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Tillage and Nitrogen Source Impacts on Relationships between Nitrous Oxide Emission and Nitrogen Recovery Efficiency in Corn

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Abstract

Quantitative understanding of relationships between N_2O emission and plant N uptake are needed to select environmentally optimal management systems for corn (*Zea mays* L.) production. Studies were conducted from 2014 to 2016 in Indiana to assess long-term tillage and N source effects on N_2O emission, and in 2015 and 2016 on relationships between N_2O losses and N recovery efficiency (NRE) and N use efficiency (NUE), in a continuous corn system. Tillage treatments (mostly in place since 1975) consisted of no till (NT), strip till (ST), chisel plow (CP), and moldboard plow (MP), whereas the N source comparison involved sidedress urea ammonium nitrate applied at 220 kg N ha^{-1} with and without nitrapyrin. Grain yield averaged 6.5% greater for MP than for CP and NT in the 3-yr period. Nitrapyrin never increased grain yield or NRE but reduced cumulative seasonal N_2O emission in 1 yr. Tillage affected N_2O emission in 2 of 3 yr, when emissions decreased in the order MP > CP > ST > NT. Significant negative linear relationships existed between N_2O emission and NRE under NT and ST, and between N_2O and NUE under ST, but not for CP and MP. Overall, N_2O losses under ST and NT decreased by 17 and 13 g N ha^{-1}, respectively, per unit increase of NRE, and by 63 g N ha^{-1} per unit increase of NUE under ST. Our results confirmed that selected management systems such as NT or ST that improved NRE and/or NUE can potentially reduce N_2O emissions during continuous corn production.

Core Ideas

- Seasonal N_2O losses were lower for no till (NT) and strip till (ST) vs. chisel and moldboard plow.
- Mean N recovery efficiency (NRE) in continuous corn with 220 kg N ha^{-1} exceeded 70%.
- Negative linear relationships existed between NRE or NUE and N_2O under NT and ST.
- Rate of cumulative N_2O emission decline per unit gain in NRE was highest under NT.

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NITROUS OXIDE is both an important ozone-depleting chemical (Ravishankara et al., 2009) and a major greenhouse gas believed to contribute to global climate change with a potency that is about 265 times the global warming potential of CO_2, over a 100-yr timescale (Myhre et al., 2013; IPCC, 2014). In agricultural soils, N_2O is produced predominantly through bacterial-mediated transformations of inorganic N (Bremner and Blackmer, 1978; Klemedtsson et al., 1988; Bremner, 1997). However, the quantity of inorganic N available for transformation is determined by the balance between the amount of N applied and the amount taken up by crop plants, after a complex interaction among N management, tillage, and rotation practices, and dominant environmental factors (Venterea et al., 2012). Therefore, the common assumption among scientists is that adoption of management practices that increased N uptake, N recovery efficiency (NRE) and/or N use efficiency (NUE) will reduce N_2O emission during crop production.

In the Corn Belt and elsewhere in the United States, where corn (*Zea mays* L.) production consumed ~6.3 Tg or 47% of the 13.3 Tg of the N fertilizers in 2014 (USDA-ERS, 2018), the consequences of individual N management options such as rate (Breitenbeck and Bremner, 1986a; McSwiney and Robertson, 2005; Halvorson and Bartolo 2014; Venterea et al., 2016), source (Breitenbeck and Bremner, 1986b; Liu et al., 2007; Halvorson et al., 2010a, 2011; Venterea et al., 2010, 2011; Halvorson and Del Grosso, 2012; Omonode and Vyn. 2013), timing (Liu et al., 2005; Engel et al., 2010; Drury et al., 2012; Burzaco et al., 2013; Venterea and Coulter, 2015), and placement (Liu et al., 2006; Fujinuma et al., 2011; Halvorson and Del Grosso, 2013) on N_2O emission have been well documented. Tillage system effects on N_2O emissions have also been reported (Liu et al., 2005; Halvorson et al., 2008, 2010b; Omonode et al., 2011), albeit with inconsistencies attributed to contrasting tillage effects on soil biophysical properties (van Kessel et al., 2013). Similarly, effects of tillage (Al-Kaisi and Kwaw-Mensah, 2007), N management options (Cassman et al., 2002; Randall et al., 2003; Randall and Vetsch, 2005; Ciampitti and Vyn, 2011; Burzaco et al., 2014; Wang et al., 2014; Rubin et al., 2016), and crop residue

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Abbreviations: CP, chisel plow; DAP, days after application; FIEF, fertilizer-induced emission factor; GNU, grain nitrogen uptake; GY, grain yield; MP, moldboard plow; NRE, nitrogen recovery efficiency; NT, no till; NUE, nitrogen use efficiency; ST, strip till; TNU, total aboveground nitrogen uptake; N_2O_{GY}, yield-scaled nitrous oxide; $\Sigma_{GS}N_2O$, cumulative seasonal nitrous oxide; UAN, urea ammonium nitrate; VWC, volumetric water content.

removal (Sawyer et al., 2017) on NRE and NUE in corn production have been fairly well documented. However, most of these authors showed that, on average, corn NRE seldom exceeded 50% when N fertilizer rates were close to their agronomic optimums, regardless of management intensity and agroecology. Thus, in theory, much of the N applied during crop production is either lost through leaching or made available for bacterial denitrification, whereby some is subsequently emitted as N_2O.

