Journal of Environmental Quality
TECHNICAL REPORTS
ATMOSPHERIC POLLUTANTS AND TRACE GASES

Does Nitrogen Fertilizer Application Rate to Corn Affect Nitrous Oxide Emissions from the Rotated Soybean Crop?

Javed Iqbal,* David C. Mitchell, Daniel W. Barker, Fernando Miguez, John E. Sawyer, Jose Pantoja, and Michael J. Castellano

Abstract

Little information exists on the potential for N fertilizer application to corn (*Zea mays* L.) to affect N_2O emissions during subsequent unfertilized crops in a rotation. To determine if N fertilizer application to corn affects N_2O emissions during subsequent crops in rotation, we measured N_2O emissions for 3 yr (2011–2013) in an Iowa, corn–soybean [*Glycine max* (L.) Merr.] rotation with three N fertilizer rates applied to corn (0 kg N ha^{-1}, the recommended rate of 135 kg N ha^{-1}, and a high rate of 225 kg N ha^{-1}); soybean received no N fertilizer. We further investigated the potential for a winter cereal rye (*Secale cereale* L.) cover crop to interact with N fertilizer rate to affect N_2O emissions from both crops. The cover crop did not consistently affect N_2O emissions. Across all years and irrespective of cover crop, N fertilizer application above the recommended rate resulted in a 16% increase in mean N_2O flux rate during the corn phase of the rotation. In 2 of the 3 yr, N fertilizer application to corn (0–225 kg N ha^{-1}) did not affect mean N_2O flux rates from the subsequent unfertilized soybean crop. However, in 1 yr after a drought, mean N_2O flux rates from the soybean crops that received 135 and 225 kg N ha^{-1} N application in the corn year were 35 and 70% higher than those from the soybean crop that received no N application in the corn year. Our results are consistent with previous studies demonstrating that cover crop effects on N_2O emissions are not easily generalizable. When N fertilizer affects N_2O emissions during a subsequent unfertilized crop, it will be important to determine if total fertilizer-induced N_2O emissions are altered or only spread across a greater period of time.

J. Environ. Qual. 44:711–719 (2015)
doi:10.2134/jeq2014.09.0378
Supplemental material is available online for this article.
Received 8 Sept. 2014.
Accepted 12 Jan. 2015.
*Corresponding author (jiqbal.soil@yahoo.com).

Greenhouse gas emissions from intensively managed, corn-based agroecosystems are dominated by N_2O (Robertson, 2000). In the United States, N fertilizer and manure application account for 74% of agricultural N_2O emissions (USEPA, 2014). Although sufficient N fertilizer is necessary to maintain high crop yields, excessive N fertilizer rates lead to a number of environmental costs, including water quality impairment and rising atmospheric N_2O concentration (Robertson and Vitousek, 2009). Reports suggest that NO_3 leaching and N_2O emissions from cropland increase exponentially when N fertilizer inputs exceed crop demand (Erickson et al., 2001; McSwiney and Robertson, 2005; Lawlor et al., 2008; Van Groenigen et al., 2010). Consistent with these reports, N fertilizer additions exceeding crop demand cannot be accounted for in soil nitrogen stocks (Brown et al., 2014).

Several states in the midwestern United States have adopted an economic approach to guide N fertilizer inputs to corn (Sawyer et al., 2006). In this approach, many recent N rate trials in the two dominant corn-based crop systems (corn–soybean rotation and continuous corn) are used to estimate economically profitable N input rates at different fertilizer and corn prices. The most profitable N rate, referred to as the maximum return to N (MRTN), identifies the N rate estimated to return the maximum profit as well as the rates within one dollar per acre of the maximum profit (Nafziger et al., 2004; Sawyer et al., 2006). The MRTN recommendations are updated annually with new N rate trials and made available through the online Corn Nitrogen Rate Calculator (Sawyer et al., 2006). With the focus on economic return, the MRTN rate is necessarily lower than the agronomic optimum rate. Using this N fertilization approach to predict N_2O emissions, Millar et al. (2010) suggested that optimization of N fertilizer inputs could lead to N_2O emissions reductions of more than 50%. However, the authors also highlighted the importance of considering additional strategies for emissions reductions.

The use of cover crops has been suggested as one such strategy (Eagle and Olander 2012). Nonleguminous cover crops are

J. Iqbal, D.C. Mitchell, D.W. Barker, F. Miguez, J.E. Sawyer, and M.J. Castellano, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011; J. Pantoja, Dep. of Life Sciences and Agriculture–IASA, Sangolqui, Ecuador. Assigned to Associate Editor Pierre-Andre Jacinthe.

Abbreviations: MRTN, maximum return to nitrogen; PVC, polyvinyl chloride; WFPS, water-filled pore space.

well known to decrease soil NO_3 (Tonitto et al., 2006), and soil NO_3 is often positively associated with N_2O emissions (Lin et al., 2010). Accordingly, it has been hypothesized that nonleguminous cover crops may also reduce N_2O emissions (Baggs et al., 2000; Jarecki et al., 2009). However, unlike the effects of cover crops on NO_3 leaching, the effects of cover crops on N_2O emissions are not easily generalizable: in a meta-analysis of 106 observations, Basche et al. (2014) found that cover crops increased N_2O emissions in 60% of observations and decreased N_2O emissions in 40% of observations.

Although growing research indicates that N fertilizer rate is the most important management factor affecting N_2O emissions from a N-fertilized crop (Millar et al., 2010), we know of no research that has investigated the potential for N fertilizer rate to affect N_2O emissions from subsequent crops in rotation that do not receive N fertilizer (e.g., soybean). Nevertheless, these crops cover vast production areas: in the United States, the 2014 soybean crop occupied 34.0 million ha (USDA–NASS, 2014). More than 80% of this area is concentrated in the upper midwestern United States (Ash, 2012).

