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Greenhouse Gas Emissions with Low Disturbance Liquid Dairy Manure Incorporation into a Live Winter Cereal Cover Crop-Corn System

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Abstract: Dairy manure is an important nutrient source for crops but can also contribute to ammonia (NH_3) and greenhouse gas (GHG) emissions. While incorporating manure into the soil reduces nutrient loss potential in surface runoff, impacts on GHGs are unclear. Here, our objective was to quantify NH_3, nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) fluxes for two seasons after liquid dairy manure was spring-applied to a live winter cereal cover crop-corn system with different incorporation methods. Broadcast application and no manure controls were compared to manure incorporated by vertical tillage (VT) or chisel plowing (CP). Corn yields did not differ in 2018 but were greater for CP in 2019. Mean NH_3 emissions for VT were 70 and 23% of broadcast and 7 and 11% of broadcast for CP in 2018 and 2019, respectively. While VT N_2O-N fluxes were also about 70% lower than broadcast both years, CO_2 fluxes were larger for VT. On average, CP and VT had 16 and 4% lower global warming potential (GWP) index values than broadcast, respectively. Despite differing effects on N_2O, our results showed that CP more effectively conserved NH_3 while reducing GWP from liquid manure compared to VT, stressing the importance of site-specific soil-manure-tillage interactions when quantifying dairy system GHG fluxes.

Keywords: dairy systems; cover crops; manure; planting green; greenhouse gas emissions

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1. Introduction

The use of dairy manure as a fertilizer is common in Wisconsin and the upper Midwest where dairy production is prevalent, but the use of manure on cropland can increase greenhouse gas (GHG) release from soils [1–4], particularly nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4). Manure addition to corn (*Zea mays* L.) or other crops also affects soil properties and carbon (C) sequestration that can further influence GHG fluxes [5]. Dairy manure additions can also lead to ammonia (NH_3) loss, sometimes considered to be a secondary N_2O emitter. Ammonia volatilization is also a major N loss pathway to the air, particularly with surface application [6–8]. Incorporating manure thus conserves more NH_3 and decreases nitrogen (N) and phosphorus (P) runoff risk [9–11].

While tillage incorporation of manure or injection decreases NH_3 loss, N_2O fluxes can increase as a result of greater inorganic N availability [12]. Mineralization of manure organic N to NH_4^+ with subsequent nitrification (i.e., $NH_4^+ \rightarrow NO_3^-$) provides ample NO_3^- for denitrification reactions that drive N_2O formation [13–16]. Tillage practices affect aeration status and interact with other factors including soil fertility, organic matter turnover/decomposition, C availability and therefore influence N_2O dynamics [17].

Cover crops are utilized in corn production systems to decrease sediment and associated N and P losses in surface runoff, particularly in colder climates where winter runoff is a major contributor to annual loads [18–20], as well as reduce N leaching between cropping seasons through N assimilation [21,22]. Some studies suggest that soil C from cover crops can increase GHG emissions, especially N_2O [23]), however, and the incorporation of the cover crop residues may significantly contribute to these increases [24]. Delaying cover crop termination for 1–2 weeks after planting or "planting green" into a cover crop is relatively new and few studies have examined agri-environmental benefits. By delaying cover crop termination until later, soil moisture can continue to be transpired, decreasing water-filled pore space and decreasing potential N_2O release [21,25–28]. Later termination may also help slow decomposition, delaying N release to later in the season when corn needs more N [27–29].

Some studies show a potential yield depression with delaying cover crop termination near corn planting time or later [25–29]. Some degree of tillage and/or manure incorporation may help decrease this corn yield depression risk. Raimbault et al. [30] found moving residue out of the row area in no-till plots reduced negative effects on growth, while Ewing et al. [31] reported that subsoiling improved water availability to crops and increased grain yield where cover crops were present. However, Duiker and Curran [32] found no benefit of in-row tillage to no-till on crop yield or weed control with rye killed in the late boot-stage. Such studies document corn yield risks with planting green and ways to minimize potential yield losses, and in particular, post-planting cover crop (live) management schemes. While this is an important aspect of corn (*Zea mays*, L.) production, few studies have focused on water quality and GHG aspects of planting green [33]. Research on the effect of this practice on GHG emissions has been relatively non-existent.