Although many studies in the United States have assessed the effects of N management options on a corn crop's NUE and NRE, or separately assessed management consequences for N_2O emissions, little research has been conducted that simultaneously evaluated management effects on corn NRE and N_2O emissions (Omonode et al., 2017; Venterea et al., 2016), and even less research has assessed the relationships between N_2O emission and N uptake and/or NUE (Omonode et al., 2017). In their recent study involving data collected across N management systems for corn in North America, Omonode et al. (2017) found a significant negative relationship between N_2O loss and NRE, especially in the context of N rate and timing management variables. However, the analysis by these authors did not include the influence of tillage or nitrification inhibitor application on these relationships. To the best of our knowledge, no research has been conducted to quantify the relationship of N_2O with corn N uptake and use efficiencies in long-term tillage systems. The objectives of this study were to assess the effects of long-term tillage and N application with and without nitrification inhibitor on (i) seasonal N_2O emissions, (ii) corn N use efficiencies, and (iii) the relationships between seasonal N_2O loss and N use efficiencies in rainfed corn.

Materials and Methods

Site Description and Experimental Design

The study was conducted in long-term tillage plots established in 1975 at the Purdue University Agronomy Center for Research and Education near West Lafayette, IN. The tillage treatments consisted of no till (NT), moldboard (MP), chisel plow (CP), and strip till (ST) applied to continuous corn; individual tillage plots measured ~46 m long and 10 m wide. The ST treatment was established in 2009 after conversion from ridge tillage that was applied from 1975 to 2008. For this study, the experimental layout was a split-plot design where tillage was the main plot, and the subplot was N source, which consisted of urea ammonium nitrate (UAN) with and without a nitrification inhibitor (nitrapyrin).

Corn was planted in 76-cm rows with a John Deere 1780 six-row planter on 24 Apr. 2014 (Pioneer P1221AMX; HXX, LL, RR2), 23 May 2015 (Pioneer P1360CHR), and 20 Apr. 2016 (Pioneer P1360CHR) with starter N applied at 26 kg N ha^{-1} as ammonium polyphosphate (10–34–0 N–P–K) in all 3 yr. In 2014, the tillage plots were divided into two halves (subplots, 46-m lengths of six corn rows) at the V4 corn growth stage (Abendroth et al., 2011), and UAN alone was applied at the rate of 220 kg N ha^{-1} to one half, and the other half received the same amount of N plus nitrapyrin (UAN+nitrapyrin). In 2015 and 2016, the UAN and UAN+nitrapyrin treatments were applied as occurred in 2014, but only to two-thirds of the subplot lengths, whereas the other one-third received zero N without nitrapyrin and acted as control plots to enable estimation of yield-scaled N_2O, NRE, and NUE. For this location and soil type, Burzaco et al. (2013, 2014) showed that corn yield and N_2O emission were similar with and without nitrapyrin application when no N was applied.

The UAN was sidedressed by coulter injection (~10 cm deep into the soil) on 22 May 2014, 11 June 2015, and 20 May 2016 using a seven-knife DMI NutriPlacer 2800 liquid N applicator equipped with one coulter per knife. The nitrapyrin source was Instinct 2 (Dow Agrosciences), a recent commercially available, reformulated water-soluble nitrapyrin especially designed for application with liquid N sources. Nitrapyrin was applied by pumping it from a companion tank into the UAN fertilizer line at the recommended rate of 2.6 kg ha^{-1} (~0.44 kg a.i. ha^{-1}). All treatments were replicated three times, and other agronomic practices including application of lime, P, and K were performed consistent with practices in the last 40 yr.

Nitrous Oxide Emission Measurement

Daily fluxes of N_2O were measured from 23 May to 20 Aug. 2014, 16 June to 2 Sept. 2015, and from 23 May to 2 Sept. 2016 for a total of 19, 14, and 21 measurement days, respectively. Flux measurements commenced ≤3 d after UAN application, and gas samples were collected twice weekly for 6 to 8 wk, and weekly thereafter for the rest of the growing season, using static vented chambers (Mosier et al., 2006). On each sampling date, gas samples were collected from the chamber headspace through a rubber septum at 0-, 10-, 20-, and 30-min intervals after chamber deployment using a gas-tight syringe, and then 25 mL of the sampled gas was transferred into preevacuated 12-mL Exetainer vials (Labco). All gas sampling activities occurred between 1200 and 1500 h of each sampling date, when biological activity and flux rates were considered to represent the daily average emission for Indiana (Omonode and Vyn, unpublished data, 2015). Gas samples were immediately transported to the laboratory, where N_2O concentrations in the samples were determined on a gas chromatograph equipped with an automatic Combi-Pal injection system, using a 3.05-m-long Porapak Q with Ar (95%) carrier gas with an electron capture detector set at 350°C (Varian 3800 GC).

Flux rates of N_2O were calculated by linear regression of N_2O concentration versus time since closure of the chamber top. The N_2O flux measured by the static chambers was calculated using the rate of change in the N_2O concentration (∂_c/∂_t mol min^{-1}) inside the chamber during a 30-min cover deployment expressed as

$$F_{N_2O} = \left(\frac{\partial_c}{\partial_t}\right)\left(\frac{M}{V_m}\right)\left(\frac{V}{A}\right)$$

where ∂_c is the change of N_2O concentration in the chamber headspace during an enclosure period (μL L^{-1}), ∂_t is the enclosure period (h), M is the molar mass of N in N_2O (g mol^{-1}), V_m is the molar volume of gas at the sampling temperature and atmospheric pressure (L mol^{-1}), V is the headspace volume (m^3), and A is the area covered (m^2); (V/A) is the chamber headspace height.

