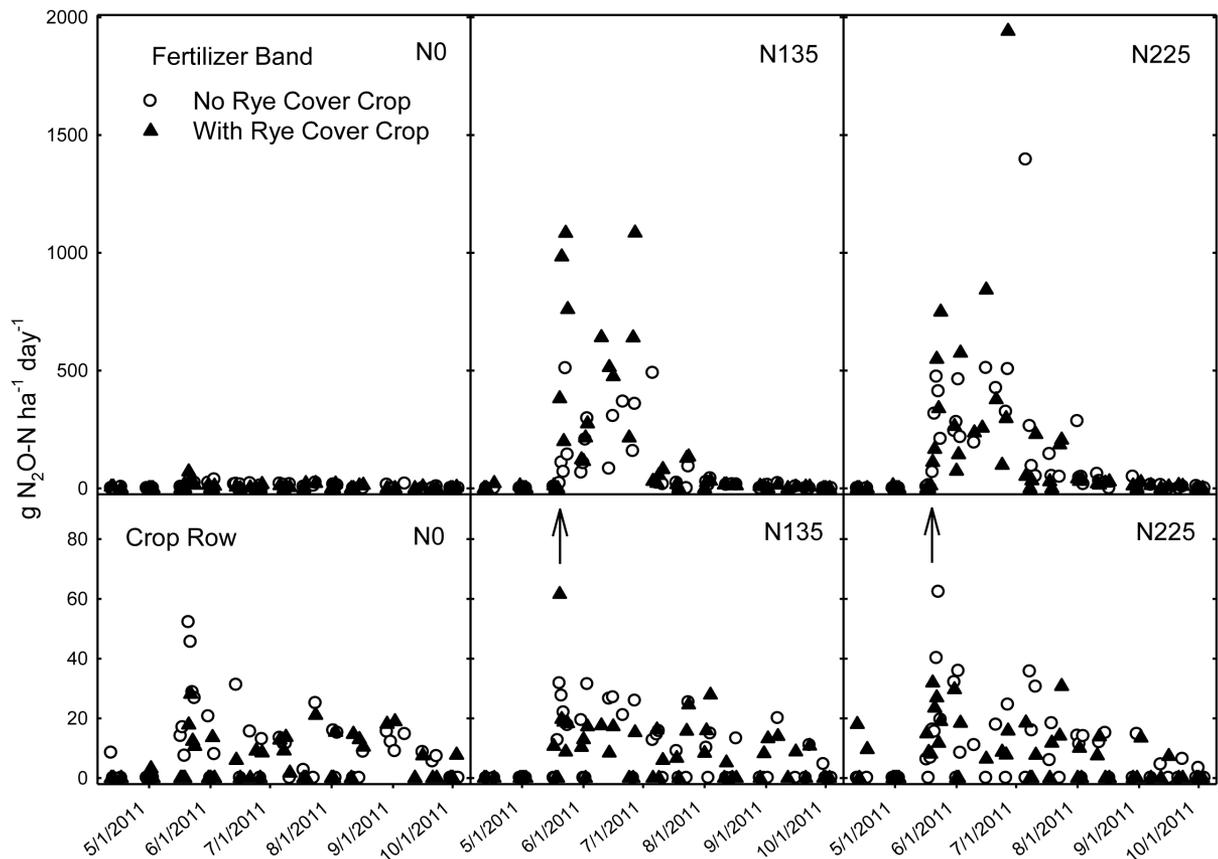


Fig. 3. Soil $N_2O\text{-N}$ emissions at 0 (N0, left), 135 (N135, center), and 225 kg fertilizer N ha^{-1} (N225, right) over the period of field gas flux measurements (11 Apr. –3 Oct. 2011) in the (top panels) fertilizer bands and (bottom panels) crop rows. Note difference in y axis scaling between top and bottom panels. Arrows show date of fertilizer application in bands receiving fertilizer (19 May 2011).