The objective of this study was to investigate the impact of a winter cereal rye cover crop and three N fertilizer rates (zero N, a rate within the MRTN, and an excessive rate) on soil N_2O emissions from corn and soybean phases of a corn–soybean rotation. Two key questions were addressed: (i) Do cover crops and N fertilizer rate interact to affect N_2O emissions from the corn–soybean rotation? and (ii) Does greater than optimal N application to corn affect N_2O emissions from the subsequent unfertilized soybean phase of the crop rotation?

Materials and Methods

The study was conducted from 2011 to 2013 at the Iowa State University Agricultural Engineering and Agronomy Research Farm in Boone County, Iowa (42.02 N, 93.77 W). Average annual temperature and precipitation are 9.4°C and 872 mm yr^{-1}, respectively. Soils at the site are predominantly Clarion series (fine-loamy, mixed, superactive, mesic Typic Hapludolls), with 2.4% total organic C, 0.2% total N, and pH of 6.4 in water (1:1 soil-to-water ratio) from the 0- to 15-cm depth (Mitchell et al., 2013). The site was established to determine the effect of a rye cover crop on the MRTN of corn following soybean in a no-till system (Pantoja, 2013). The Corn Nitrogen Rate Calculator indicates the long-term MRTN for corn in an Iowa corn–soybean rotation without cover crop is 154 kg N ha^{-1}, with a range of rates from 141 to 167 kg N ha^{-1} that return a profit within one dollar per acre of the maximum profit at a fertilizer to grain price ratio of 0.1. The Corn Nitrogen Rate Calculator provides N fertilizer rate guidance for most land grant universities in the midwestern United States (Sawyer et al., 2006; Robertson and Vitousek, 2009).

The research site contained plots arranged in a split-plot design with six N fertilizer rates applied to corn in four replicates with and without rye cover crop. The presence or absence of winter rye cover crop was the main plot treatment, whereas N fertilizer rate to corn was the subplot treatment. Each year, half of the site was planted with corn, and the other half was planted with soybean. Crops were switched each year. Of the six N fertilizer treatments in each crop phase, three N fertilizer treatments (0, 135, and 225 kg N ha^{-1}; hereafter N0, N135, and N225) with and without rye cover crop were selected for this study. Soybean received no N fertilizer. Each plot was 6.1 m wide by 15.2 m long. The cover crop treatments were first implemented in fall 2008, and N fertilizer was first applied in spring 2009. Thus, before the first year of this study, all plots received one N fertilizer input to corn. Each year, the rye cover crop was drilled after fall grain harvest at 70 kg seed ha^{-1}. The rye was terminated with glyphosate [*N*-(phosphonomethyl) glycine] at 1 to 2 kg active ingredient ha^{-1} between 0 and 20 d before planting of the main (grain) crop each spring (Table 1). Immediately before glyphosate application, aboveground rye biomass was sampled using a 0.09-m^2 frame at six random locations per replicate. Each year, soil NO_3–N concentration after soybean did not differ between N rates, so rye biomass samples were pooled from all N rates per replicate for rye following soybean. For rye following corn, each plot was sampled. Rye biomass samples were dried at 60°C, ground to pass through a 2-mm sieve, and analyzed for total C and N using dry combustion (LECO CHN-2000 analyzer, LECO Corp.). Rye N fertilizer uptake was determined from N concentration and rye dry matter as described by Pantoja (2013). Nitrogen fertilizer was side-dressed 9 to 26 d after corn planting, depending on soil conditions, as urea ammonium nitrate solution (32% N) injected in bands to 15-cm depth between every other corn row (Table 1). Phosphorus (triple superphosphate, 0–46–0) and K (potash, 0–0-60) fertilizers were applied at approximate crop removal rates for the corn–soybean rotation as needed to maintain soil tests (56 kg P ha^{-1} and 140 kg K ha^{-1} every 2 yr).

Soil N_2O Emission Measurements

Soil N_2O emissions were measured when soil temperatures were >7.2°C (Apr.–Sept. 2011 and 2012 and May–Oct. 2013). Each replicate of each treatment within both crops of the rotation in each growing season was measured approximately fortnightly, with more frequent sampling after spring fertilizer applications in corn. Our measurement frequency was designed to determine if there was a treatment effect on the mean rate of N_2O emissions, not to determine the cumulative amount of N_2O emissions from each treatment. In 2011 and 2012, two polyvinyl chloride (PVC) rings (25 cm diameter by 10 cm

Table 1. Timing of treatment applications and crop management.

Parameter/year	Corn			Soybean		
	2011	2012	2013	2011	2012	2013
Cover crop planting (fall of prior year)	5 Oct.	3 Oct.	20 Sept.	5 Oct.	6 Oct.	20 Sept.
Cover crop termination	2 May	6 Apr.	27 Apr.	10 May	25 Apr.	15 May
Row crop planting	10 May	26 Apr.	17 May	10 May	11 May	24 May
Nitrogen fertilization	19 May	11 May	13 June	–	–	–
Row crop harvest	5 Oct.	17 Sept.	8 Oct.	30 Sept.	19 Sept.	2 Oct.

height) were placed in corn plots so that one ring covered the fertilizer band while the other covered the adjacent crop row and part of the next inter-row space, which did not receive N fertilizer. The equivalent positions for ring placement were used in N0 in corn and all soybean plots. In 2013, to reduce the labor and time requirements for gas sampling, aluminum rectangular frames (82 cm long × 44 cm wide × 10 cm height) were installed in the same position covered previously by two PVC rings in both crop phases. The PVC rings and rectangular frames served as gas chamber bases and were left in place during the sampling periods except when temporarily removed to allow field operations. Both sampling chamber designs are recommended by the USDA GraceNet greenhouse gas sampling protocol, and this protocol was used to guide sampling (Parkin and Venterea, 2010). During the study period, changes in N_2O concentration inside the chambers were measured in situ with a 1412 Infrared Photoacoustic Gas Monitoring System (Innova Air Tech Instruments) or by gas chromatography analysis in the laboratory, depending on the labor availability and time constraints. These two techniques have been shown to produce statistically identical results (Ambus and Robertson, 1998; Iqbal et al., 2013). Gas measurements were performed between 0800 and 1400 h to obtain representative daily gas fluxes (Adviento-Borbe et al., 2010).