Cumulative N_2O emissions during the measurement periods were calculated by linearly interpolating F_{N2O} between sampling dates, and cumulative seasonal emission ($\Sigma_{GS}N_2O$) was estimated as the sum of all sampling dates.

Grain Yield, Nitrogen Uptake, and Use Efficiency Parameters

At physiological maturity, corn N uptake was determined by sampling the total plant aboveground biomass (plant biomass). Plant biomass was measured from 10 consecutive corn plants in the third or fourth row. The plants were manually cut <5 cm above the soil surface and separated into ears and stover, ears were air dried and shelled, all aboveground plant components (grains, stover, and cobs) were further dried at 65°C to a constant weight, and plant biomass yield was recorded. Subsamples were taken, ground, and analyzed for N concentration with an elemental analyzer (VarioMax, Elementar) in a commercial laboratory (A&L Great Lakes Laboratories, Fort Wayne, IN). Total plant N uptake (TNU) on a kilogram-per-hectare basis was calculated as the product of the grain, stover, plus cob dry matters and their N respective concentrations in each plot. Thereafter, corn in the center two rows of each six-row plot was machine harvested, its grain was weighed, and its moisture content was determined, and final grain yields (GY) were adjusted to 155 g kg^{-1} moisture content.

Nitrogen use efficiency in terms of GY (NUE) and the amount of applied N recovered by the corn plants (NRE) were calculated as

$$\mathrm{NUE}\left(\mathrm{kg\,kg^{-1}}\right)=\frac{\mathrm{GY_N}-\mathrm{GY_0}}{\Delta\mathrm{N_{applied}}}$$

$$\mathrm{NRE}\ (\%)=\left(\frac{\mathrm{TNU_N}-\mathrm{TNU_0}}{\Delta\mathrm{N_{applied}}}\right)100$$

where GY_N and GY_0 are GY for fertilized and unfertilized plots respectively, TNU is total (grain + stover + cob) N uptake with TNU_N being the TNU of N-fertilized plots and TNU_0 being the TNU of unfertilized plots, and $\Delta N_{applied}$ is the differential of N fertilizer applied.

Data Analysis and Statistical Procedures

Treatment effects on GY and N uptake and use efficiency parameters were assessed using the PROC GLM procedure where tillage and N source were considered fixed, and block (or replicate), year, and their interactions constituted random effects. The normality of N_2O data distribution was assessed using the PROC UNIVARIATE procedure, and the data was natural log transformed when necessary before they were used in further analysis. Treatment effects on daily N_2O emissions were assessed using the analysis of repeated measurement in the PROC MIXED procedure where tillage, N source, measurement dates, and their interactions were considered fixed effects, blocks and tillage × N source interaction constituted random effects, and the repeated option was N source nested in tillage. Thereafter, the data were pooled and analyzed, with the year of measurement as an additional random effect.

Fertilizer-induced N_2O emission factor (FIEF) for the treatments was calculated by subtracting the cumulative seasonal N_2O for the unfertilized control ($\Sigma_{control}N_2O$) from the $\Sigma_{GS}N_2O$ of the treatment plots and dividing by the amount of N applied. Yield-scaled N_2O (N_2O_{GY}, amount of N emitted as N_2O per unit of GY) was estimated by dividing $\Sigma_{GS}N_2O$ by GY. Treatment effects on $\Sigma_{GS}N_2O$, FIEF, and N_2O_{GY} were assessed using the PROC GLM procedure; tillage and N source were fixed factors, and block replicate, year, and their interactions were considered random effects. The treatment effect was declared significant at $P \leq 0.05$, and means were separated using the PDIFF option in the LSMEANS statement of PROC GLM when the effect was significant.

The relationships between N_2O and TNU, NUE, and NRE within tillage and N source were assessed using single-factor regression models where N_2O was considered the response variable, and N uptake, NUE, and NRE were the independent variables. The strengths of the relationships were assessed by the values of the regression r^2, and the relationship was considered significant at $P = 0.05$. When regression models were significant, equality of model coefficients across treatments were tested using Proc GLM/SOLUTION, and the CONTRAST "test equal slopes" statement. Regression slopes were considered equal at the $P \leq 0.05$ level. All analyses were performed using the SAS 9.3 package (SAS Institute, 2013).

Results

Grain Yield, Nitrogen Uptake, and Use Efficiency

Grain yield was significantly affected by tillage ($P = 0.003$) and N source in 2014 ($P = 0.008$), but neither tillage nor N source affected GY in 2015 and 2016. Similarly, yield was not affected by tillage × N source interactions in any year (Supplemental Table S1). Treatment effects on TNU and grain N uptake (GNU), NUE, and NRE in 2015 and 2016 are presented in Table 1.

