Soil Fertility & Plant Nutrition

Agro-Environmental Consequences of Shifting from Nitrogen- to Phosphorus-Based Manure Management of Corn

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The relationships among corn (*Zea mays* L.) grain yield, N supply, and N_2O emissions as influenced by a change from N-based surface applications of manure (no incorporation) to a P-based (crop removal) management system with immediate incorporation of manure were studied in 2014 and 2015. Treatments were annual spring applications of separated dairy solids (34 and 90 Mg ha^{-1}), liquid dairy manure (93 and 159 kL ha^{-1}), and two inorganic N fertilizer rates (0 and 112 kg ha^{-1}). In 2015, half of each manure-amended plot received 168 kg N ha^{-1} at sidedressing time to assess if yields were N-limited. Shifting from N- to P-based management resulted in 5 and 3% yield decreases in the manure and solids treatments, respectively. Corn yields and N uptake increased with N sidedressing in 2015, reflecting an N limitation in those treatments. Shifting from N- to P-based manure with tillage incorporation increased soil NO_3–N levels at planting and sidedressing in 2014 but not in 2015, consistent with weather differences. Nitrous oxide emissions ranged from 216 g N_2O ha^{-1} yr^{-1} (zero-N control) to 964 g N_2O ha^{-1} yr^{-1} (112 kg N ha^{-1}) in 2014 and from 249 g N_2O ha^{-1} yr^{-1} (P-based solids) to 776 g N_2O ha^{-1} yr^{-1} (112 kg N ha^{-1}). In both years, soil N_2O emissions increased linearly with N availability and, therefore, corn grain yield. Our results suggest that N_2O emissions increase with yield when N is yield-limiting, independent of N sources.

Abbreviations: CSNT, corn stalk nitrate test; DM, dry matter; PSNT, pre-sidedress nitrate test; SOM, soil organic matter; VWC, volumetric soil water content

Core Ideas

- **Soil nitrate and moisture are primary drivers for N_2O emissions.**
- **Where N limits yield, N_2O emissions increase linearly with yield.**
- **Phosphorus-based manure management can lead to deficiencies in N supply.**
- **Supplemental fertilizer N in P-based systems increases N_2O emissions.**

The main greenhouse gases of concern for dairy agriculture are CO_2, CH_4, and N_2O. According to the USEPA (2014), N_2O emissions represent 44% of the annual GHG emissions from US agriculture. Soil N_2O emissions primarily result from denitrification, an anaerobic microbial process that converts NO_3^- to gaseous forms of N, including NO, N_2O, and N_2 gas (Meisinger et al., 2008). Therefore, the availability of soil NO_3^- and labile C as an energy source, water-saturated (anaerobic) soils, and warm soil temperatures drive N_2O emissions through denitrification processes (Butterbach-Bahl et al., 2013).

In New York, dairy is the primary agricultural sector (USDA-NASS, 2015) and corn is a major agricultural crop. More than 275,000 ha of corn were harvested for grain in 2014 and another 198,000 ha were harvested for silage (USDA-NASS, 2015). Dairy manure and fertilizer are the primary N sources typically applied to meet corn N needs. Manure addition reduces the need for fertilizer N purchases and application (Ketterings et al., 2003a; Sadeghpour et al., 2016a), and there is also evidence (Eghball and Power, 1999; Sadeghpour et al., 2016b) and recognition among farmers (Ketterings et al., 2012) that manure application can improve or maintain soil health and productivity over time.

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Surface application of raw manure at rates to meet crop N needs often leads to over-application of P and K compared with crop removal, and can cause odor issues (Eghball and Power, 1999; Maguire et al., 2008; Sadeghpour et al., 2016a). A shift from surface applications of manure at N-based rates to crop P-removal-based management with immediate (<1 h) incorporation of the manure can reduce P and K buildup in soils (Sadeghpour et al., 2016b, 2017). The direct incorporation will increase the N value of manure through abating N volatilization (Dell et al., 2012; Ketterings et al., 2013; Sadeghpour et al., 2015), but a crop yield reduction can occur if N availability at P-based application rates is not sufficient (Sadeghpour et al., 2016a). In these cases, addition of supplemental N fertilizer can increase N availability but additional fertilizer can also impact N_2O emissions.

Studies that evaluate yield and N_2O emissions in N-based versus P-removal-based manure management are scant. Review papers by Webb et al. (2010) and Maguire et al. (2011) have summarized N_2O emissions where manure was surface-applied, incorporated, banded, or injected. With some exceptions, most studies have shown an increase in N_2O loss when manure was injected or tillage-incorporated immediately after application, consistent with the greater inorganic N availability (lower N volatilization loss) when manure is mixed with the soil (Webb et al., 2010). However, most of these studies did not adjust (lower) the application rate when manure was incorporated.

Although the literature lacks data on N_2O emission from direct comparisons of N-based versus P-removal based application rates, there are studies that have compared emissions from different sources, including untreated manure, compost, and inorganic N fertilizer rates (Ginting et al., 2003; Venterea et al., 2010; Sistani et al., 2011; Pelster et al., 2012; Asgedom et al., 2014; Halvorson et al., 2016). Lower N_2O emissions are reported from land applications of composted manure (pig and cattle) or separated (pig and cattle) solids compared with untreated or liquid slurry (Amon et al., 2006; Fangueiro et al., 2008). Fangueiro et al. (2008) reported 38% greater N_2O emissions with land application of cattle slurry than with fresh solid cattle manure. Lower N_2O emissions were reported up to threefold in Canada when separated dairy solids were applied compared with liquid dairy manure, as reported in a review by VanderZaag et al. (2011). Similar to several other researchers (Rochette et al., 2000; Velthof et al., 2003; Chantigny et al., 2010), VanderZaag et al. (2011) suggested that a more labile C, higher moisture content, and quicker release of N with liquid dairy manure were the primary reasons for the greater N_2O emissions from liquid dairy manure than from separated dairy solids.

A recent study by Sadeghpour et al. (2016a) showed that soil NO_3–N availability after application of composted dairy solids was lower than when liquid dairy manure or fertilizer N were applied. This resulted in 13% lower corn silage yields, reflecting limited N release from composted dairy solids. The manure source could impact N_2O emissions as well. However, the literature on the effect of N source on N_2O emissions is inconsistent. Some reports have suggested greater N_2O emissions with manure addition than with fertilizer N (Rochette et al., 2000; Chantigny et al., 2007; Pelster et al., 2012), although others have reported no differences (López-Fernández et al., 2007; Halvorson et al., 2016) or lower N_2O emissions with manure than with inorganic N application (Hernandez-Ramirez et al., 2009; Chantigny et al., 2010; Asgedom et al., 2014). Comparing the impact of manure and inorganic N sources on N_2O emissions across sites is difficult because of the differences in the method, rate, and timing of applications, and soil chemical and physical properties, including soil texture, soil pH, soil organic matter (SOM), manure history, soil drainage, and climatic conditions.

The literature is more conclusive on the effect of N rate on N_2O emissions. Most research suggests greater N_2O emissions will occur with a higher N rate (Lessard et al., 1996; Jarecki et al., 2009; Dell et al., 2014; Halvorson et al., 2014). For example, Lessard et al. (1996) reported a 0.47 kg ha^{-1} increase in N_2O emissions when dairy manure rates increased from 170 to 339 kg N ha^{-1}. Halvorson et al. (2014) reported a linear increase in N_2O emissions (3.7 g N_2O ha^{-1} per 1 kg of N ha^{-1}) with increasing fertilizer N rate from 0 to 250 kg N ha^{-1}. If N is limiting corn yield, a linear increase in N_2O emissions with N application rate suggests a fixed N_2O emission rate per unit of yield. Addition of N beyond what a crop can use is expected to lead to an increase in N_2O loss per unit of yield.