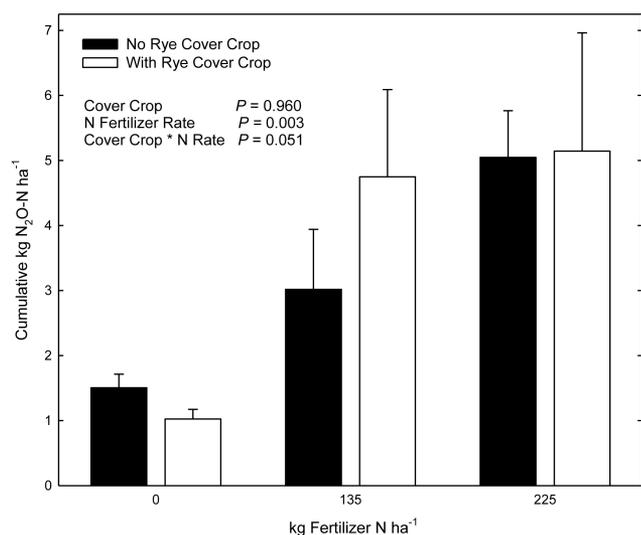


Fig. 4. Cumulative N₂O-N emissions from the field study (11 Apr. –3 Oct. 2011) with one-way analysis of variance results. Data were log-transformed for statistical analysis. Error bars show standard errors of means of four replicates.

can decrease soil NO₃ concentrations through uptake during growth and microbial immobilization during residue decomposition, they have potential to decrease N₂O emissions from denitrification (Baggs et al., 2000; McSwiney et al., 2010). However, despite decreasing soil NO₃ concentrations at all N rates (Fig. 2), the rye cover crop in this study only decreased cumulative N₂O emissions at N0, and increased cumulative N₂O emissions at N135 (Fig. 4 and Table 1). Although the cover crop had no consistent effect on cumulative N₂O emissions at N225, variability at this N rate with cover crop was exceptionally high (Fig. 3 and 4). These results indicate that N₂O emissions from denitrification were not limited by NO₃ availability in the fertilizer band soils due to the very high NO₃ concentrations in these soils. Since soil moisture, temperature, and NH₄ concentrations did not differ between cover crop treatments, the increase in N₂O emission with the rye cover crop at N135 cannot be explained by cover crop effects on these factors.

Limitation of N₂O emission by available C may partially explain the inconsistent relationships between N₂O emissions and fertilizer and cover crop treatments. Cover crop residue C inputs to NO₃-rich soils can stimulate N₂O production by denitrification (McKenney et al., 1995; Huang et al., 2004), especially when the cover crop kill coincides with N fertilizer application (Sarkodie-Addo et al., 2003; Petersen et al., 2011). In our study,

Table 2. Initial NO₃-N and NH₄-N concentrations and cumulative incubation CO₂-C emissions over 10 d in soils collected from the fertilizer bands of the field site in June 2011. Cumulative CO₂-C emissions are means across NO₃ and glucose addition treatments. Nitrate-N and NH₄-N concentrations were log-transformed before statistical analysis. Different letters indicate significant differences at P = 0.05 determined by LSD means comparison.

Fertilizer N concentrations	NO ₃ -N	NH ₄ -N	CO ₂ -C
kg fertilizer N ha ⁻¹	mg kg ⁻¹ soil		
0	5a	3a	200a
135	200b	203b	209a
225	339c	525c	216a

the rye cover crop provided 160 to 345 kg C ha⁻¹ in above-ground residue, in addition to root residue (not quantified), much of which was likely available for microbial mineralization after N application. Although we did not measure mineralizable organic C in the field directly, C availability was necessarily greater in the plots with the rye cover crop because no plants were growing in the plots without rye before maize planting. Thus, C inputs from cover crop residue may have influenced the increased N₂O emissions with the cover crop at N135 by stimulating denitrification after N application.