Gas measurements were performed by placing vented PVC chambers on the rings or vented aluminum rectangular chambers on the rectangular bases. The PVC chambers were covered with reflective tape and rectangular chambers with thermal insulation sheet to minimize the temperature changes inside the chambers during the sampling period. When using the infrared photoacoustic gas monitoring system method, N_2O concentration was measured every 2 min during a 14-min chamber closure. When using the GC method, gas samples (10 mL) were collected with polypropylene syringes at 0, 15, 30, and 45 min after chamber closure, immediately injected into evacuated glass vials (6 mL), and brought to the laboratory for GC analysis. The gas chromatograph (Restek Corp.) was operated with an electron capture detector at 350°C for N_2O measurements. Gas species separation was accomplished with stainless steel packed columns (Porapak Q, 80/100 mesh) maintained at 85°C. The increase in N_2O concentration over time was best fit with linear regression.

During each gas sampling event, soil temperature was measured at 5 cm depth with a digital thermometer (AcuRite; ±0.5°C). At the same time, volumetric soil moisture content was measured at 5 cm depth with a TH300 theta probe (Dynamax Inc.; ±3% volumetric water content). Because soil bulk density values did not differ across sampling dates within the first growing season, random-date soil sampling with a 2 × 10 cm auger were performed during the 2012 and 2013 growing seasons, and soil bulk density values were averaged for each season. Soil bulk density was determined using soil weight (moisture corrected) and core volume. Soil water-filled pore space (WFPS) was calculated by using volumetric soil moisture content and bulk density. At each gas sampling event, soil was sampled with a 2-cm-diameter probe to a depth of 10 cm from the outside of each chamber in fertilizer bands and the equivalent position in nonfertilized plots. Soils were sampled from fertilizer bands because previous research showed that fertilizer bands were the source of most N_2O emissions (Mitchell et al., 2013). Soil samples were extracted with 2 mol L^{-1} KCl solution (5:1 solution/soil ratio) with shaking for 1 h at 180 rpm. Extracts were subsequently filtered through preleached Whatman 1 filter paper. Extracts were frozen until analyzed for NO_3 + NO_2–N (hereafter NO_3–N) and soil NH_4–N concentration 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).

During the study period, daily precipitation data were collected from the Iowa State University Agronomy Farm Research Station. Cumulative growing degrees were calculated following (Abendroth et al., 2011) using 10°C as the base temperature and 30°C as the maximum temperature.

Statistical Analysis

Because soil N_2O flux rates and NO_3–N data were not normally distributed, they were log transformed to meet the assumption of normal distribution before analysis with SAS 9.4 (SAS Institute Inc.). Data for individual years and each crop phase were analyzed separately. Differences in soil temperature, WFPS, soil N_2O flux rates, soil NO_3–N, and soil NH_4–N for across fertilizer rates, cover crop treatment, time, and their interactions were analyzed through repeated measures PROC MIXED. Corn and soybean yields and rye biomass and N uptake differences among treatments were analyzed using PROC ANOVA, with rye cover crop the main plot and N rate the split-plot. The pdiff option was used to identify significant differences ($P \leq 0.05$) between main effects of N rate and cover crop and interactions between N rate and cover crop.

Results

Weather and Crop Yield

Annual precipitation was lower than the 30-yr average (872 mm yr^{-1}) in 2011 (816 mm), the drought year of 2012 (637 mm), and 2013 (852 mm). However, precipitation in the early part of the 2013 growing season (May–July) was higher (418 mm) than average (353 mm) (Supplemental Fig. S1). Compared with the long-term mean annual temperature of 9.4°C, mean annual air temperatures were higher in 2011 (10°C) and 2012 (12°C) but lower in 2013 (8.7°C). Relative to the 30-yr average, growing degree days were higher in the drought year of 2012 but lower in 2011 and 2013 (Supplemental Fig. S1).

Across all years with and without cover crop, corn yield in N0 was significantly lower than N135 and N225, although the latter two N rates were not significantly different from each other in 2011 and 2012 (Table 2). Nitrogen fertilizer rate to corn did not affect soybean yield in any year (Table 2). Corn yield was significantly lower with cover crop (10.5 Mg ha^{-1}) compared with no cover crop (11.3 Mg ha^{-1}; $P < 0.01$) (Table 2) (Pantoja, 2013), whereas soybean yield was not affected by cover crop treatment (3.57 Mg ha^{-1} with cover vs. 3.61 Mg ha^{-1} without cover crop) (Pantoja, 2013). In the 2011 soybean phase, aboveground rye biomass and N uptake did not differ between treatments. However, in the 2012 and 2013 soybean phase, there were significant differences in rye biomass and N uptake

Table 2. Mean annual yields of corn and soybean grain, rye dry biomass, and N uptake.