Research is needed to evaluate crop yield, N needs, and N_2O emissions for various manure management practices, taking into account that manure application rates should be lower when manure is incorporated in the spring (Sadeghpour et al., 2016a, 2017). The objective of this study was to evaluate the influence of a corn fertility management change from N-based applications of manure and separated dairy solids (without incorporation) to a P-removal-based management of manure (immediate incorporation) and solids on corn yield, N balances, and N_2O emissions, in a field with a long-term history of manure, solids, and inorganic N fertilizer addition during the corn years in a corn–alfalfa (*Medicago sativa* L.) rotation. Our hypothesis was that total N_2O emissions would increase linearly with the N application rate when N is the only yield-limiting factor.

MATERIALS AND METHODS

Experimental Site

A trial was conducted in 2014 and 2015 in Aurora, NY (42.73°N, 76.65°W, 253 m asl) on a Lima silt loam (fine-loamy, mixed, active, mesic Oxyaquic Hapludalfs) soil. In April 2014, plots that had received separated solids, liquid manure, and fertilizer N treatments in corn years (2001–2005 and 2011–2013), had a soil pH (0–20 cm depth) of 7.6, 7.6, and 7.4; SOM content of 39, 31, and 31 g kg^{-1}; Morgan-extractable NO_3–N of 3.9, 6.2, and 3.7 mg kg^{-1}; Morgan-extractable soil test P concentrations of 16, 12.8, and 6.7 mg kg^{-1}; and Morgan-extractable soil test K content of 91, 112, and 65 mg kg^{-1}, respectively. According to the P and K guidelines in New York (Ketterings et al., 2003b, 2003c), soil P and K were not a limiting factor in this study.

Table 1. Application rates and characteristics of liquid dairy manure and separated solids applied in 2014 to 2015 (nutrient measurements on a dry weight basis).

	Application rates									
Year	N-based	P-based	Total N	Ammonia N	Organic N	P	K	Total solids	Total N/P	Total N/K
						Dairy liquid manure				
	——kL ha^{-1}——		———————————		g kg^{-1}	———————————				
2014	159	93	2.7	1.1	1.6	0.4	2.3	34.8	6.7	1.2
2014	159	93	2.1	0.7	1.4	0.4	1.5	44.4	5.2	1.4
						Separated dairy solids				
	——Mg ha^{-1}——		———————————		g kg^{-1}	———————————				
2014	90	34	4.5	0.7	3.8	0.9	3.0	222.9	5.0	1.5
2015	90	34	5.7	1.1	4.6	1.1	2.6	292.2	5.2	2.2

Mean air temperatures from April through to October were 15.9°C in 2014 and 16.4°C in 2015, just below the 30-yr average (17.3°C) for Aurora, NY. Cumulative growing season precipitation was 587 mm in 2014 and 686 mm in 2015. In 2015, June was very wet (210 mm) compared with the same month in 2014 (70 mm). Average precipitation in the months after manure application (May and June) was 84 mm in 2014 and 164 in 2015. Average precipitation after sidedressing fertilizer N (July to September) was 91 mm in 2014 and 79 mm in 2015.

Liquid Dairy Manure and Separated Dairy Solids Sampling and Analysis

Each year, before application of liquid manure and separated solids, subsamples were collected (n = 3 per source). Information about liquid and solid manure separation can be found in Gooch and Pronto (2009). Samples were frozen until laboratory analysis. Total N was determined via combustion in an Elementar Vario Max (Elementar Analysensysteme, Hanau, Germany) (Association of Official Analytical Chemists, 2000). After extraction by KCl, a Lachat QuickChem 8000 flow injection calorimetric analyzer (Lachat Instruments, Loveland, CO) was used to determine ammonium N and NO_3–N. To determine P and K, nitric acid digestion using a CEM Mars Express microwave (CEM Corporation, Matthews, NC) was used and digested samples were analyzed in a Thermo Scientific iCAP 6500 inductively coupled plasma–atomic emission spectrometer (Thermo Electron Corp., Waltham, MA). The composition of liquid manure and separated solids is presented in Table 1.

Experimental Design and Treatments

In 2014, the experimental design was a randomized complete block design with six fertility treatments and five replicates. The six treatments were: (i) P-based application (wet basis) of separated dairy solids (34 Mg ha^{-1}), (ii) N-based application (wet basis) of separated dairy solids (90 Mg ha^{-1}), (iii) P-based addition of liquid dairy manure with immediate (<1 h) tillage incorporation (93 kL ha^{-1}), (iv) N-based liquid dairy manure application (159 kL ha^{-1}), (v) zero-N control (0 kg N ha^{-1}), and (vi) sidedressed inorganic N (urea ammonium nitrate) at the rate of 112 kg N ha^{-1}, which is the recommended sidedressed N application rate derived from Ketterings et al. (2003a) and supported by findings of Sadeghpour et al. (2016c). The first four treatments are hereafter referred to as organic treatments. In 2015, four treatments were added to the six treatments mentioned above. Treatments for both years can be found in Table 2 and Table 3. Application rates were based on Sadeghpour et al. (2016a). Year-to-year variation in the composition of liquid manure and separated solids (Table 1) resulted in

Table 2. Corn grain yield, N concentration, pre-sidedress nitrate test (PSNT) (0–30 cm), and end-of-season corn stalk nitrate test (CSNT) as influenced by separated solids, liquid manure and inorganic N fertilizer application in 2014 and 2015.

	Grain yield		N concentration		PSNT‡		CSNT§	
Treatments†	2014	2015	2014	2015	2014	2015	2014	2015
	Mg DM ha^{-1}		—— g kg^{-1}——		—mg kg^{-1}—		—mg kg^{-1}—	
CN + N0	7.5 b¶	4.0 d	12.4 b	12.2 d	6.1 c	4.2	91 b	106 d
CN + N168	–	7.1 ab	–	15.0 a	–	–	–	4866 a
CP + N0	7.2 bc	2.8 e	11.7 c	12.1 d	8.2 bc	6.9	90 b	70 d
CP + N168	–	7.1 ab	–	14.0 bc	–	–	–	2772 bc
MN + N0	8.5 a	5.2 c	12.3 b	12.2 d	14.3 ab	6.0	434 a	90 d
MN + N168	–	7.7 a	–	15.3 a	–	–	–	4749 a
MP + N0	8.1 ab	3.4 de	13.0 ab	13.2 c	18.9 a	6.6	254 ab	88 d
MP + N168	–	6.4 bc	–	15.3 a	–	–	–	3811 b
N0	6.5 c	3.3 de	12.2 b	12.0 d	9.3 bc	5.7	90 b	84 d
N112	8.5 a	6.1 c	13.4 a	14.7 ab	7.8 bc	4.3	425 a	1672 c
P-value	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01	0.1369	≤0.01	≤0.01

† Specific treatments include: N-based separated dairy solids (CN + N0, 90 Mg ha^{-1}), N-based separated dairy solids plus 168 kg N ha^{-1} inorganic N (CN + N168, 90 Mg ha^{-1}), P-removal-based separated dairy solids (CP + N0, 34 Mg ha^{-1}), P-removal based separated dairy solids plus 168 kg N ha^{-1} inorganic N (CP + N168, 34 Mg ha^{-1}), N-based liquid dairy manure without incorporation (MN + N0, 159 kL ha^{-1}), N-based liquid dairy manure without incorporation plus 168 kg N ha^{-1} inorganic N (MN + N168, 159 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application (MP + N0, 93 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application plus 168 kg N ha^{-1} inorganic N (MP + N168, 93 kL ha^{-1}), starter N application only (N0), and 112 kg N ha^{-1} sidedressed N (N112).

‡ PSNT < 21 mg kg^{-1} suggests that NO_3–N was deficient and a PSNT > 25 indicates that NO_3–N was sufficient.

§ CSNT < 250 mg kg^{-1} indicates that N was insufficient, 250–750 mg kg^{-1} indicates that N was marginal, 750–2000 mg kg^{-1} indicates that N was sufficient, and CSNT > 2000 mg kg^{-1} indicates that N was excessive

¶ Mean comparisons were done for each year individually where the overall treatment effect was significant ($\alpha \le 0.05$). Means followed by a different letter within each column are significantly different at $\alpha \le 0.05$.