In 2015, TNU, GNU, and NRE were affected by both tillage and N source, but not by the tillage × N source interaction. Total N uptake for 2015 was similar for NT and ST and was much lower for MP and CP. Similarly, NRE for 2015 was greater for NT and ST (average = 57%) versus CP (45%), and NRE was 10% greater for UAN alone than for UAN+nitrapyrin. Neither tillage nor N source affected NUE in 2015. In 2016, N uptake and NRE were not affected by tillage, N source, and the tillage × N source interaction (Table 1). Averaged across treatments, TNU, GNU, and NRE were significantly higher in 2016 than in 2015. Across years, NUE averaged 37 kg kg^{-1}, and NRE averaged 72% across tillage and N sources (Supplemental Table S2).

Nitrous Oxide Emission

Daily N_2O emission was affected by tillage and tillage × N source interaction in 2014, and by tillage, N source, and their interaction in 2016. Neither tillage, N source, nor tillage × N source affected N_2O emissions in 2015 (Table 2). In 2014, N_2O emission was relatively low between 23 May and 3 June (11 d after application [DAP]), increased rapidly from a prior average of 41 to 69 g N ha^{-1} on 10 June (19 DAP), then declined rapidly to ~40 g N ha^{-1} on 17 June, except for MP where emission remained high and averaged 70 g N ha^{-1} (Fig. 1a). During this period, N_2O emission was significantly greater for MP relative to CP and ST, which were in turn greater than NT, and for UAN compared with UAN+nitrapyrin (Fig. 1b). Thereafter, emission increased rapidly again across treatments to peak at ~64 g N ha^{-1} on 24 June (34 DAP); these emissions remained high until 1 July, then declined rapidly to near baseline on 11 July (51 DAP) and remained low for the rest of the growing season. On average, daily N_2O was greatest for MP (47.1 g N ha^{-1} d^{-1}) and smallest for NT (38 g N ha^{-1} d^{-1}), and N_2O intensity was in the order MP > ST = CP = NT but was identical for UAN and UAN+nitrapyrin (Table 2).

Similar to the pattern observed for 2014, relatively small but distinct emission peaks occurred on 23 June 2015 (12 DAP), when average N_2O increased from 47 to 58 g N ha^{-1} d^{-1}, and again from 31 g N ha^{-1} on 15 July to 50 g N ha^{-1} d^{-1} on 21 July (40 DAP), followed by relatively high N_2O loss in the next 7 d before declining rapidly to baseline by 14 August (Fig. 1c and 1d). In contrast, the daily N_2O emission pattern for 2016 was such that one prominent N_2O emission peak was observed on 2 June (12 DAP) when N_2O increased dramatically from 37 g N ha^{-1} d^{-1} starting on 23 May to peak at 72 g N ha^{-1} d^{-1}, averaged across tillage systems (Fig. 1e), and then declined as dramatically to ~15 g N ha^{-1} on 20 June (from 46 to 105 kg N ha^{-1} d^{-1} across N sources, Fig. 1f). However, much smaller but equally significant emission peaks also occurred on 24 June (24 DAP) when N_2O increased from ~10 g N ha^{-1} d^{-1} on 20 June to ~40 g N ha^{-1}, and on 21 July when N_2O peaked at 25 g N ha^{-1} d^{-} for CP and MP (51 DAP) and thereafter

Table 1. Generalized linear model showing probability of significant tillage and N source effects on mean total (TNU) and grain N uptake (GNU) and N use (NUE) and recovery efficiency (NRE) in 2015 and 2016 cropping seasons near West Lafayette, IN.

Tillage or N source†	2015				2016			
	TNU	GNU	NUE	NRE	TNU	GNU	NUE	NRE
	P value							
Tillage	0.008	0.022	0.503	0.033	0.593	0.183	0.788	0.358
N source	0.010	0.007	0.807	0.007	0.755	0.557	0.680	0.761
Tillage × N source	0.236	0.146	0.871	0.185	0.621	0.529	0.637	0.638
	Treatment means							
	—— kg ha^{-1} ——		kg kg^{-1}	%	—— kg ha^{-1} ——		kg kg^{-1}	%
NT	171.5ab‡	123.8a	39.5	55.8ab	261.3	133.4	37.1	85.5
ST	188.4a	136.2a	35.1	58.5a	263.9	129.9	36.7	90.2
CP	144.2c	104.5b	37.2	45.2c	275.0	141.9	38.5	96.8
MP	160.0bc	121.7ab	37.9	47.9bc	276.6	141.7	37.0	89.3
UAN	177.3a	131.4a	37.7	56.9a	267.7	135.4	37.6	89.8
UAN+nitrapyrin	154.7b	111.7b	37.2	46.8b	270.7	138.1	37.1	91.1

† NT, no till; ST, strip till; CP, chisel plow; MP, moldboard plow; UAN, urea ammonium nitrate.

‡ Within tillage and N source, columns that are followed by the same letters are not significantly different.

Table 2. Mixed model analysis showing probability of significant tillage and N source effects on daily N_2O emissions in 2014, 2015, and 2016, and across growing seasons near West Lafayette, IN.

Treatment	Year									
	2014				2015	2016				2014–2016
	Daily N_2O emission									
	g N ha^{-1} d^{-1}									
Tillage†										
NT	37.64c‡				39.86	31.46ab				35.81
ST	41.67b				40.57	27.73b				35.96
CP	40.18bc				37.22	34.67a				37.27
MP	47.02a				39.01	31.50ab				38.90
	NT	ST	CP	MP		NT	ST	CP	MP	
N source§										
UAN	40.31a	39.83	39.59	47.02	38.13	31.17	30.54a	39.19	36.87a	37.96
UAN+NP	34.97b	43.51	40.78	47.02	40.13	31.74	24.91b	30.15	26.12b	36.01
	Probability level									
F-test¶										
D/Y	0.001				0.001	0.001				0.001
T	0.001				0.447	0.014				0.421
N	0.918				0.190	0.001				0.187
D/Y × T	0.001				0.015	0.008				0.137
D/Y × N	0.318				0.807	0.002				0.063
T × N	0.041				0.076	0.031				0.738
D/Y × T × N	0.554				0.994	0.986				0.482

† NT, no-till; ST, strip-till; CP, chisel plow; MP, moldboard plow.