Treatment†	Year	Corn grain yield with rye	Corn grain yield without rye	Rye dry biomass before corn planting‡	Rye N uptake before corn planting‡	Soybean grain yield§	Rye dry biomass before soybean planting	Rye N uptake before soybean planting
		Mg ha^{-1}			kg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}
N0	2011	3.82 ± 0.19b¶	6.12 ± 0.23b	–	–	3.87 ± 0.07a	0.74 ± 0.05a	15.80 ± 0.93a
N135		11.40 ± 0.26a	11.63 ± 0.16a	–	–	3.74 ± 0.04a	0.70 ± 0.09a	15.69 ± 1.26a
N225		12.26 ± 0.51a	12.44 ± 0.35a	–	–	3.72 ± 0.04a	0.60 ± 0.08a	14.98 ± 1.52a
‡		–	–	0.62 ± 0.12	19.81 ± 3.05	–	–	–
N0	2012	3.15 ± 0.24b	5.50 ± 0.22b	–	–	4.24 ± 0.13a	1.67 ± 0.26b	25.94 ± 4.17b
N135		10.69 ± 0.95a	11.7 ± 0.89a	–	–	4.42 ± 0.12a	1.94 ± 0.20b	33.73 ± 4.40b
N225		10.59 ± 1.00a	11.26 ± 0.71a	–	–	4.29 ± 0.10a	2.94 ± 0.29a	69.30 ± 8.67a
‡		–	–	1.07 ± 0.08	27.58 ± 1.31	–	–	–
N0	2013	2.84 ± 0.06b	3.64 ± 0.18c	–	–	2.88 ± 0.06a	1.54 ± 0.13b	22.17 ± 2.08b
N135		7.94 ± 0.64a	8.21 ± 0.30b	–	–	2.70 ± 0.14a	2.31 ± 0.41ab	44.76 ± 10.25b
N225		8.80 ± 0.28a	9.96 ± 0.26a	–	–	2.63 ± 0.13a	3.05 ± 0.19a	70.76 ± 8.79a
‡		–	–	0.58 ± 0.05	16.49 ± 1.07	–	–	–

† N0, N135, and N224 indicate 0, 135, and 224 kg N fertilizer ha^{-1}, respectively.

‡ Because soil NO_3–N concentration after soybean each year did not differ between N rates, rye biomass was pooled together from all N rates per replicate.

§ Means of soybean grain yield with and without rye.

¶ Values are mean ± SE. Different letters within a column and year indicate significant differences among treatments at $P \leq 0.05$.

between the treatments, with higher values in N225 than N135 and N0 (Table 2).

Soil Temperature and Water-Filled Pore Space

During the 3 yr of this study, soil temperature did not differ among N fertilizer rates except in the corn phase of 2011 and the soybean phase of 2013, when it was significantly higher in N0 compared with N135 and N225, with the latter two N rates not significantly different (Table 3). No cover crop effect on soil temperature was observed (Fig. 1). Water-filled pore space did not differ among N fertilizer rates (Table 3) but was significantly higher in cover crop compared with no cover crop treatment at certain times during the corn phase of 2012 (Fig. 1).

Soil Nitrate Concentration

Average soil NO_3–N concentration was significantly different among all N fertilizer rates in all three corn years (Fig. 2; Table 4). No significant differences in NO_3–N were observed among N fertilizer treatments in the soybean year of 2011 (Table 4). However, there were small but significant effects of N fertilizer rate applied to corn on NO_3–N concentration in the soybean year of 2012, with higher NO_3–N concentration in N0 and N225 than N135, and the soybean year of 2013, with higher NO_3–N concentration in N225 compared with N135 and N0 (Fig. 2; Table 4). Overall, the NO_3–N concentration in the 2012 drought year in soybean was 64 to 72% higher than in year 2011 and 28 to 57% higher than in year 2013.

Within fertilizer rates, the cover crop did not have a consistent effect on soil NO_3–N concentration. In corn, no significant reduction in NO_3–N concentration in the cover crop vs. no cover crop treatment was found except in N225 during 2011 (Fig. 3). In soybean, however, the cover crop significantly reduced soil NO_3–N concentration across several N rates and years: N0 in 2011, N225 in 2011, N0 in 2013, and N135 in 2013 (Fig. 3). Cover crop and time interacted to affect NO_3–N concentration so that NO_3–N concentrations were lower in the cover crop treatments during part of the corn phase in all years and part of the soybean phase during 2013 (Table 4).

Soil N_2O Flux Rates

Averaged across all 3 yr and cover crop treatments, the increase in N fertilizer rate from N135 (a rate near the MRTN) to N225 (excessive N rate) increased mean soil N_2O flux rates by 16% in

Table 3. Mean soil temperature and water-filled pore space in corn and soybean phases.

Treatment/year†	Corn			Soybean		
	2011	2012	2013	2011	2012	2013
	Soil temperature (°C)					
N0	20.32 ± 0.63a‡	20.46 ± 0.54a	21.96 ± 0.38a	19.43 ± 0.69a	20.68 ± 0.67a	20.23 ± 0.38a
N135	19.70 ± 0.57b	22.67 ± 1.86a	21.40 ± 0.42a	19.25 ± 0.71a	20.36 ± 0.72a	19.70 ± 0.38b
N225	19.41 ± 0.57b	20.59 ± 0.46a	21.47 ± 0.39a	18.96 ± 0.70a	20.22 ± 0.67a	19.69 ± 0.43b
	Water-filled pore space (%)					
N0	50.08 ± 1.10a	33.77 ± 1.36a	48.63 ± 1.92a	46.78 ± 1.04a	46.36 ± 1.93a	48.79 ± 2.18a
N135	48.73 ± 1.09a	33.54 ± 1.25a	47.50 ± 1.90a	47.24 ± 0.98a	44.91 ± 1.80a	49.03 ± 2.11a
N225	50.25 ± 1.07a	32.76 ± 1.33a	49.08 ± 2.07a	47.51 ± 1.07a	46.00 ± 2.19a	47.88 ± 2.35a

† N0, N135, and N224 indicate 0, 135, and 224 kg N fertilizer ha^{-1}, respectively.