Table 3. Credited available N, corn grain N removal, and balances as influenced by separated solids, liquid manure, and inorganic N fertilizer application in 2014 and 2015.

	Available N					
	Applied	Removed	Balance	Applied	Removed	Balance
Treatments†	2014			2015		
	kg N ha^{-1}					
CN + N0	144	109 c‡	35 a	168	57 de	111 d
CN +N168	–	–	–	336	127 ab	209 a
CP + N0	61	100 d	–39 d	60	40 e	20 e
CP +N168	–	–	–	228	117 bc	111 d
MN + N0	143	123 b	20 b	134	75 d	59 e
MN + N168	–	–	–	302	139 a	163 c
MP + N0	156	124 b	32 a	126	53 de	73 e
MP +N168	–	–	–	294	114 bc	180 b
N0	28	95 d	–67 e	28	46 e	–18 g
N112	140	133 a	7 c	140	105 c	35 f
P-value	–	≤0.01	≤0.01	–	≤0.01	≤0.01

† Specific treatments include: N-based separated dairy solids (CN + N0, 90 Mg ha^{-1}), N-based separated dairy solids plus 168 kg N ha^{-1} inorganic N (CN + N168, 90 Mg ha^{-1}), P-removal-based separated dairy solids (CP + N0, 34 Mg ha^{-1}), P-removal-based separated dairy solids plus 168 kg N ha^{-1} inorganic N (CP + N168, 34 Mg ha^{-1}), N-based liquid dairy manure without incorporation (MN + N0, 159 kL ha^{-1}), N-based liquid dairy manure without incorporation plus 168 kg N ha^{-1} inorganic N (MN + N168, 159 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application (MP + N0, 93 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application plus 168 kg N ha^{-1} inorganic N (MP + N168, 93 kL ha^{-1}), starter N application only (N0), and 112 kg N ha^{-1} sidedressed N (N112).

‡ Mean comparisons were done for each year individually where the overall treatment effect was significant ($\alpha \le 0.05$). Means followed by a different letter within each column are significantly different at $\alpha \le 0.05$.

different actual nutrient applications in each year, as presented in Table 3.

Application rates were set in 2001 assuming corn silage harvest with associated crop removal according to Ketterings et al. (2003b, 2003c). Rates were set to meet corn N needs in the third year of application, or to meet the estimated P removal of corn based on projected corn silage yields (yield potential), as discussed in Sadeghpour et al. (2016a). A corn silage yield potential of 18 Mg dry matter (DM) ha^{-1} was predicted for Lima silt loam (Ketterings et al., 2003a). A corn grain yield potential of 8.7 Mg DM ha^{-1} was predicted for the same soil type according to Ketterings et al. (2003a). Corn P removal was estimated to be ~ 95 kg P_2O_5 ha^{-1} assuming 2.3 g P kg^{-1} DM [the average reported by Dairy One (2007)]. Estimated total N needs (starter plus sidedressed N) ranged from 125 to 145 kg N ha^{-1} according to the algorithms outlined by Ketterings et al. (2003a). To meet the expected corn N needs, the inorganic N sidedressing rate was set at 112 kg N ha^{-1}. The organic N availability of liquid dairy manure and separated dairy solids was assumed to be 35 and 25% in the year of application, respectively; organic N availability was set at 12 and 5% in Years 2 and 3, respectively, for both sources (Ketterings et al., 2003a). The availability of N from the inorganic N fraction in the N-based manure was assumed to be zero because the manure and separated solids were not incorporated until 5 d or more after application; however, for P-based manure, 65% conservation of inorganic N was assumed with direct incorporation with a chisel plow after application (Ketterings et al., 2003a). The inorganic N content of composted separated solids was so small that incorporation would not conserve additional N, and thus no direct incorporation was done for compost treatments.

The field was in its 14th and 15th year of the corn and alfalfa rotation and, as a result, the manure- and solids-amended fields had a manure history. During the first 5 yr of the study (2001–2005), composted dairy solids were used; the actual composition and application rates have been described in Sadeghpour et al. (2016a). No manure or solids were added during the alfalfa years (2006–2010). In 2011, the first year of corn after alfalfa, no manure or compost was applied, as first-year corn is unlikely to need additional N (Lawrence et al., 2008). In 2012 and 2013, application rates were 34 and 90 Mg ha^{-1} for P-based and N-based application (wet basis) of separated dairy solids, respectively. Phosphorus-based liquid dairy manure with immediate (<1 h) tillage incorporation was applied at 93 kL ha^{-1} and N-based liquid dairy manure was applied at 159 kL ha^{-1}. The same rates were applied during the 2014 and 2015 growing seasons but actual N and P loadings differed from year to year depending on the composition of the liquid manure and separated solids.

Each year, at the time of planting, organic treatments received 11 kg N ha^{-1}, 25 kg P_2O_5 ha^{-1} (11 kg P ha^{-1}), and 25 kg K_2O ha^{-1} (21 kg K ha^{-1}) in the starter band 5 cm below and 5 cm to the side of the seed furrow. Each of the inorganic fertility treatments received 28 kg N ha^{-1}, 56 kg P_2O_5 ha^{-1} (25 kg P ha^{-1}), and 56 kg K_2O ha^{-1} (46 kg K ha^{-1}). In 2014, excluding the starter fertilizer, no inorganic N fertilizer was applied to the organic fertility treatments.

Because the results in 2014 suggested an N limitation in several of the organic treatments, 168 kg N ha^{-1} was applied as sidedressed N in half of each plot that received manure or solids in 2015. This expanded the number of treatments from 6 to 10 (Table 2 and Table 3). This additional sidedressed N treatment allowed us to determine if N supply was limiting yields in each of the organic treatments.

Plots Size, Manure Application, and Cultural Management Practices

Plots were 54 m long and 12 m wide for organic fertility treatments and 54 m long and 6 m wide for inorganic treatments. Liquid manure and separated solids were applied on 21 to 23 May in 2014 and 20 to 22 May in 2015. The P-based liquid manure was immediately incorporated (20 cm depth) with a chisel plow to conserve manure ammonia-N. The other treatments (N-based liquid manure and separated solids) were left unincorporated for approximately 7 d to allow N volatilization. For all treatments, seedbed preparation consisted of one-time disking and then rolling with a cultimulcher. Optimum N rate (112 kg N ha^{-1}) was sidedressed using a John blue (four-row) sidedresser unit with a LM-2450 pump (The Pump Co. Huntsville, AL) on 23 June in 2014 and 6 July in 2015. A John Deere 7000 Max Emerge planter

(John Deere, Moline, IL) with a row spacing of 76 cm was used to plant corn at 74,131 plants ha^{-1} in both years. The corn hybrids in 2014 and 2015 were 'Dekalb DKC43–10RIB' and 'Dekalb DKC42–37RIB', respectively. No irrigation was applied, as this is not common in New York. In both years, weeds were controlled with herbicide application.

Soil Sampling and Analysis

Fifteen soil cores were collected before manure application, at planting, at sidedressing, and at harvest from each plot at 0 to 20 cm depth to determine soil NO_3–N (Morgan, 1941). The same number of cores (15 per plot) were collected at sidedressing at 0 to 30 cm depth for the pre-sidedress nitrate test (PSNT). Soil samples were oven-dried (<50°C) for at least 48 h and crushed to pass 2 mm before analysis following standard procedures in the Northeast (Griffin et al., 2011). Soil NO_3–N was determined colorimetrically (Murphy and Riley, 1962) with a Technicon Autoanalyzer I (Pulse Instrumentation Ltd., Saskatoon, SK, Canada).