‡ Within year, tillage, and N source, treatments that are followed by the same letters are not significantly different.

§ UAN, urea ammonium nitrate; NP, nitrapyrin.

¶ T, tillage; D/Y, day/year of measurement; NP, nitrapyrin.

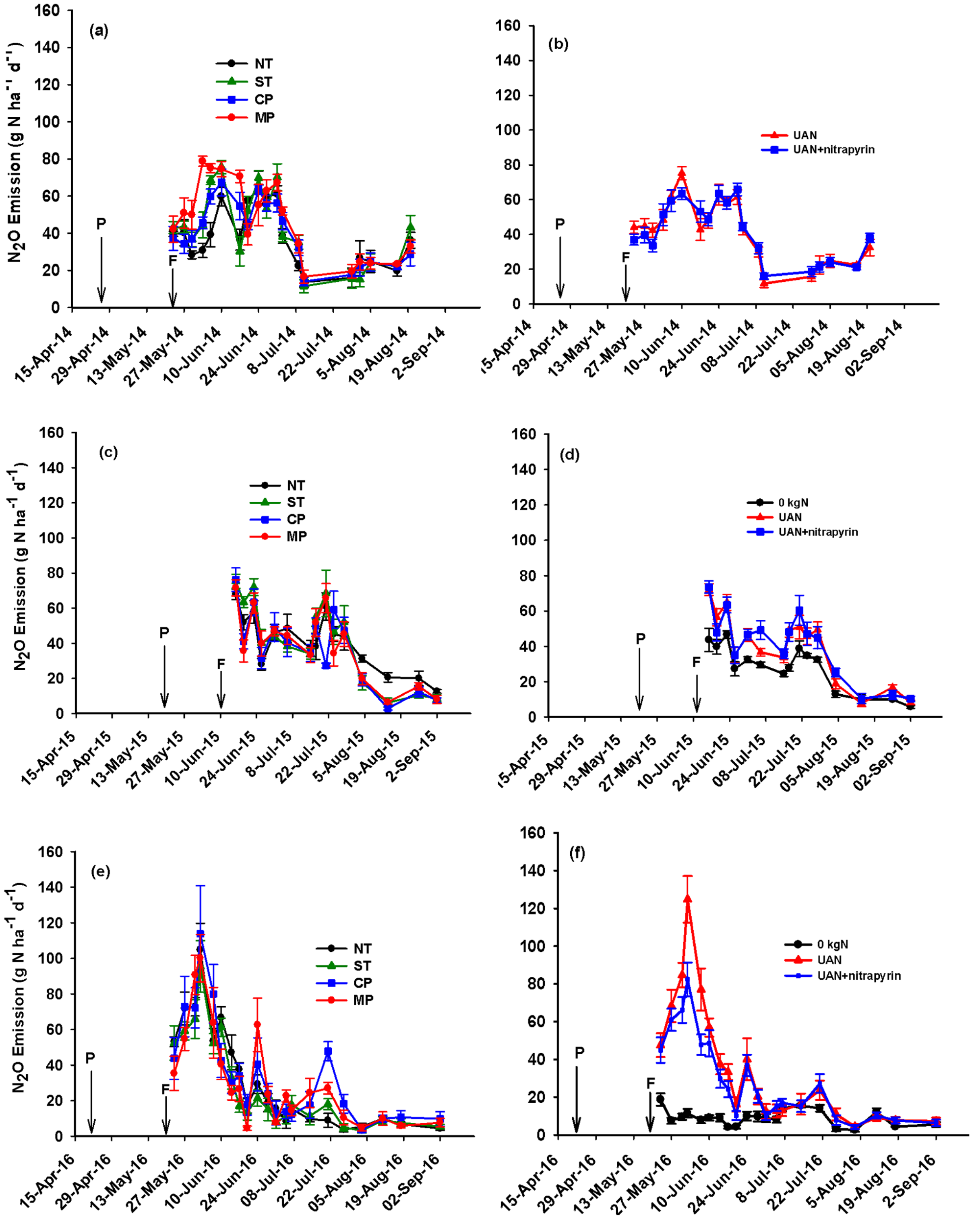

Fig. 1. Daily N_2O emission as influenced by tillage (no till [NT], strip till [ST], chisel [CP], and moldboard [MP]) and N source (urea ammonium nitrate [UAN] with and without nitrapyrin) in 2014 to 2016 near West Lafayette, IN. P = corn planting date, F = N application date.

declined rapidly to baseline levels by 2 August. Overall, average daily N_2O emission for 2016 (Table 2) was significantly greater for CP (34.6 g N ha^{-1} d^{-1}) than for ST (27.7 g N ha^{-1} d^{-1}). Similarly, average daily N_2O emission was 22% lower for UAN+nitrapyrin (28.2 g N ha^{-1} d^{-1}) than for UAN alone (34.4 g N ha^{-1} d^{-1}).