Planting into live or recently terminated cover crops is gaining more interest, particularly with no-till and reduced tillage farms, however relatively few if any studies have investigated the impacts of manure incorporation on GHG and NH_3 losses in upper Midwest corn-cover crop systems. The objective of our experiment was to quantify NH_3, N_2O, CH_4, and CO_2 fluxes in the field for two seasons after liquid dairy manure was either applied on the surface (broadcast) or incorporated via chisel plowing (CP) or vertical tillage (VT). We additionally measured corn and cover crop yield and monitored changes in soil C, N, and other properties.

2. Materials and Methods

This field experiment was conducted on a moderately well drained Loyal silt loam soil (fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs; 1–6% slope) located on the University of Wisconsin Marshfield Agricultural Research Station at Stratford, WI. The field used was planted 12 September 2017 with a Brillion seeder to Triticale (*Triticale hexaploide* L.) at 224 kg ha^{-1} and 23 October 2018 to winter rye (*Secale cereale*) at 112 kg ha^{-1}. Plots were arranged in a randomized complete block design with 4 blocks and 4 treatments, each 4.6 × 15.2 m in size. Blocks were set up along two transects (up and down the slope) with a 3-m-wide border between blocks within each transect and a 17-m-wide border between transects to accommodate the size and turning radius of field equipment. Plots were positioned and applications of dairy slurry were made along the longer dimension of the rectangle oriented perpendicular to the slope. Triticale was cut at a 10 cm height and harvested on 29 May 2018. Rye growth averaged a height of 25 cm in 2019 and was minimal enough to plant directly into the crop without cutting and harvesting.

Treatments consisted of a no-manure control (control) and three dairy manure treatments applied all on the same day each year (on 4 June 2018 and 6 June 2019). Dairy manure treatments were broadcast using a toolbar with drop tubes (Yetter Avenger, Yetter Manufacturing, Colchester, IL, USA) set at 30 cm spacings raised to a height of 38 cm above the soil surface in both years. The three manure treatments were: (1) surface application with no incorporation (broadcast); (2) surface application incorporated using a McFarlane Incite 5000 (McFarlane Manufacturing, Sauk City, WI, USA) vertical tillage tool at a 3° disk angle (VT) to a 3.5 cm depth; and (3) surface application incorporated using a Brillion chisel plow (Landoll Farm Equipment, Brillion, WI, USA) to a depth of 15 cm (CP), followed by a pass with the VT tool to smooth the surface for corn planting. The VT and CP plots received tillage within 10 min of manure application. Plots were immediately planted to silage corn (*Zea mays* L.; Prairie Estates C-2908 hybrid, Middleton, WI, USA 2018, 69,000 seeds ha^{-1};

Dekalb DKC38-01 hybrid, St. Louis, MO, USA 2019, 84,785 seeds ha^{-1}) after manure application and incorporation (CP and VT) using a John Deere Max Emerge six row planter (John Deere, Moline, IL, USA).

During the application process manure was sampled twice and subsequently tested (University of Wisconsin Soil and Forage Laboratory, Marshfield, WI, USA) for TN, TP, ammonium-N (NH_4-N), water extractable P and solids content [34]. Manure application rates were approximately 66,200 L ha^{-1} in 2018, which supplied an average of 14.6 kg P ha^{-1} and 106 kg N ha^{-1}, and 142,000 L ha^{-1}. In 2019, an applicator mistakenly over-applied manure, supplying 66.7 kg P ha^{-1} and 293 kg N ha^{-1}. Liquid fertilizer (7-9-13-2[S]) was applied via the planter in a 2 × 2 configuration (50 mm to the side of the seed row and 50 mm deep at a rate of 93.5 L ha^{-1}. Cereal stubble was sprayed 25 June 2018 and 11 June 2019 with Roundup® (Monsanto, St. Louis, MO, USA) and Status® (BASF, Florham Park, NJ, USA) to reduce competition, the silage corn hybrid planted in 2018 was not roundup ready and the field was replanted 29 June 2018 with silage corn (Legacy 2847, Scandinavia, WI, USA) in the same manner as on 4 June 2018, except with no starter fertilizer.