‡ Values are mean ± SE. Different letters within a column and a year indicates significant differences among treatments at $P \leq 0.05$.

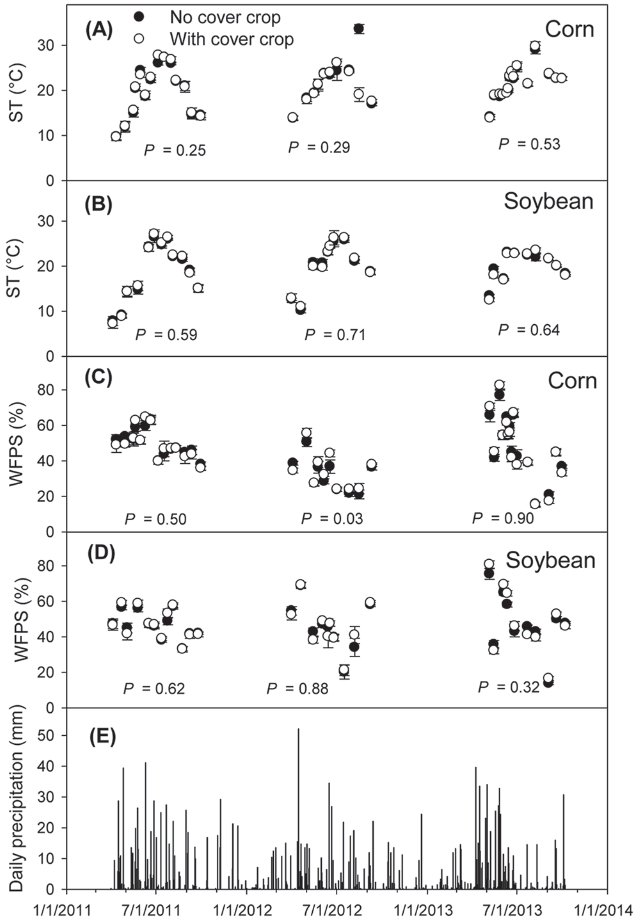

Fig. 1. Mean soil temperature (ST; °C) (A, B) and percent water-filled pore space (WFPS %) (C, D) at 0- to 5-cm soil depth over the periods of gas flux measurements (4 Apr.–25 Sept. 2011, 1 Apr.–8 Sept. 2012, and 7 May–10 Oct. 2013) and daily precipitation in mm (E) from April 2011 to October 2013. Vertical bars indicate SEM (*n* = 4). Probability values (repeated measures PROC MIXED) for the main effect of cover crop on mean ST and WFPS in each crop phase are shown.

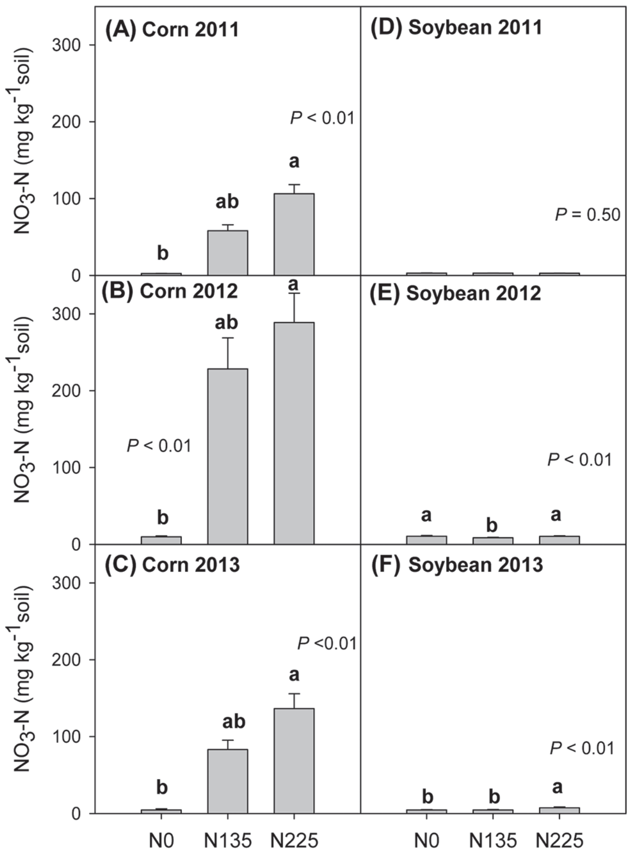

Fig. 2. Corn phase (A–C) and soybean phase (D–F) mean soil NO_3–N concentration at 0- to 10-cm soil depth with 0 (N0), 135 (N135), and 225 (N225) kg N fertilizer ha^{-1} applied in the corn phase only. Probability values (repeated measures PROC MIXED) for the main effect of N fertilizer on mean soil NO_3–N concentration are shown within each graph. Different letters indicate significant difference among treatments ($P \leq 0.05$). Vertical bars indicate SEM.

corn (Fig. 4). This increase in N_2O flux rate was accompanied by a 6% increase in corn yield (Table 2).

In 3 yr of the corn phase, soil N_2O flux rates were significantly different between the two N fertilizer treatments and control, being higher in N225 and N135 compared with N0 (Fig. 4; Table 5). However, N fertilizer rate to corn did not affect N_2O flux rates in the subsequent soybean phase except in 2013, when N_2O flux rates from N225 and N135 were 70 and 35% higher than N0, respectively (Fig. 4).