Cumulative seasonal N_2O ($\Sigma_{GS}N_2O$), N_2O_{GY}, and FIEF due to tillage and N source calculated by year, and averaged across years, are presented in Table 3 and Supplemental Table S3, respectively. Cumulative N_2O was affected by tillage in 2014, but not in 2015 and 2016 (Table 3). In 2014, $\Sigma_{GS}N_2O$ for MP was 21% greater than for NT and 14% greater than for CP. Similarly, FIEF for 2015 was greater under NT (0.45%) than under CP (0.27%), but this was reversed for 2016, when FIEF was greatest with CP (0.91%) and smallest with ST (0.54%). Overall, FIEF was generally less than the 1% value reported by the Intergovernmental Panel on Climate Change, regardless of treatment or year of application. In contrast, N_2O_{GY} was similar among tillage and N source treatments in all 3 yr of application. Averaged across treatments, $\Sigma_{GS}N_2O$ for 2014 was 21% greater than 2015 and 2016, and N_2O_{GY} for 2014 was 12% greater than for 2016 (Supplemental Table S3). The FIEF for 2016 (0.77%) was more than double that for 2015. Across years, $\Sigma_{GS}N_2O$, N_2O_{GY}, and FIEF were not significantly different among tillage and N source treatments (Supplemental Table S3).

Relationship between Nitrous Oxide and Nitrogen Uptake, and Use Efficiency

The direction and strength of the relationships between N_2O and TNU, NUE, and NRE varied by tillage, and N source. With zero N application, a significant ($P = 0.015$), relatively strong ($r^2 = 0.65$), and negative linear relationship existed between N_2O and TNU such that N_2O decreased by 39 g N for every kilogram per hectare increase of TNU (Supplemental Fig. S1). In contrast, N source (UAN alone vs. UAN+nitrapyrin) had no measurable influence on the relationships between N_2O and TNU, NRE, and NUE, as these relationships were weak ($r^2 < 0.05$) and statistically not significant ($P = 0.090$–0.313). Here, we note that the relationship between N_2O and TNU was significantly weakened with the addition of 220 kg N (with and without nitrapyrin); the slope of the regression was dramatically reduced from 0.039 (39 g N ha^{-1}) with zero N to 0.003 (3 g N ha^{-1}) for UAN+nitrapyrin (Supplemental Fig. S1).

Tillage affected the relationships between N_2O and TNU, NRE, and NUE more than N source (Table 4). A notable ($r^2 = 0.32$) but nonsignificant ($P = 0.053$) linear relationship between N_2O and TNU was only evident under NT, whereby N_2O decreased by 4 g N ha^{-1} for every kilogram increase of TNU. Similarly, significant and moderately strong negative linear relationships existed between N_2O and NRE under NT and ST systems (NT: $P = 0.02$, $r^2 = 0.43$; ST: $P = 0.038$, $r^2 = 0.36$). However, a slope equality test showed that the regression slopes for these relationships under NT and ST were not significantly different (Table 4). Overall, the models showed that N_2O decreased by 13 g N ha^{-1} for every 1% increase of NRE under NT, and by 17 g N ha^{-1} for every 1% increase of NRE under ST. Similarly, N_2O decreased by 63 g N for every kilogram per kilogram gain of NUE when tillage was ST. However, we note that the relationships between N_2O and N uptake and use efficiencies under CP were confounded, weak ($r^2 = 0$–0.16), and positive linear (Table 4).

Discussion

Grain Yield, Nitrogen Uptake, and Use Efficiency

The average GY, N uptake, and NUE values reported in this experiment were similar to those previously reported for this location when N was applied at 180 to 220 kg N ha^{-1} as anhydrous ammonia (Kovács et al., 2014) and UAN (Burzaco et al., 2014). Greater GY for 2014 and 2016, and higher NRE for 2016 than for 2015, were due to the combination of early planting and more favorable weather conditions, especially the quantity and distribution of precipitation in July and August of 2014 and 2016 (Supplemental Fig. S2). Precipitation in June 2015 shortly after N application was rather excessive (40% greater than in June 2016, 48% greater than the 30-yr average) and probably resulted in N loss and lower GY and NRE in 2015. However, greater GY for MP relative especially to NT was probably because MP provided more favorable soil physical and chemical conditions that included lower bulk density, higher soil temperature, and organic matter mineralization (Gentry et al., 2013) and, consequently, a better and earlier corn plant establishment. The variable effects of nitrapyrin on GY were consistent with results from previous studies that examined the effects of fall- or spring-sidedressed nitrapyrin and enhanced efficiency fertilizers on corn yield. In this study, sidedressed UAN+nitrapyrin depressed GY in 2014 but had no effect in 2015 and 2016, and thus supported earlier reports where nitrapyrin was applied in the fall, spring, and split applied (Touchton et al., 1979; Randall et al., 2003; Burzaco et al., 2013, 2014). Similar inconsistent effects of enhanced efficiency fertilizers (e.g., ESN) on GY have also been widely reported (Dell et al., 2014; Halvorson and Bartolo, 2014; Sistani et al., 2014).