Concentrations of N_2O, NH_3, CO_2, and CH_4 were measured using static chambers, (similar the GRACEnet protocol) [35] modified to work with a portable closed path Fourier-transform infrared spectrophotometer (FTIR, Gasmet DX4040, Vantaa, Finland). Chambers consisted of stainless-steel bases (81.3 × 38.1 × 15.2 cm) based on the design of Venterea [36], centered over the second and fifth row of each plot. Bases were inserted leaving an average height of 5 cm above soil surface to account for surface topography. Chambers were moved for field operations only, at which time they were alternately placed 1.5 or 2.5 m from plot edge in the respective row. Insulated stainless steel lids (81.3 × 38.1 × 15.2 cm) equipped with 0.64 cm quick connect fittings to connect to FTIR tubing were sealed (weather stripping) on top of bases during measurement by clipping steel lids to bases with binder clips. Gas samples were collected by FTIR, pumped through 4 m long 4 mm ID PTFE tubing equipped with a 47 mm polycarbonate membrane filter on the instrument inlet line to remove moisture and other debris, sample air was then pumped back into the chamber as part of the closed loop. Sample gas concentrations were determined every 40 s over a 7 min period and were typically determined in a window between 0800 h and 1300 h to approximate mean daily temperature. Gas fluxes were calculated from the rate of change in concentration over the sampling period with linear regression and adjusted for theoretical underestimation as described by Venterea [36] to compensate for chamber deployment. The method also permits estimates of GHG consumption by soils (expressed as negative fluxes on graphs).

Plot-level soil volumetric moisture content (5 cm depth; Delta-T Devices Theta Probe) and temperature (5 cm depth; digital soil thermometer) were measured at each sampling for necessary GHG flux adjustments. Measurement began about 1 day after manure application in 2018 and 2 days after in 2019 and continued into winter as weather allowed. Sampling resumed in the spring and was done approximately weekly (more frequently after manure or rain, less frequently late in the season) through corn harvest.

Soil bulk density was measured (two 48 mm-diam. × 0.1 m deep cores per plot) 4 to 6 times per year at the beginning of each sampling year and after field activities expected to affect bulk density (used for flux underestimation adjustments [36]). Soil samples were collected approximately monthly (6, 2 cm diameter cores/plot, 0 to 10 and 10 to 20 cm depths). Nitrate-N and NH_4-N concentrations were determined after extraction by 2 M potassium chloride [34] and measured on a flow injection analyzer using standard techniques [37,38]. Prior to the start and after harvest in 2019 a more thorough soil sampling was done. Fifteen, 2 cm diameter cores/plot were collected and divided into 0 to 5; 5 to 10; 10 to 20; and 20 to 30 cm depths in addition to 3, 2 cm diameter cores taken at 30–60 cm depth. Samples were dried, ground (2-mm) and analyzed for plant available P, and potassium (K) [36], NO_3-N, and NH_4-N as described earlier, and OM by loss on ignition [39,40]. Wet soil aggregate stability was measured using 100 g subsamples (for 0 to

10, 10 to 20 and 20 to 30 cm depths) to determine mean weight diameter (MWD) and percent large (>2 mm diameter) and small (>0.25 mm to <2 mm diameter) macro-aggregates, and micro-aggregates (<0.25 mm diameter) [41].