Corn Stalk Nitrate Test

When whole-plant moisture was between 600 and 700 g kg^{-1}, 15 corn stalks 20 cm in length were cut at 0.15 m above the ground, following sampling protocols for the corn stalk nitrate test (CSNT) as outlined in Binford et al. (1990). Each sample was divided into four quarters and one quarter was retained, dried at 60°C, and then ground to pass a 2-mm screen prior to NO_3 analysis. Extractable NO_3 was analyzed with 0.05 mol L^{-1} $Al_2(SO_4)_3$ and a 2 mol L^{-1} $(NH_4)_2SO_4$ ionic strength adjustor according to Wilhelm et al. (2001). A nitrate-selective electrode and a 710A pH/ISE meter (Thermo Scientific Orion, Waltham, MA) were used.

Corn Grain Yield and N Content

Because of the lack of access to silage harvest equipment, the plots were harvested for grain only in 2012 to 2015. The corn was machine-harvested on 13 Nov. 2014 and 15 Nov. 2015. Targeted moisture content was between 160 and 200 g kg^{-1}. A Case IH 2144 combine (Case, Watertown, SD) with a mounted yield monitor was used to harvest the grain. Within each plot, all plants were counted to determine stand density at harvest. Grain was subsampled to fill a 3.78-L plastic bag, sealed, and kept in a cooler before drying in a 60°C forced-air oven for a minimum of 48 h on arrival in the laboratory. The oven-dried subsamples were ground to pass a 1-mm screen, and analyzed for crude protein as per Association of Official Analytical Chemists (2000) at Cumberland Valley Analytical Services, Inc., Hagerstown, MD. Crude protein data were divided by 6.25 and reported as N concentration in the grain.

Nitrogen Balance

To determine the N balance for each treatment, N removed by harvesting (kg grain yield ha^{-1} × %N in the grain) was subtracted from the applied (credited) N for compost, manure, and fertilizer N treatments in each year. Nitrogen balances varied from year to year because of the variability in manure and compost composition and year-to-year differences in corn grain yield.

Nitrous Oxide Emissions

Vented chambers were constructed following a design presented in Dell et al. (2014). Stainless steel cafeteria serving pans (Vollrath Corporation, Sheboygan, WI) were used with a port fitted on top for sampling with a needle and syringe. To form an airtight seal after installing the chambers in the soil, foam rubber strips were attached to the lower lip of the chamber. The bottoms of the additional serving pans were cut to create chamber bases at 10 cm height. One base was installed (~5 cm deep in the soil) in every plot prior to measuring N_2O emissions. Bases were removed for field operations including seedbed preparation, planting, and sidedressing and installed again at the same place for the remaining sampling period. At each sampling time, air samples (30 mL) were removed with a syringe and a needle at 0, 15, 30, and 45 min after chamber deployment and transferred into evacuated 12.5-mL exetainers (Labco Ltd., Lampeter, UK) right after removal from the chamber. Air was sampled 32 times in 2014 and 22 times in 2015 in all main plots, excluding the areas within each organic treatment that had been sidedressed. Air sampling was more intensive (at least three times a week) after manure application and sidedressing fertilizer N. Air sampling intensity was also adjusted on the basis of rainfall events; sampling dates were aimed to collect samples just before and right after major rainfall. After about 2 mo following sidedressing, air sampling frequency was reduced to once or twice a week following the USDA-ARS GraceNet protocol (Parkin and Venterea, 2010).

The analysis of N_2O in the exetainers was performed with an Agilent 7890A (G3440A, Agilent Technologies, Santa Clara, CA) gas chromatogram system with a flame ionization detector, and an electron capture detector (Christen et al., 2014). Samples were injected with a Combi-Pal autosampler (CTC Analytics, Zwingen, Switzerland) capable of sampling 100 exetainers. Samples were drawn from the exetainers using a 2.5-mL N_2-purged glass syringe, with a HD-Type polytetrafluoroethylene-tipped syringe plunger and a 23-gauge needle (CTC Analytics AG) and injected into the gas chromatogram's heated (110°C), stainless steel purged-packed inlet with N_2 (99.999%) as a carrier gas with a flow rate of 21 mL min^{-1} at a constant flow (Column 1) and 22.3 mL min^{-1} (Column 2) at a constant pressure (Christen et al., 2014).

To calculate N_2O emission rates, N_2O concentration was regressed linearly vs. time since closure of the chamber top. If regression of N_2O emissions at the latest sampling time (45 min) against time resulted in a nonlinear response, only the initial three measurements were included to obtain linear regressions for all sampling events. This occurred occasionally at dates with low or very low emissions. At dates with high N_2O emissions, linear regression was always the best fit for calculating N_2O fluxes. Summation of N_2O emissions was done by adding all the N_2O emissions at each sampling date over time. This summation was done to obtain a relative measure of total N_2O emissions to compare treatments. These results should not be interpreted as total seasonal emissions.

At each sampling date, a field scout TDR soil moisture meter (Spectrum Technologies, Inc., Aurora, IL) was used to measure volumetric soil water content (VWC) from 0- to 12-cm depth. Along with soil moisture, soil temperature (0–10 cm depth) was monitored at each sampling date using a soil dial thermometer (Reotemp, San Diego, CA).

Statistical Analysis

Data for corn grain yields, grain N concentration, N removal, PSNT, and CSNT, N balance, and summation of soil N_2O emissions were analyzed via mixed models (Littell et al., 1996; SAS Institute 2009). The CSNT data were $\log_{10}$-transformed to fit the assumptions of the model. The fixed effect in the model was treatment and block was a random effect. Data for each year were analyzed individually because of weather patterns and the potential for carryover of N benefits from liquid manure and separated solids in 2014 into 2015. To evaluate the differences among fertility sources (solids, liquid manure, and inorganic fertilizer N), data for each year were analyzed with treatments (solids, liquid manure, and inorganic fertilizer N) as fixed effects and block as a random effect. Nitrogen balance was analyzed by year, where treatments were fixed effects and block was a random effect.

To analyze soil NO_3–N and N_2O trends, block and treatment nested within block (indicating plots) were random effects. In addition, an autoregressive covariance structure was specified for the plots being repeatedly measured over the sampling date within a year. Nitrous oxide emission data were not normally distributed and were $\log_{10}$-transformed before the analysis. The fixed effects in the model were year, treatment, sampling date, and all the interactions. Summed N_2O emissions for each sampling period (the sum of several dates) were analyzed with treatments as fixed effects and block as a random effect. The same statistical approach was applied to total N_2O emissions (the sum of all sampling dates in each year).

When treatment effects were significant, predicted means for each treatment were obtained and a post hoc comparison was done. Least square means were separated using the PDIFF option of LSMEANS in SAS PROC Mixed; LSD values are reported at $P \leq 0.05$. We used a linear regression to determine the relationship between soil NO_3–N and N_2O emissions, and between corn yield and N_2O emissions.

RESULTS AND DISCUSSION

Corn Grain Yield, N Concentration, and N Balance

In 2014, corn grain yield ranged from 6.5 Mg DM ha^{-1} in the zero-N control to 8.5 Mg DM ha^{-1} in N-based manure and 112 kg N ha^{-1} treatments (Table 2). Corn grain yields in the 112 kg N ha^{-1} treatment were 2% less than the yield potential for the soil type and 7% greater than the statewide average, reflecting sufficient N supply when 112 kg N ha^{-1} was sidedressed, combined with decent weather conditions in 2014. A shift from N-based to P-based separated solids and liquid manure did not decrease corn yields. However, the yield for corn that had received manure at N-based rates was 1.0 Mg DM ha^{-1} greater than for corn grown with N-based separated solids, consistent with the N limitation reported for corn grown for silage in the first 5 yr of the study (Sadeghpour et al., 2016a). Corn grain yields of plots that had received separated solids were 16% less than the yield potential listed for the site, 12% less than what was obtained with the optimum N fertilizer rate, and 6% less than the statewide average in 2014, reflecting N limitations in the plots amended with separated dairy solids. Corn grain yields for P-based manure in 2014 were 0.6 Mg DM ha^{-1} less than the yield potential and 0.4 Mg DM ha^{-1} less than what was obtained with the optimum N fertilizer rate, but still 0.3 Mg DM ha^{-1} above the statewide average (Table 2).