Overall, our average NRE value of 70% was higher than the 41 to 59% previously reported for this location for sidedress N applications (Burzaco et al., 2014; Kovács et al., 2015), and the

Table 3. Generalized linear model analysis showing probability of significant tillage and N source effects on cumulative seasonal ($\Sigma_{GS}N_2O$) and yield-scaled (N_2O_{GY}) N_2O emissions, and fertilizer-induced emission factor (FIEF) in 2014, 2015, and 2016 cropping seasons near West Lafayette, IN.

Treatment†	2014			2015			2016		
	$\Sigma_{GS}N_2O$	N_2O_{GY}	FIEF	$\Sigma_{GS}N_2O$	N_2O_{GY}	FIEF	$\Sigma_{GS}N_2O$	N_2O_{GY}	FIEF
					P value				
Tillage	0.025	0.5971	–	0.401	0.558	0.215	0.333	0.510	0.191
N source	0.986	0.420	–	0.497	0.514	0.343	0.119	0.161	0.103
Tillage × N source	0.443	0.6109	–	0.674	0.599	0.398	0.706	0.618	0.674
					Treatment means				
	kg N ha^{-1}	g N Mg^{-1}	%	kg N ha^{-1}	g N Mg^{-1}	%	kg N ha^{-1}	g N Mg^{-1}	%
NT	3.01b‡	214.0	ND§	2.91	244.83	0.45a	2.52	193.50	0.84ab
ST	3.33ab	231.3	ND	2.69	203.50	0.37ab	2.27	175.33	0.54b
CP	3.28b	222.6	ND	2.46	221.67	0.27b	3.01	223.67	0.91a
MP	3.82a	238.6	ND	2.60	214.33	0.32ab	2.66	198.17	0.78ab
UAN	3.36a	221.2	ND	2.60	214.17	0.32	2.84	214.00	0.87
UAN+NP	3.36a	232.2	ND	2.73	228.00	0.38	2.38	181.33	0.67

† NT, no till; ST, strip till; CP, chisel plow; MP, moldboard plow; UAN, urea ammonium nitrate; NP, nitrapyrin.

‡ Within tillage and N source, rows followed by the same letters are not significantly different.

§ ND, not determined.

Table 4. Linear regression model parameters for the relationships between N_2O emission and total N uptake (TNU), recovery (NRE), and use efficiency (NUE) under tillage systems.

Tillage†	*n*	Regression parameters		
		Model	R^2	$P > F$
		TNU		
NT	12	$y = 3.68 - 0.004x$	0.32	0.053
ST	12	$y = 3.95 - 0.006x$	0.32	0.056
CP	12	$y = 2.27 + 0.001x$	0.06	0.456
MP	12	$y = 3.023 - 0.002x$	0.04	0.547
		NRE		
NT	12	$y = 3.72 - 0.013x$	0.43	0.020
ST	12	$y = 3.75 - 0.017x$	0.36	0.038
CP	12	$y = 2.36 + 0.002x$	0.03	0.605
MP	12	$y = 3.05 - 0.006x$	0.05	0.469
		NUE		
NT	12	$y = 4.60 - 0.048x$	0.19	0.160
ST	12	$y = 4.77 - 0.063x$	0.33	0.050
CP	12	$y = 2.00 + 0.013x$	0.04	0.532
MP	12	$y = 4.53 - 0.050x$	0.28	0.075
		Test for equality of slopes‡		
	df	Contrast sum of squares	*F* value	Pr > *F*
NRE (NT vs. ST)	1	0.026	0.20	0.663

† NT, no till; ST, strip till; CP, chisel plow; MP, moldboard plow.

‡ Test for equality of regression slopes presented is for treatments where the relationship between N_2O emission and NRE was significant at *P* = 0.05.

55% average reported from across North America corn systems for N rates >150 kg N ha^{-1} (Omonode et al., 2017) in studies that measured both NRE and $\Sigma_{GS}N_2O$. Our NRE was twofold higher than the 31 to 37% reported for north-central US locations (Cassman et al., 2002; Al-Kaisi and Kwaw-Mensah, 2007; Rubin et al., 2016). However, the average NUE value of 37 kg kg^{-1} was similar to the values previously reported for this location (Burzaco et al., 2014; Kovács et al., 2015), and thus indicated that coapplication of UAN and nitrapyrin and long-term tillage management did not influence the amount of grain produced from an equivalent amount of N applied in this environment.

Nitrous Oxide Emission

Variability in daily N_2O emission with tillage and year reflected the significant sampling date, date× tillage, and date × N source effects due to the differences of weather and soil conditions at the time of measurements. The N_2O emission peaks that occurred around 10 and 24 June 2014 were attributed to the collective impacts of 14 to 22 mm of precipitation events on 9, 11, and 19 June, soil temperatures of 19 to 25°C, and volumetric water content (VWC) that increased from 27 m^3 m^{-3} on 2 June to 51 m^3 m^{-3} on 10 June, and from 25 m^3 m^{-3} on 17 June to 60 m^3 m^{-3} on 23 June. The peaks of 23 June and 22 July 2015 were also the result of the 26- and 46-mm precipitation events that occurred on 22 June and 18 July, which increased VWC that was already >44 m^3 m^{-3}, and soil temperature that averaged 23°C. Similarly, the high N_2O peak of 2 June 2016 resulted from the dramatic increase in VWC after 7 to 14 d of little or no precipitation when soil temperature averaged 23°C. In general, the significant tillage effects that resulted in greater mean daily N_2O for MP than for NT, ST, and CP in 2014, and for CP relative to ST in 2016, were attributed to treatment differences of soil temperature and VWC. In 2014, soil temperature and VWC accounted for 11 of 22% of the total variability associated with N_2O emissions, and for 11 of 17% total variability of N_2O emission in 2016 (data not shown).