The rye cover crop did not have a consistent effect on N_2O flux rate across N fertilizer treatments in corn (Table 5; Fig. 5): in 2011, the cover crop significantly reduced N_2O flux in the N0 treatment but increased N_2O emission in the N135 treatment. No significant effects of cover crop or cover crop by N rate interactions were found in corn for the other years. Cover crop effects on N_2O flux rate were also inconsistent during soybean (Fig. 5): the cover crop reduced flux rate in 2011 (Table 5) but had no effect in other years.

Discussion

Nitrogen Carry-Over from Corn to Soybean

To our knowledge, the potential for N fertilizer to affect N_2O emissions from a subsequent unfertilized crop in rotation

Table 4. Probability values (repeated measures PROC MIXED) for the main effect of N fertilizer rate (NF), cover crop (CC), time, and their interaction on soil NO_3–N concentrations measured during the growing seasons of 2011, 2012, and 2013.

Effect/year	Corn			Soybean		
	2011	2012	2013	2011	2012	2013
NF	<0.01	<0.01	<0.01	0.50	<0.01	<0.01
Time	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NF × time	<0.01	<0.01	<0.01	0.43	0.12	0.01
CC	<0.01	0.51	0.48	<0.01	0.44	<0.01
NF × CC	0.89	0.44	0.05	0.14	0.84	0.08
CC × time	0.03	<0.01	<0.01	0.17	0.19	<0.01
NF × CC × time	0.40	0.41	<0.01	0.33	0.03	0.93

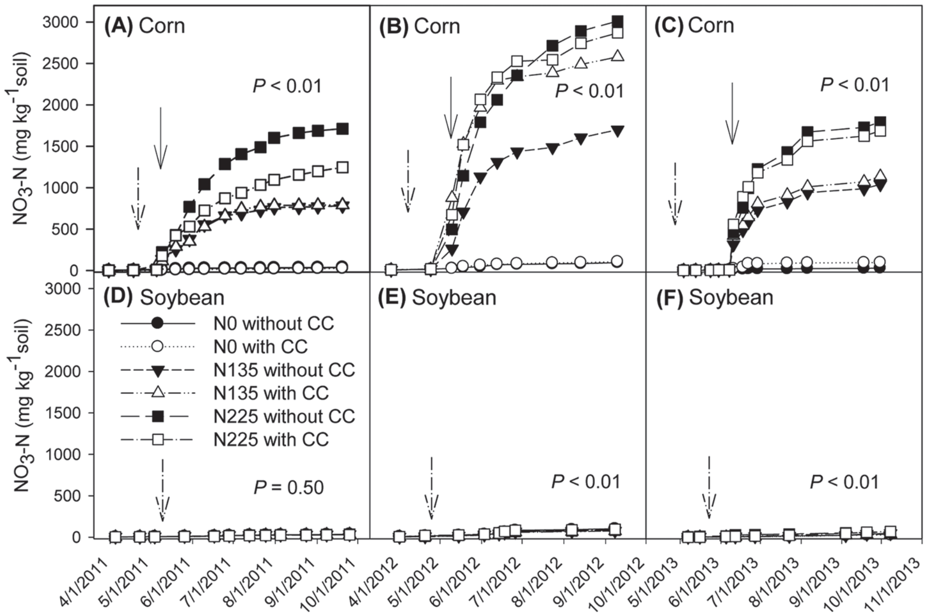

Fig. 3. Corn phase (A–C) and soybean phase (D–F) cumulative mean soil NO_3–N concentrations at 0- to 10-cm soil depth with 0 (N0), 135 (N135), and 225 (N225) kg N fertilizer ha^{-1} applied in the corn phase only with or without cover crop (CC) over the period of gas flux measurements. Solid arrows indicate the date of N fertilizer application to corn crop; dash-dot arrows indicate the date of cover crop termination. Probability values (repeated measures PROC MIXED) for the main effect of N fertilizer on mean soil NO_3–N concentration are shown within each graph. The instantaneous soil NO_3–N concentration for each date can be calculated by subtracting the preceding value in time (i.e., if soil NO_3–N concentration was 0, there is no change from one sample date to the next). An increase in slope between consecutive sample points indicates an increase in soil NO_3–N concentration; a decrease in slope between consecutive sample points indicates a decrease in soil NO_3–N concentration.

has not been reported. We tested this potential and found that N fertilizer input to corn affected N_2O emissions from the subsequent soybean crop after a year of drought. Although this effect was limited to unusual weather conditions, the effect was large: excessive N fertilizer application (N225) resulted in a 75% increase in mean N_2O flux rate during the soybean year.

In situations when N input to corn affects N_2O emissions from the subsequent crop, there are two possible scenarios for