In 2015, yields were 3.3 Mg DM ha^{-1} in the zero-N control and 6.1 Mg DM ha^{-1} in 112 kg N ha^{-1} treatments (Table 2). Corn grain yields for the optimum N rate (112 kg N ha^{-1}) were 30% below the yield potential, 15% below the statewide average, and 28% less than grain yields in 2014, reflecting an extremely wet June and a 19-d dry period in July in 2015 coupled with western rootworm (*Diabrotica virgifera virgifera* Le Conte) damage and lodging. Shifting from N-based to P-based separated solids without additional sidedressed N resulted in a 30% yield reduction. Corn grain yields for N- and P-based separated solids were 2.1 and 3.3 Mg ha^{-1} less than yields at the optimum N fertilizer rate and 3.5 and 4.4 Mg ha^{-1} less than grain yields for N- and P-based separated solids in 2014, respectively.

Nitrogen-based manure, with a yield of 5.2 Mg DM ha^{-1}, was the only treatment that yielded similar to the optimum N rate. A switch from N-based to P-based liquid dairy manure decreased corn DM yield by 35% (Table 2). The average yield with P-based manure was 2.7 and 4.4 Mg ha^{-1} less than the optimum N rate and the statewide average, respectively. The considerably lower yield most probably reflected N losses (mainly through leaching) caused by an extremely wet June in 2015 combined with an overestimation of N credits for separated solids as the N source and for incorporation of liquid manure as an application method.

Sidedressing of N increased yields in both N-based and P-based separated solids and liquid manure, confirming an N limitation for those treatments (Table 2). With fertilizer N addition, the yields in the N-based manure and both N- and P-based separated solid treatments were greater than what could have been obtained with fertilizer N only, suggesting the enhanced ability of the soil in those treatments to support crop growth. This is consistent with the increase in SOM reported for N-based composted dairy solids during the first 5 yr (2001–2005) of the rotation (Sadeghpour et al., 2016b) and reflects an increase in the biological buffering capacity of the soil and overall soil quality (Meisinger et al., 2008; Long and Ketterings, 2016).

Nitrogen concentration in the corn grain was significantly influenced by fertility treatments in each year as well. In 2014, corn N concentration was greatest in the 112 kg N ha^{-1} treatment (13.4 g kg^{-1}) followed by P-based manure (13.0 g kg^{-1}) (Table 2), slightly less than the 16-yr corn grain N averages reported by Dairy One in New York (13.9 g kg^{-1}). Shifting from N-based to P-based separated solids resulted in a 6% N concentration reduction compared with no significant change in N content with a shift from N-based to P-based liquid manure (Table 2).

Similarly, in the 2015 growing season, the N concentration in the optimum N rate treatment was greater than that in all the other organic fertility treatments when no N was sidedressed. This could reflect the extremely wet June that year; separated solids and liquid manure were applied prior to planting but the fertilizer N was applied in late June when the corn crop was at its rapid growth stage and able to benefit from the readily available N provided by inorganic N fertilizer. A switch from N-based to P-based separated solid management did not influence N concentration in corn grain, whereas the N concentration in corn was less in N- than P-based manure, possibly reflecting a yield-driven dilution effect in the N-based plots (Table 2). Nitrogen concentration in the grain increased with sidedressing of the manure- and solid-amended plots with fertilizer N, further supporting the hypothesis of an N limitation in the organic treatments. The results in 2015 show a 1 Mg DM ha^{-1} yield increase per 11.1 g kg^{-1} increase in the N concentration of grain ($P < 0.01$; $R^2 = 0.73$; RMSE = 1.13), consistent with the N deficiency that year. We did not find a significant relationship between grain N concentration and corn grain yield in 2014, reflecting higher yields and more efficient N use.

The amount of credited N, estimated from Ketterings et al. (2003a), ranged from 61 (P-based separated solids) to 156 kg N ha^{-1} (P-based manure) in 2014 (Table 3). The estimated available N levels in liquid manure treatments were close to the estimated corn N needs according to N guidelines in New York (Ketterings et al., 2003a). There were no differences in the estimated available N in N- vs. P-based manure, supported by both yield and N concentration data in 2014 (Table 2). Application of separated solids at the P-based rate resulted in 58% less estimated available N (61 kg N ha^{-1}) than for the N-based separated solids treatment (144 kg N ha^{-1}) (Table 3), because of a lack of ammonia-N availability in separated solids. The lower amount of available N was also reflected in the lower yields and N concentrations of corn grain where separated solids were applied at the P-based rate (Table 2). Similar trends were observed in 2015, when applied N was lower than expected corn N removal where separated solids were applied at the P-based rate; for the other organic treatments (N-based separated solids, and N- and P-based liquid manure), the application rates were similar to the targeted N removal rate.

During the 2014 growing season, N removal (133 kg N ha^{-1}) was greatest in the optimum N treatment and 7 kg N ha^{-1} less than what was initially targeted (140 kg N ha^{-1}) (Table 3). Nitrogen removal rates with application of N- and P-based separated solids were 109 and 100 kg N ha^{-1}, respectively, 31 and 40 kg N ha^{-1} less than the designed N removal and 24 and 33 kg N ha^{-1} below what had been achieved with the optimum N rate. These results are consistent with lower yields and N concentrations in the N-based separated solids and suggest that the current N crediting system as documented by Ketterings et al. (2003a) overestimates N availability in separated solids. Previous studies by Eghball and Power (1999) and Sadeghpour et al. (2016a) also suggested that the current N decay series for compost (40 to 42% N availability) is too high and needs to be re-assessed. Nitrogen removal in the N-based and P-based liquid manure treatments was 123 and 124 kg N ha^{-1}, 17 and 16 kg N ha^{-1} less than what was targeted, and 10 and 9 kg N ha^{-1} less than what was removed with fertilization at the optimum N rate (Table 3).

In 2015, N removal was greatest (89 kg N ha^{-1}) in the optimum N rate treatment and all organic fertility treatments had a twofold reduced N removal than what was targeted. Compared with N removals in 2014, all organic fertility treatments except the N-based manure treatment showed at least a twofold lower N removal, consistent with both the N limitations in those treatments and the yield reduction caused by rootworm damage that year. It is likely that the very wet June in 2015 impacted N availability from liquid manure and separated solids, and that perhaps better application timing (sidedressing of manure) could have resulted in greater yields.

Sidedressing organic plots (N-based and P-based liquid manure and separated solids) with 168 kg N ha^{-1} increased N removal from 48 to 108 kg N ha^{-1} (N-based separated solids), 34 to 99 kg N ha^{-1} (P-based separated solids), 64 to 118 kg N ha^{-1} (N-based liquid manure), and 45 to 97 kg N ha^{-1} (P-based liquid manure), indicating the clear yield benefit of using separated solids (N-based and P-based) and N-based manure as fertility source when N is not a limiting factor. When N is not a yield-limiting factor, soils with a greater biological buffering capacity are likely to result in higher yields beyond what could have been achieved with fertilizer N alone (Long and Ketterings, 2016).

In 2014, the N balance was highest in N-based separated solids (35 kg N ha^{-1}) and P-based liquid manure (32 kg N ha^{-1}) treatments and lowest in the zero-N control (−67 kg N ha^{-1}) (Table 3). As expected, a shift from N- to P-based separated solids decreased the N balance from 35 to −39 kg N ha^{-1}, consistent with the N deficiency observed when P-based solids were applied. Shifting from N- to P-based liquid manure increased the N balance by 12 kg N ha^{-1} but this might reflect an overestimation of the N availability (65% N conservation with direct incorporation) used to calculate N balances in the P-based manure treatment. In 2015, a switch from N- to P-based separated solids decreased the N balance by 78%. There were no significant differences in N balances between N-based and P-based liquid manure, which could be explained by lower N addition combined with lower N removal in P-based manure treatments. Sidedressing of 168 kg N ha^{-1} of plots with a manure or solids history resulted in greater N balances, higher yields, and higher N concentrations in grains.