Overall, $\Sigma_{GS}N_2O$ for 2014 was 21% higher than for 2015 and 2016 (average = 2.64 kg N ha^{-1}), perhaps due to the combined effects of weather and the amount of the applied N that was available for denitrification in the first 30 d after N application. Large precipitation events in June and July of 2015 and 2016 shortly after N application (Supplemental Fig. S2, insert) probably resulted in significant N leaching losses, smaller amounts of N available for denitrification, and, consequently, lower seasonal N_2O emissions. Although tillage effects on $\Sigma_{GS}N_2O$ were significant only in one of 3 yr, $\Sigma_{GS}N_2O$ loss was generally in the order MP > CP > ST > NT, thus affirming our earlier observations from these and other tillage plots in this location (Omonode et al., 2011., 2015). The pattern of N_2O loss also supported findings from several other field research studies that found greater N_2O emitted from tilled compared with NT or reduced-tillage systems (Jacinthe and Dick, 1997; Kessavalou et al., 1998).

The variable effect of nitrapyrin on N_2O emission (significant effect on daily N_2O under NT in 2014 and under ST and MP in 2016, but no effect on cumulative N_2O) was not entirely unexpected, as contrasting effects of nitrapyrin on N_2O emissions have been reported more frequently in the literature (Parkin and Hatfield, 2010; Omonode and Vyn, 2013; Burzaco et al., 2013). Thus, although nitrapyrin has the potential to delay the nitrification of ammoniacal fertilizers (Omonode and Vyn, 2013), its potential to actually reduce N_2O emission across the growing season is limited because nitrapyrin's effects on interrupting the conversion of NH_4^+ to NO_2^- in soil are short-lived (Parkin and Hatfield, 2010) and appear to be dependent on the tillage system applied. Delayed nitrification is also not helpful in substantially reducing N_2O emissions if there is no gain in synchrony in the timing of availability of N released by nitrification and plant N uptake, and available N is not taken up by corn plants before being denitrified. Overall, this study generally indicated that nitrapyrin was unlikely to improve corn NRE and reduce N_2O emissions at higher rates of in-season N application, such as those applied in this experiment. For this location, Burzaco et al. (2013) reported that nitrapyrin addition significantly reduced N_2O loss from UAN when N was applied at a rate of 90 kg N ha^{-1}, but not at 180 kg N ha^{-1}.

Relationship between Nitrous Oxide and Nitrogen Uptake, and Use Efficiency

Relatively little research has been conducted to quantify the relationships between N_2O and N uptake, NRE, or NUE (Van Groenigen et al., 2010; Venterea et al., 2016; Omonode et al., 2017), and even less research has examined these relationships in long-term tillage systems. Thus, it was difficult to compare our results with the existing literature. Nevertheless, the significant and negative linear relationship between N_2O and TNU and NRE under NT and ST supported the long-postulated hypothesis that an increase of N uptake or NRE in corn will reduce N_2O emission. These findings were also similar to those reported by Van Groenigen et al. (2010) in a meta-analysis that aggregated NRE across different crop species, and by Omonode et al. (2017) in analyses that used data aggregated over North America's corn cropping systems. The dramatic reduction of regression parameter values for the relationship between N_2O and TNU due to addition of 220 kg N was similar to reports by Omonode et al. (2017) and was attributed to simultaneous increase of plant N uptake and N_2O emissions as N rate was increased up to and beyond the crop requirement.

Overall, the moderately strong and significant relationship of N_2O emission with NRE for NT and ST was attributed to the combination of low synchrony between the peak periods of N_2O emission (<24 DAP in this study) and the recovery of applied N by the plant, and to the fact that N_2O was the only source of N loss considered in the models. Halvorson and Del Grosso (2012) and Omonode et al. (2011) showed that ∼50 to 80% of seasonal cumulative N_2O emissions occur in 30 to 40 DAP, when the corn plant was in its early growth stages (e.g., V5–V7) and plant N uptake was relatively small; in this study, ∼56 to 66% of seasonal N_2O emission occurred in ≤30 DAP. Several studies also found that N_2O accounted for only a small fraction of the total N lost from the system after N application; most N losses occurred as NH_3 volatilization and/or NO_3^- leaching, which, respectively, accounted for ∼10 and 30% of applied N compared with ∼3% for N_2O losses (Mosier et al., 1998; De Klein et al., 2006; Venterea et al., 2012). Nevertheless, because our average NRE levels were high, it is possible that those other reactive N losses (as a fraction of applied N) were considerably lower in our experiments.

Conclusion

Our results confirmed that relatively strong functional relationships existed between seasonal N_2O emissions and N recovery efficiency; cumulative seasonal N_2O loss abated as corn NRE or NUE were improved under NT and ST when N was sidedressed at the recommended rate. However, the N_2O abatement rate was greater under ST than under NT. The analysis showed that NT or a reduction in tillage intensity, as in ST, has the potential to maintain yield, improve NRE, and reduce seasonal N_2O emissions. More research is needed where N_2O emissions and NRE are simultaneously measured to better understand and model the functional relationships between N_2O and NRE in the weeks after banded N applications to corn.

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