Incubation Treatments and Limitation on Nitrous Oxide Emission

Potential N₂O emissions from incubated soils were limited by NO₃ availability at N0 and by mineralizable C availability at N135 and N225. Nitrate addition did not increase N₂O emissions from soils collected from fertilized bands (Fig. 5), while glucose addition did increase N₂O emissions from these soils (Fig. 6). These results agree with previous studies demonstrating that denitrification rates and N₂O emission can be limited by availability of NO₃ in low-NO₃ soils and mineralizable C in high-NO₃ soils (e.g., Weier et al., 1993; Gillam et al., 2008). The results from this incubation demonstrate that mineralizable C inputs from the rye cover crop residue could have stimulated N₂O emissions from denitrification in the fertilizer band soils in this study.

Nitrous oxide emissions in incubating soils did not represent total denitrification rates because some N₂O produced was likely reduced to N₂ before diffusing from the soil. Some studies have found mineralizable C additions to decrease N₂O emissions from soils incubated at high water contents, attributed to greater reduction of N₂O to N₂ with increased C availability

Table 1. P values from pairwise t tests comparing mean cumulative N₂O-N emissions for each cover crop × N fertilizer rate treatment combination (shown in Fig. 4). Data were log-transformed before statistical analysis.

N fertilizer treatment	Cover crop treatment	N0		N135		N225	
		With rye cover crop	No rye cover crop	With rye cover crop	No rye cover crop	With rye cover crop	No rye cover crop
- P > t -							
N0	No rye cover crop	0.09	0.02	<0.01	<0.01	<0.01	<0.01
	With rye cover crop		<0.01	<0.01	<0.01	<0.01	<0.01
N135	No rye cover crop			0.05	0.01	0.03	0.03
	With rye cover crop				0.36	0.65	0.65
N225	No rye cover crop					0.63	0.63

Table 3. Analysis of variance of cumulative N₂O produced over 10 d in incubating soils. Cumulative emission data were log-transformed before statistical analysis.

Treatment	P > F
N fertilizer rate	<0.001
NO ₃ addition	0.308
Glucose addition	0.002
N fertilizer rate × NO ₃ addition	<0.001
N fertilizer rate × glucose addition	0.391
NO ₃ addition × glucose addition	0.344
N fertilizer rate × NO ₃ addition × glucose addition	0.382

(e.g., Miller et al., 2008; Sánchez-Martín et al., 2008). However, in this experiment, substantial reduction of N₂O to N₂ was likely inhibited by the high NO₃ concentrations in the fertilized soils (Blackmer and Bremner, 1978; Senbayram et al., 2012). In addition to denitrification, nitrification may have produced N₂O in the incubating soils; however, substantial production of N₂O by nitrification was unlikely because of the high WFPS at which soils were incubated (Firestone and Davidson, 1989).

Cover Crop Effects on Nitrous Oxide Emissions

The use of cover crops has been proposed to decrease N₂O emissions from cropping systems due to their ability to decrease mineral N availability for N₂O-producing processes (McSwiney et al., 2010; Eagle and Olander, 2012). However, the effects of cover crops on factors influencing N₂O emissions are complex and interact with other management practices. When N fertilizer is broadcast and incorporated, N immobilization by cover crops may decrease mineral N concentrations sufficiently to decrease N₂O emissions (McSwiney et al., 2010). In contrast, in this study, fertilizer was applied in concentrated bands, coincident with high rainfall (Fig. 1). Due to the high mineral N availability in soils in and directly adjacent to the bands, N immobilization in cover crop residue was likely insufficient to decrease N₂O emissions by decreasing NO₃ availability (Jarecki et

al., 2009). At the same time, given the favorable conditions for denitrification in these soils following N application, C substrate provided by cover crop residue likely stimulated denitrification and N₂O emissions at N135, the N rate closest to the economic optimum. It is not clear why this effect was not also observed at N225.