Soil NO_3–N Trends, PSNT, and CSNT

Soil NO_3–N levels in April 2014, prior to the addition of manure or separated solids, ranged from 3.2 mg kg^{-1} (inorganic N plots) to 6.2 mg kg^{-1} (plots with a P-based liquid manure history; Fig. 1). These low NO_3–N levels are consistent with the early spring NO_3–N levels in the first 5 yr of this experiment (2001–2005) reported in Sadeghpour et al. (2016b), reflecting the fall showers and spring snowmelt and rainfall events that are typical for New York. In May, the NO_3–N levels were threefold greater where liquid manure and separated solids had been ap-

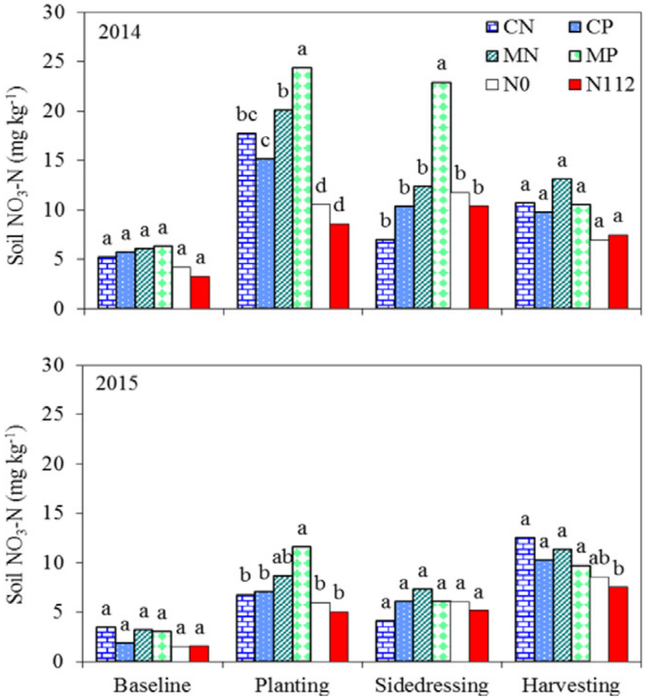

Fig. 1. Soil NO_3–N (0–20 cm depth) as influenced by separated solids, liquid manure, and inorganic N fertilizer applications in 2014 and 2015. Specific treatments include: N-based separated dairy solids (CN, 90 Mg ha^{-1}), P-removal-based separated dairy solids (CP, 34 Mg ha^{-1}), N-based liquid dairy manure without incorporation (MN, 159 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application (MP, 93 kL ha^{-1}), starter N application only (N0), and 112 kg N ha^{-1} sidedressed N (N112). Mean comparisons were done for each year and each date individually where the overall treatment effect was significant ($\alpha \le 0.05$). Means followed by a different letter within each column are significantly different at $\alpha \le 0.05$.

plied. The greater NO_3–N levels in P-based (24.3 mg kg^{-1}) than in N-based liquid manure (20.1 mg kg^{-1}) probably reflected some N conservation with immediate incorporation, as well as increased microbial activity caused by the tillage operation. In contrast, a shift from N-based (17.8 mg kg^{-1}) to P-based (15.1 mg kg^{-1}) applications of separated solids (no tillage incorporation) did not change soil NO_3–N levels in May. Soil NO_3–N levels at planting were 28% greater with liquid manure addition than with separated solids, reflecting the slow release nature of N in separated solids. At PSNT time, soil NO_3–N values of the top 20 cm ranged from 7.0 mg kg^{-1} (N-based separated solids) to 22.9 mg kg^{-1} (P-based liquid manure). A shift from N-based to P-based liquid manure increased mid-season soil NO_3–N values by 46% vs. no measurable difference in soil NO_3–N between the two separated solids treatments. At harvest time, soil NO_3–N levels were similar among all treatments, reflecting plant N removal later in the season.

In 2015, soil NO_3–N levels were low (<5 mg kg^{-1}) in April, similar to what was observed in 2014 (Fig. 1) and prior corn years (Sadeghpour et al., 2016b). Soil NO_3–N levels increased twofold (N-based separated solids) to fourfold (P-based separated solids) from April to May (planting time), but NO_3–N levels were twofold lower than in May 2014, consistent with the wet June in 2015. At planting in 2015, unlike 2014, NO_3–N levels in P-based manure (11.6 mg kg^{-1}) were not different from that of N-based manure (8.7 mg kg^{-1}). Similar to 2014, manure application resulted in 19% higher NO_3–N levels than when separated solids were applied. That year, all treatments had similar NO_3–N levels at sidedressing time and at harvest.

The PSNT (0–30 cm depth) levels ranged from 6.1 mg kg^{-1} (N-based separated solids) to 18.9 mg kg^{-1} (P-based manure) in 2014, and from 4.2 mg kg^{-1} (N-based compost) to 6.6 mg kg^{-1} (P-based manure) in 2015 (Table 2). The low PSNT levels suggest that corn plants were N-limited in both years (Klausner et al., 1994; Ketterings et al., 2003a). The lower PSNT levels in separated solids than in liquid manure plots suggest that separated solids supply less plant-available N to the plants, consistent with the lower yields and N concentrations in the grain.

In 2014, CSNT results ranged from 90 mg NO_3–N kg^{-1} (zero-N control) to 434 mg NO_3–N kg^{-1} (N-based manure) (Table 2). Low CSNT levels (<250 mg NO_3–N kg^{-1}) further support the hypothesis of an N limitation with addition of separated solids in 2014. Marginal CSNT levels (250–700 mg NO_3–N kg^{-1}) in liquid manure treatments coupled with decent yields in 2014 suggested more efficient use of N in that year. In 2015, CSNT results for corn amended with separated solids were low and similar to those seen in 2014. The CSNT levels for liquid manure were lower than those from 2014, reflecting weather challenges and possibly N loss caused by excessive rainfall during June. These findings are consistent with the lower yields, N concentrations, and PSNT levels where liquid manure was applied as the N source. In 2015, only the stalks of corn that had received the optimum N rate treatment were classified as optimum; CSNT levels were low (<250 mg NO_3–N kg^{-1}) for all organic fertility treatments (Table 2). Sideressing organic treatments with 168 kg N ha^{-1} resulted in excessive (>2000 mg kg^{-1}; Table 2) CSNT levels for all four treatments, reflecting application of fertilizer N beyond crop N needs (Table 2). These results suggest that plants grown in manure- and solid-amended plots that had received the extra sidedressed N application were not N-limited.

Soil N_2O Emissions

Baseline (April–May) N_2O fluxes were low and similar among fertility treatments (Supplemental Fig. S1 and Supplemental Fig. S2), consistent with the low NO_3–N availability prior to land application of manure in both years (Fig. 1). Daily N_2O fluxes increased approximately 14 d after the addition of manure and separated solids in 2014 (Supplemental Fig. S1). Regardless of the organic fertility source, N_2O fluxes were twofold higher in N-based than in P-based managements on 10 June (the first N_2O emission peak after manure or solids addition). A major rainfall (36 mm) event occurred 34 d after liquid manure and separated solids addition and right after sidedressing N fertilizer in June 2014. A shift from N-based to P-based separated solids decreased N_2O fluxes by 44%. Shifting from N-based to P-based liquid manure application decreased N_2O fluxes by 10%, reflecting ammonia-N conservation with tillage incorporation combined with a high VWC (38%) (Supplemental Fig. S1 and Supplemental Fig. S2). Nitrous oxide fluxes right after the major rainfall event, averaged over the two rates, were greater when liquid manure had been applied than when separated solids had been applied, reflecting the slow release of N from separated solids.