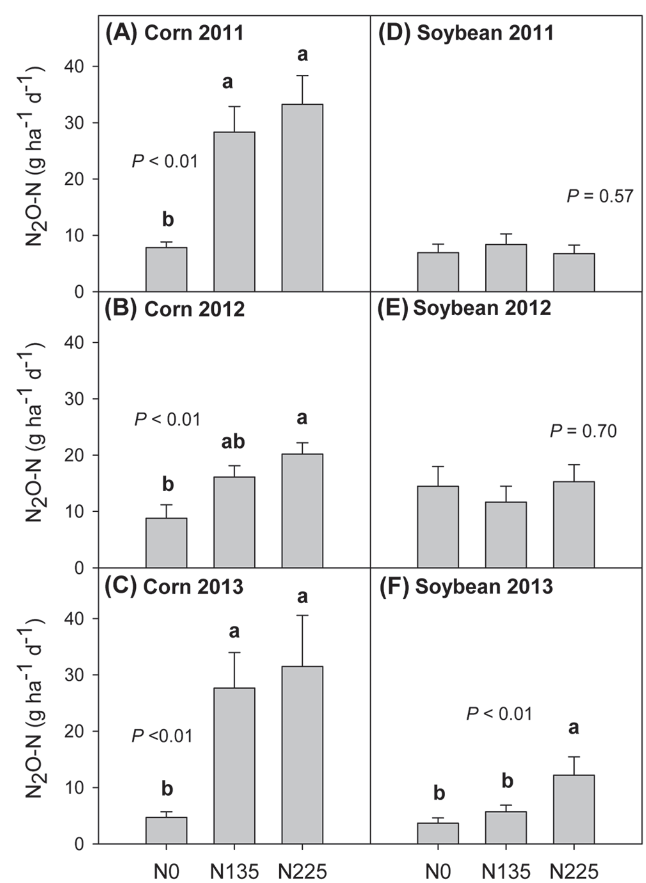

Fig. 4. Corn phase (A–C) and soybean phase (D–F) mean soil N_2O–N emissions with 0 (N0), 135 (N135), and 225 (N225) kg N fertilizer ha^{-1} applied in the corn phase only. Probability values (repeated measures PROC MIXED) for the main effect of N fertilizer on mean soil N_2O–N emissions are shown within each graph. Different letters indicate significant difference among treatments ($P \le 0.05$). Vertical bars indicate SEM.

Table 5. Probability values (repeated measures PROC MIXED) for the main effect of N fertilizer rate (NF), cover crop (CC), time, and their interaction on N_2O–N emissions measured during the growing seasons of 2011, 2012, and 2013.

Effect/year	Corn			Soybean		
	2011	2012	2013	2011	2012	2013
NF	<0.01	<0.01	<0.01	0.57	0.70	<0.01
Time	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NF × time	<0.01	<0.01	<0.01	0.86	0.80	0.31
CC	0.79	0.65	0.44	0.05	0.18	0.47
NF × CC	0.01	0.34	0.44	0.82	0.62	0.14
CC × time	0.62	<0.01	0.01	0.06	0.17	0.12
NF × CC × time	0.28	0.74	0.62	0.42	0.62	0.70

total N_2O emissions. Either the sum of N_2O emissions from the 2-yr rotation is increased, or the sum of N_2O emissions from the 2-yr rotation is unchanged in total amount but shifted across years (i.e., less N_2O emissions during the corn phase, more N_2O emissions during the soybean phase). For example, N_2O emissions from N fertilizer treatments during the 2012 drought year in corn (N fertilizer input crop) were lower than the nondrought years of 2011 and 2013 (Fig. 5). Future field studies with greater measurement frequency are needed to determine cumulative N_2O emissions.

In the upper midwestern United States, the largest N flux from the corn–soybean system to the surrounding environment is NO_3–N loss in soil water drainage, which frequently exceeds 30 kg NO_3–N ha^{-1} yr^{-1} (Randall et al., 1997; Jaynes et al., 2001; Kladivko et al., 2004; David et al., 2010). When a lack of soil water precludes soil water drainage and crop N uptake, soil profile NO_3–N accumulates and can exceed 250 kg NO_3–N ha^{-1} (Randall et al., 1997). It is possible that such an accumulation may enhance the sum of N_2O emissions from each crop phase of the 2-yr rotation because surface soils are the primary source of N_2O production in these systems (Iqbal et al., 2015) and because surface soils often become saturated (thus promoting N_2O emissions) despite unsaturated subsoil and no drainage (Goldberg, 2009).

Cover Crop Effects

A number of factors may have resulted in the lack of a consistent cover crop effect on soil NO_3–N concentrations in this study. Winter rye is terminated at an earlier date when preceding corn than soybean because (i) corn is typically planted earlier than soybean and (ii) corn grain yield can be negatively affected when there is a short time lag between cover crop termination and corn planting, whereas soybean yield is unaffected by the proximity of cover crop termination and soybean planting (e.g., Table 1) (Pantoja, 2013). The longer growth period for the cover crop may have been one reason why cover crop presence before the soybean phase of the rotation significantly reduced soil NO_3–N concentrations in 2 of 3 yr, whereas cover crop presence before the corn phase of the rotation significantly reduced soil NO_3–N concentration in only 1 yr.