While cover crops may not decrease N₂O emissions from the soil surface, these emissions do not represent the total effect of cover crops on the global warming potential of agricultural systems. Non-legume cover crops, such as rye, can substantially decrease NO₃ leaching from agricultural soils (Tonitto et al., 2006). Since a percentage of leached NO₃ is expected to be denitrified to N₂O downstream, cover crops may decrease total N₂O emissions through their effect on NO₃ leaching (Snyder et al., 2009). Cover crops also affect soil C balance, both by providing inputs of C and by affecting crop yield (Thorup-Kristensen et al., 2003; Eagle and Olander, 2012). Consideration of these factors, in addition to N₂O emissions from the soil surface, is necessary to evaluate the total impact of cover crops on the greenhouse effect.

CONCLUSIONS

Despite decreasing soil NO₃ concentrations at a range of N fertilizer rates, a rye cover crop preceding maize only decreased N₂O emissions from unfertilized soils and increased N₂O emissions from soils treated with N fertilizer at a rate close to the economic optimum. The degree of mineral N immobilization by over-wintering cover crops may not be sufficient to decrease soil N₂O emissions from soil treated with banded N fertilizer when N is applied after the cover crop is killed. Furthermore, the input of mineralizable C in cover crop residue may stimulate N₂O production from denitrification in soils treated with banded fertilizer, increasing N₂O emissions from the soil. The effects of cover crops on multiple factors controlling N₂O emissions, including C availability, may impact N₂O emissions from cropping system soils.

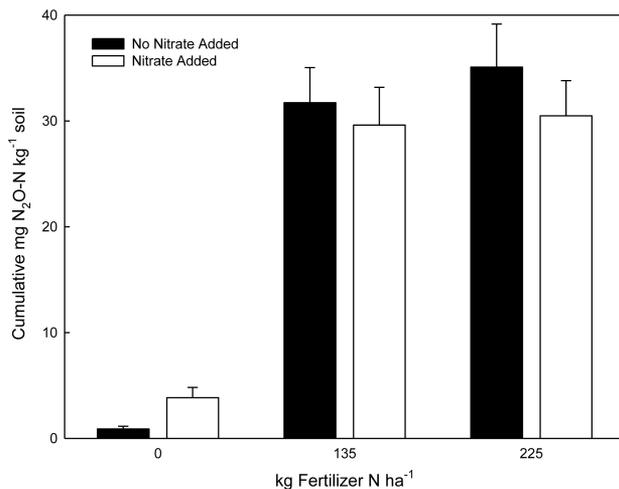


Fig. 5. Cumulative N₂O-N emissions over 10 d from soils collected from the fertilizer bands of the field site and incubated at 0.8 cm³ cm⁻³ WFPS, showing the effect of NO₃ addition at each N fertilizer rate across glucose addition treatments. Error bars show standard errors of means of four replicates.

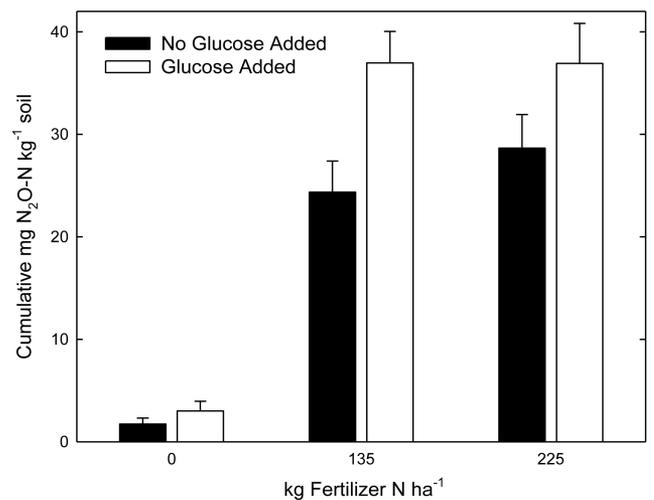


Fig. 6. Cumulative N₂O-N emissions over 10 d from soils collected from the fertilizer bands of the field site and incubated at 0.8 cm³ cm⁻³ WFPS, showing the effect of glucose addition at each N fertilizer rate across NO₃ addition treatments. Error bars show standard errors of means of four replicates.

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