After sidedressing of N in the optimum N rate treatment, there were several daily fluxes which started from 26 June (3 d after sidedressing) until 4 August (42 d after sidedressing). This suggests that not all NO_3–N in urea ammonium nitrate was readily available (gradual N release). In this same time period, the daily N_2O fluxes were low for both separated solids and liquid manure regardless of the application rate.

In 2015, both baseline sampling and end-of-season N_2O fluxes were small and were not impacted by fertility source or the rate of application, similar to what was observed in 2014 (Supplemental Fig. S1). Daily N_2O fluxes increased approximately 10 d after addition of manure and separated solids that year. The peak in daily N_2O fluxes occurred on 2 June in both N- (94 g N_2O ha^{-1} d^{-1}) and P-based manure (122 g N_2O ha^{-1} d^{-1}) treatments. Nitrous oxide fluxes remained high on 3 June for both N- and P-based manure (122 g N_2O ha^{-1} d^{-1}) and June sixth for P-based manure only. The peak daily N_2O fluxes never exceeded 40 g N_2O ha^{-1} in the N- and P-based separated solids treatments in 2015 and were much lower than in 2014 (233 for N-based and 122 g N_2O ha^{-1} for P-based separated solids on 10 June). The low N_2O fluxes seen when separated solids had been applied are consistent with an N limitation, and lower yields, grain N concentration, PSNT, and CSNT levels. After sidedressing, daily N_2O fluxes were always low (30 g N_2O ha^{-1} d^{-1}) in organic treatments, similar to what was observed in 2014. The highest N_2O peaks were seen 4 d (110 g N_2O ha^{-1} d^{-1}) and 10 d (282 g N_2O ha^{-1} d^{-1}) after sidedressing in the optimum N treatment, reflecting a combination of N availability and sufficient VWC (33%) over that time period (Supplemental Fig. S2).

In 2014, the summation of N_2O fluxes in early June to late June (before sidedressing of fertilizer N) showed higher values with N-based liquid manure and separated solids addition than in the two controls (Fig. 2). In this time period (in 2014), N-based solids management resulted in N_2O fluxes of 318 g N_2O ha^{-1} per period vs. 190 g N_2O ha^{-1} per period for P-based management. At the same period in 2014, N-based liquid manure management resulted in N_2O fluxes of 324 g N_2O ha^{-1} per period vs. 163 g N_2O ha^{-1} per period for P-based management. High variability among replications in the same treatment resulted in no significant differences among the N- and P-based manure and separated solids treatments. In 2015, the summed N_2O fluxes between the end of May to late June were greater with liquid manure addition (548 g N_2O ha^{-1} per period; average of N-based and P-based rates) than with separated solids (188 g N_2O ha^{-1} per period; average of N- and P-based rates) or inorganic fertilizer N (260 g N_2O ha^{-1} per period).

In 2015, N-based solids management resulted in N_2O fluxes of 169 g N_2O ha^{-1} per period vs. 205 g N_2O ha^{-1} per period for P-based management (summation of end of May to late June, prior to sidedressing N fertilizer). At the same period, N-based liquid manure management resulted in N_2O fluxes of 484 g N_2O ha^{-1} per period vs. 613 g N_2O ha^{-1} per period for P-based management. The greater N_2O fluxes seen in P-based than in N-based separated solids, and in P-based than in N-based liquid manure in 2015 could be explained by the slightly higher NO_3–N availability in that sampling period (end of May to late June). Differences among years most probably reflected the challenging spring in 2015 (a wet June) combined with a very dry July.

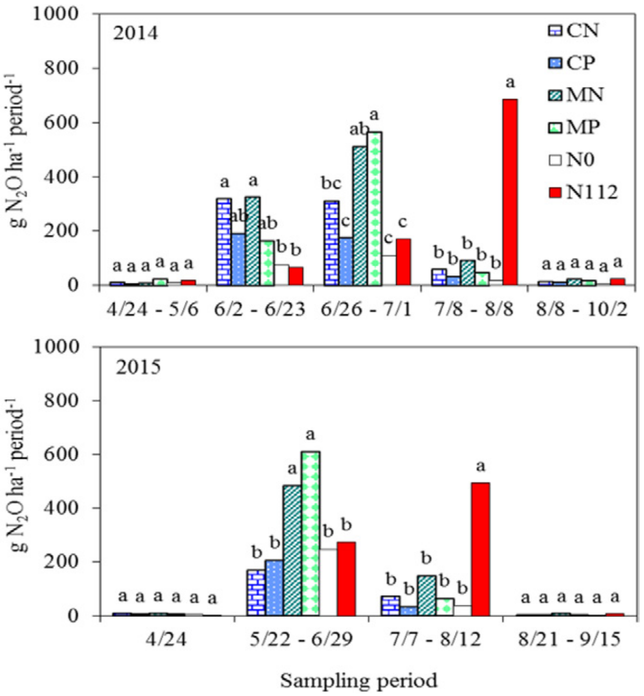

Fig. 2. Summed N_2O fluxes in each sampling period (baseline, after manure application, after a major rainfall event, after sidedressing, and before harvesting) as influenced by inorganic N, and N- vs. P-based liquid manure and separated solids application in 2014 and 2015. Specific treatments include: N-based separated dairy solids (CN, 90 Mg ha^{-1}), P-removal-based separated dairy solids (CP, 34 Mg ha^{-1}), N-based liquid dairy manure without incorporation (MN, 159 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application (MP, 93 kL ha^{-1}), starter N application only (N0), and 112 kg N ha^{-1} sidedressed N (N112). Mean comparisons were done for each year individually within each sampling period where the overall treatment effect was significant ($\alpha \le 0.05$). Means followed by a different letter within each column are significantly different at $\alpha \le 0.05$.

There was a positive linear relationship between soil NO_3–N availability and N_2O emissions ($R^2 = 0.92$; $P \le 0.01$) prior to sidedressing N in 2014 (Fig. 3). With every mg NO_3–N kg^{-1}, N_2O emissions increased by 34 g ha^{-1} per period. Small N_2O fluxes were observed in organic fertilizer treatments (N-based and P-based separated solids and liquid manure) mid-season, similar to what was observed in 2014; N_2O fluxes (mid-July to mid-August) ranged from 33 g N_2O ha^{-1} per period (P-based separated solids) to 495 g N_2O ha^{-1} per period (optimum N rate).

In 2015, similar to 2014, summed N_2O fluxes were small prior to manure addition (Fig. 2). After manure and separated solids addition, several N_2O peaks for manure treatments were recorded and therefore, the summed N_2O emissions between the end of May and late June had greater N_2O fluxes where manure had been applied than where separated solids and inorganic

N were the fertility source. In 2015, for every mg NO_3–N kg^{-1}, N_2O emissions increased by 47 g ha^{-1} per period, possibly reflecting weather conditions that were conducive to denitrification (the wet June) in 2015 in the period prior to sidedressing (Fig. 3). We found no relationship between summed NO_3–N and summed N_2O emissions, but this could reflect the lack of data for soil nitrate between sidedressing and harvesting dates in both years. The greatest N_2O fluxes (685 g N_2O ha^{-1} per period) were recorded in early July to mid-August when plots were sidedressed (optimum N rate). Summed emissions were eightfold greater for the optimum N rate than for the N-based liquid manure (90 g N_2O ha^{-1} per period) and 38 times greater than what was obtained for the zero-N control (Fig. 2). End-of-season N_2O fluxes were low with no differences among treatments, reflecting corn N removal and low NO_3–N availability.

Summed across all dates, N_2O emissions ranged from 219 (zero-N control) to 965 g N_2O ha^{-1} yr^{-1} (optimum N rate) in 2014, and from 249 (P-based separated solids) to 777 g N_2O ha^{-1} yr^{-1} (optimum N rate) in 2015 (Supplemental Table S1). A shift from N- to P-based separated solids decreased N_2O emissions by 42% in 2014, with no measurable decrease in 2015. Shifting from N- to P-based liquid manure resulted in 14% lower N_2O fluxes in 2014, with no measurable decrease in 2015.