Winter cereal rye biomass yields were estimated by gently tossing two sampling frames (0.25 × 0.25 m) into larger plots then from the location of the first sampling. Whole plant corn samples were taken at silage harvest, a 3.3 m section of rows 3 and 4 were cut 16 cm above the soil surface, chopped, and weighed. Corn and cereal biomass samples were dried (55 °C), ground (1 mm), and analyzed for N by high temperature combustion (Elementar VarioMax CN analyzer). Residue cover (corn and cereal) was measured by photographs using digital imagery analysis (SamplePoint software) [42], 2 photos per plot (each 2.25 m^2). Residue coverage was measured prior to manure application and planting and after to contrast coverage changes due to field activity. Monthly precipitation and air temperature were obtained from a portable weather station on the edge of the field (Spectrum Technologies, Aurora, IL, USA).

Plots were arranged in a randomized complete block design and manure application method was the main effect with NH_3, N_2O, CH_4, and CO_2 as dependent variables. Analysis of variance was conducted to test for main effects using the Proc Mixed procedure of the Statistical Analysis System (SAS) and least square means were separated using the PDIFF option [43]. Block was treated as a random effect. Data were tested (Proc Univariate) and transformed ($\log_{10}$ or square root) as needed for normality and homogeneity of variance. Annual cumulative GHG flux was estimated by linear interpolation between sampling times by trapezoidal integration of flux over time assuming linear changes in daily fluxes [36]. Sampling years were considered to span from the spring through the fall/early winter of each year. All dependent variables are presented as untransformed means to maintain consistency. Pearson correlation coefficients were conducted between GHGs, soil temperature, and volumetric moisture content (Proc Corr). Because of the inherent variability associated with NH_3 and GHG fluxes, treatment effects and means were considered significant at $p \leq 0.05$.

3. Results and Discussion

3.1. Weather

Average temperatures for the growing season averaged within 1% of the 40-year average (18.9 °C; Jason Cavadini, personal communication, 2017). Rain totals during the growing season were similar in 2018 (529 mm) and 2019 (517 mm) but the distribution varied. Rainfall totals were on average 19% greater than the 40-year average during the growing season (May to September). Most of the rain for 2018 fell in a few large events in June and the end of August with very few smaller events the rest of the season, while in 2019 it was more evenly distributed (additional weather data are presented in the GHG section).

3.2. Plant Yields and Soil Nutrients

There were no differences in cereal growth among treatments before the trial began in 2018 (average 6413 kg ha^{-1}) or in 2019 (average 1214 kg ha^{-1}). There were also no significant differences for corn yield (average 12.2 Mg ha^{-1}) or N uptake (average 140 kg ha^{-1}) in 2018. However, CP had significantly greater yield in 2019 (14.0 Mg ha^{-1}) with lower yields for control and broadcast (7.3 and 9.6 Mg ha^{-1}, respectively). Uptake of N also differed among treatments in 2019 with a similar trend for treatments. Soil PSNT levels differed among treatments in 2018 (data not shown) with all above the critical range for corn (21–26 mg kg^{-1}) [44,45]. In 2019, PSNT for CP was 8.2 mg NO_3-N kg^{-1} while control and broadcast were 3.8 mg kg^{-1}; the low values were likely due to a rainy period that occurred in late June 2019. While VT incorporated less manure than CP and yield and N uptake were also lower than CP, it was higher than broadcast (10.7 Mg ha^{-1} and 99.3 kg ha^{-1}, respectively). Later terminated cereal rye incorporated into the soil may release N at a time corn needs it most within the root zone [29], which may additionally have contributed to CP higher yield and N uptake and intermediate yield for VT.

There were no significant soil nutrient differences in the top three depth increments prior to treatment in 2018 (Table 1). In October of 2019, N, C, K, P, and OM were significantly lower in CP plots than VT or surface applied treatments at the 0–5 cm depth, and in some cases (N, C, and OM) were lower than the control (Table 1). At 5–10 cm CP was only significantly lower in C but had the lowest OM content of all treatments in the 10–20 and 20–30 cm depth, as well as low C and N at 20–30 cm. Tillage in some cases can cause significant C depletion due to dilution effects [46]. The CP treatment incorporated manure and stubble (approximately 15 cm of disturbance) into the soil and mixing biomass throughout the upper portion of the soil more vigorously than VT and likely contributed to lower soil C and N. Since mixing residue/manure via CP tends to decrease topsoil nutrients including labile C via mass dilution, it is possible that microbe respiration was reduced by lack of labile C, particularly if structural disruption led to surface crusting and lower oxygen diffusion [4,47], further reducing respiration/CO_2 flux.