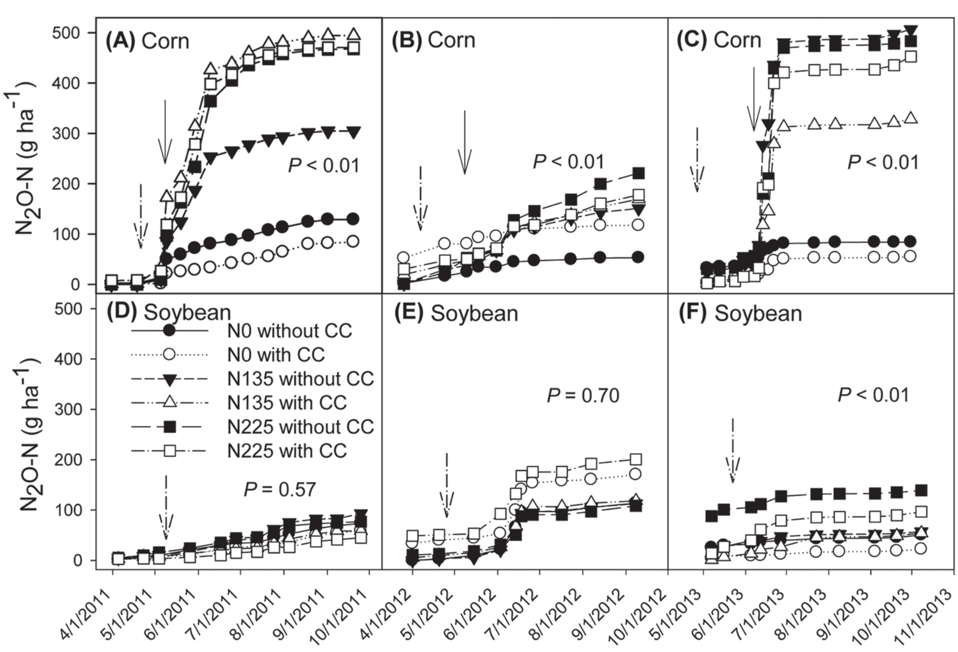

Fig. 5. Corn phase (A–C) and soybean phase (D–F) cumulative mean soil N_2O–N emissions with 0 (N0), 135 (N135), and 225 (N225) kg N fertilizer ha^{-1} applied in the corn phase only with and without rye cover crop (CC) over the period of gas flux measurements. Solid arrows indicate date of N fertilizer application; dash-dot arrows indicate the date of cover crop termination. Probability values (repeated measures PROC MIXED) for the main effect of N fertilizer on mean N_2O–N emissions are shown within each graph. The instantaneous N_2O–N flux for each date can be calculated by subtracting the preceding value in time (i.e., if soil N_2O–N flux was 0, there is no change from one sample date to the next). An increase in slope between consecutive sample points indicates an increase in soil N_2O–N emissions. A decrease in slope between consecutive sample points indicates a decrease in soil N_2O–N emissions.

Cover crops have been proposed as a strategy to reduce N_2O emissions because cover crops can reduce soil NO_3–N concentrations, which are often positively correlated with N_2O emissions (Eagle and Olander, 2012). However, consistent with our results, research demonstrates that cover crops do not consistently reduce N_2O emissions and may increase N_2O emissions in certain situations. A recent meta-analysis of published reports found that cover crops increased N_2O emissions in 60% of 106 observations, and certain management practices (e.g., cover crop residue incorporation) routinely increased N_2O emissions (Basche et al., 2014). A previous study at our research site implicated labile organic carbon inputs from cover crops as a cause of increased N_2O emissions relative to a no-cover-crop control (Mitchell et al., 2013). However, a number of factors can affect interactions among the biophysical processes that control N_2O emissions. These include, but are not limited to, the timing and method of cover crop termination and N fertilizer application. A better understanding of how cover crop management interacts with weather to affect soil processes may identify strategies that consistently reduce N_2O emissions. However, at present, it is not clear that cover crops can be managed to assuredly reduce N_2O emissions.

Exceptionally high variation of N_2O flux rates across time and treatments (Fig. 5) makes it difficult to understand the interactive effects of weather and management factors on N_2O emissions. We observed no effect of cover crop treatment on WFPS or soil temperature that would alter N_2O emissions. Thus, we suggest that high temporal variation in N_2O emissions could be due to complex interactions among cover crop, soil temperature, soil moisture, soil NO_3–N, N fertilizer application timing, and crop management. With the exception of N fertilizer inputs, our site was managed for optimum production. Thus, the time between cover crop termination and N fertilizer application date was different across years due to weather variability (17, 35, and 46 d for 2011, 2012, and 2013, respectively). Several patterns in our data suggest these differences in timing led to variation in our results. For example, in 2011, when N fertilizer was applied 17 d after cover crop termination, N135 with cover crops had higher N_2O flux rates than N135 without cover crops. However, in 2012, when N fertilizer was applied 35 d after cover crop termination, there was no effect of cover crop on N_2O flux rate in N135 or N225. Yet, in 2013, when N fertilizer was applied 46 d after cover crop termination, N135 and N225 with cover crops had lower flux rates than N135 and N225 without cover crops. Higher N_2O flux rates in the cover crop treatment when there was a short time lag (17 d) between cover crop termination and N fertilizer application date could be due to the decomposition of relatively labile, low C/N ratio cover crop residue components that promote anearobicity and provide a substrate for denitrification (Mitchell et al., 2013; Iqbal et al., 2015). Alternatively, lower N_2O flux rates in the cover crop treatment when there was a long time lag (46 d) between cover crop termination and N fertilizer application date could be due to the decomposition of more recalcitrant cover crop reside components composed of materials with high C/N ratios that promote N immobilization. In the future, coordinated field research and modeling might improve our ability to determine how weather, N input, and agronomic management interact to affect N_2O emissions.

Conclusion

Nitrogen fertilizer inputs to corn during a drought affected N_2O emissions from a subsequent unfertilized soybean crop. Although this effect was limited to a drought year, mean N_2O flux rates were 35 to 70% higher in soybean crops that received N fertilizer in the preceding corn year compared with a soybean crop that received no N application in the preceding corn year. In years when N fertilizer input to corn had no effect on N_2O flux rate in the following unfertilized soybean crop, N_2O flux rates were similar among soybean crops despite a large range of N fertilizer inputs in the previous corn phase. Our results also add to a growing amount of research that demonstrates cover crops do not have an easily generalizable effect on N_2O emissions. Nevertheless, a better understanding of how cover crops and agronomic management practices interact with weather patterns to alter N_2O emissions may identify situations when cover crops can reliably reduce N_2O emissions.

Acknowledgments

This research was funded by USDA–NIFA, Award No. 2011-68002-30190, and project title "Cropping Systems Coordinated Agricultural Project: Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems." Project Website: sustainablecorn.org. The field project is supported in part by the Iowa Department of Agriculture and Land Stewardship, Division of Soil Conservation, through funds appropriated by the Iowa General Assembly.

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