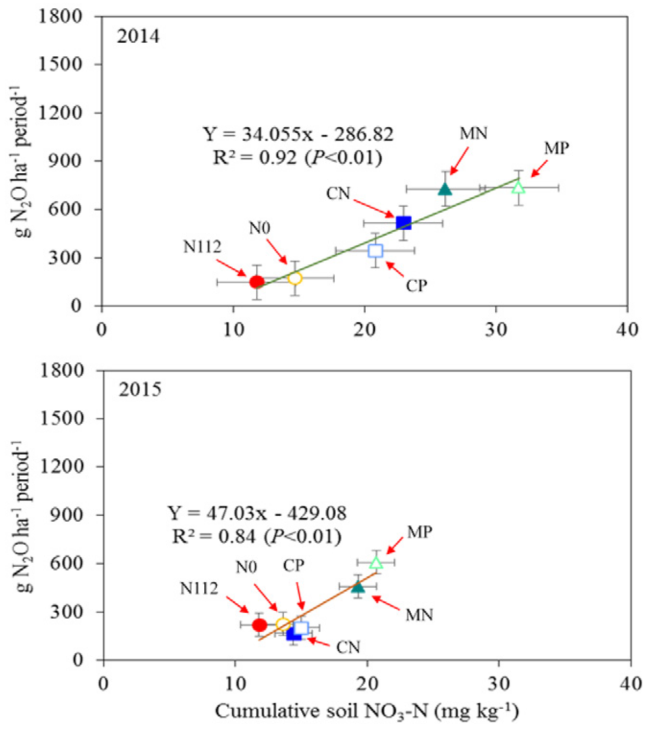

Fig. 3. Relationship between soil N_3O-N (sum of baseline, planting, and sidedressing) and summed soil N_2O emissions (sum of dates prior to sidedressing) in 2014 and 2015. Specific treatments include: N-based separated dairy solids (CN, 90 Mg ha^{-1}), P-removal-based separated dairy solids (CP, 34 Mg ha^{-1}), N-based liquid dairy manure without incorporation (MN, 159 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application (MP, 93 kL ha^{-1}), starter N application only (N0), and 112 kg N ha^{-1} sidedressed N (N112). Bars show SE and variability among treatments.

Relationship between Corn Grain Yield and Total N_2O Emissions

In 2014, total N_2O emissions were linearly related to corn grain yields (R^2 = 0.94; P < 0.01), with emissions of 398 g N_2O ha^{-1} yr^{-1} per 1 Mg DM ha^{-1} corn grain yield (Fig. 4). In 2015, P-based liquid manure showed high N_2O emissions (688 g N_2O ha^{-1} yr^{-1}) but yields were low (3.4 Mg DM ha^{-1}) because of excess rain early in the season and rootworm damage. Excluding the P-based liquid manure emission and yield data (plots were greatly impacted by rootworm damage), total N_2O emissions for all other treatments increased linearly by 174 g N_2O ha^{-1} yr^{-1} for every 1 Mg DM ha^{-1} corn grain yield (Fig. 4). Differences in slope between the 2 yr probably reflect the differences in weather patterns (rainfall). Our results suggest that total N_2O emissions vary greatly from year to year and increase with greater N availability and thus yield where N is limiting production. A shift to P-based manure management with incorporation of the manure can benefit farming systems through reduced build-up of P and K, and reduced odor, P runoff, and N volatilization losses; however, N_2O emissions will increase if the shift to a P-based system requires the addition of fertilizer N.

SUMMARY AND CONCLUSIONS

In summary, (i) a shift from N-based to P-based manure and separated solids application did not influence corn grain yield in 2014 but resulted in 30 and 35% less yield in 2015 (reflect-

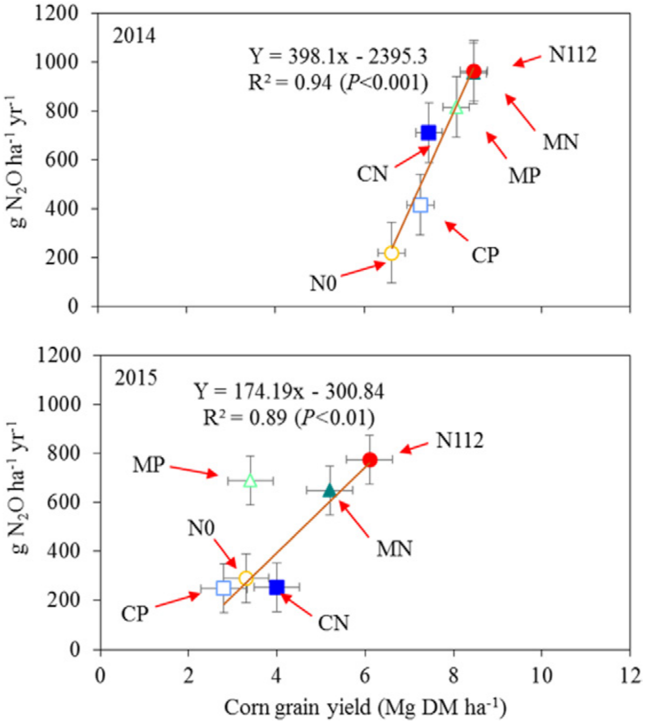

Fig. 4. Relationship between corn grain yield and summed soil N_2O emissions in 2014 and 2015. Specific treatments include: N-based separated dairy solids (CN, 90 Mg ha^{-1}), P-removal-based separated dairy solids (CP, 34 Mg ha^{-1}), N-based liquid dairy manure without incorporation (MN, 159 kL ha^{-1}), P-removal-based liquid dairy manure with incorporation of manure directly following application (MP, 93 kL ha^{-1}), starter N application only (N0), and 112 kg N ha^{-1} sidedressed N (N112). Bars show SE and variability among treatments.

ing differences in growing conditions and N availability among years); (ii) sidedressing organic plots with 168 kg N ha^{-1} resulted in yields equivalent or higher than what was achieved with the optimum N rate (112 kg N ha^{-1}); (iii) soil NO_3–N under liquid manure was 28% greater than under separated solids, reflecting the slow release of N in separated solids; (iv) N_2O emissions (for each day, period, or in total) were different from year to year reflecting soil moisture (rainfall) and N availability; (v) summed (total) N_2O emissions were linearly related to yield, indicating that soil NO_3–N was driving both yield and emissions. The results indicate that when N is a limiting factor, N_2O emissions increase with increasing N availability and thus crop yield. We conclude that a shift to P-based manure management with incorporation of the manure can benefit farming systems through reduced build-up of P and K, P runoff, and N volatilization losses, but N_2O emissions will increase if the shift to a P-based system requires the addition of fertilizer N.

Future research should focus on (i) improving N crediting systems for both liquid manure and separated solids to avoid N limitation to corn crops and (ii) using N management practices that enhance the synchronization of N release and N uptake for corn. Precision N management will be important for not exceeding the N needs of the crop, as excess N will result in an increase in N_2O emissions when soil conditions are conducive to denitrification. Based on our results, some N_2O emission losses are biologically unavoidable when N is a limiting factor.

SUPPLEMENTAL MATERIAL

The supplemental material includes Fig. S1 showing trends in soil N2O fluxes as influenced by inorganic N, and N- vs. P-based liquid manure and separated solids application in 2014 and 2015. Fig. S2 showing volumetric water content (WVC%; 0-12 cm depth) and temperature (0-10 cm depth) collected at each N2O flux sampling date from separated solids, liquid manure and inorganic N fertilizer application plots (average of 30 plots) in 2014 and 2015. Table S1 showing summed N_2O emissions as influenced by separated solids, liquid manure and inorganic N fertilizer application in 2014 and 2015.

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