Aggregate stability measurements also showed some impact of lower soil OM from CP. There were no aggregate size classes or MWD differences in 2018 for soil samples (data not shown). In 2019, CP had significantly lower MWD at all measured depths (about 50% of other treatments, average) and also significant aggregate size distribution changes compared to other treatments (10% greater microaggregates at all depths and 20% less large macroaggregates in surface soils). These results could be related to the combination of mechanical disruption, lower biological activity and OM content [48].

Table 1. Select soil nutrient properties from May 2018 and October 2019.

Depth	Treatment	OM †	P	K	N	C
(cm)		(%)	(mg kg^{-1})	(mg kg^{-1})	(g kg^{-1})	(g kg^{-1})
			May 2018			
0–5	Control	4.79	30.3	218	2.41	24.4
	Broadcast	4.88	31.0	220	2.40	25.8
	Vertical Till	4.78	31.8	223	2.46	25.3
	Chisel Plow	4.93	30.0	212	2.31	24.5
	CV	9.4	13.9	8.1	6.8	6.5
	p-value	NS ‡	NS	NS	NS	NS
5–10	Control	3.69	18.0	108	1.85	18.8
	Broadcast	3.72	18.8	121	1.90	19.1
	Vertical Till	3.68	18.8	117	1.85	18.6
	Chisel Plow	3.66	18.8	119	1.80	18.0
	CV	9.1	9.4	16.5	7.6	7.2
	p-value	NS	NS	NS	NS	NS
10–20	Control	3.14	14.5	43.3	1.51	14.6
	Broadcast	2.96	15.0	50.3	1.49	14.2
	Vertical Till	3.03	14.3	48.0	1.48	14.4
	Chisel Plow	3.13	14.3	51.8	1.40	14.2
	CV	10.4	7.1	16.5	8.8	7.9
	p-value	NS	NS	NS	NS	NS
20–30	Control	2.46	13.0	33.3	0.96	9.25
	Broadcast	2.17	11.5	34.3	0.76	7.95
	Vertical Till	2.00	10.5	33.5	0.70	7.16
	Chisel Plow	1.86	10.0	34.3	0.48	5.88
	CV	25.2	20.4	9.0	48.4	39.0
	p-value	NS	NS	NS	NS	NS

Table 1. *Cont.*

Depth (cm)	Treatment	OM [†] (%)	P (mg kg^{-1})	K (mg kg^{-1})	N (g kg^{-1})	C (g kg^{-1})
			October 2019			
0–5	Control	4.07 a [§]	25.8 c	165 b	2.44 a	23.8 b
	Broadcast	4.31 a	36.8 b	232 a	2.60 a	25.2 a
	Vertical Till	4.12 a	40.6 a	237 a	2.45 a	24.1 b
	Chisel Plow	3.40 b	28.8 c	176 b	2.03 b	19.8 c
	CV	11.3	22.6	18.1	11.8	11.7
	p-value	0.001	0.0002	0.0003	0.002	<0.0001
5–10	Control	3.37	15.0 b	78.1 b	2.02	18.90
	Broadcast	3.47	18.3 a	124 a	2.05	19.60
	Vertical Till	3.37	18.6 a	115 a	1.95	18.30
	Chisel Plow	3.13	19.6 a	109 a	1.82	17.30
	CV	9.0	15.1	20.2	9.2	9.5
	p-value	NS	0.05	0.009	NS	NS
10–20	Control	2.69 b	12.0	38.9	1.56	14.6
	Broadcast	2.86 a	13.2	49.7	1.56	14.5
	Vertical Till	2.76 ab	13.7	50.7	1.31	12.4
	Chisel Plow	2.50 c	12.4	48.4	1.21	12.2
	CV	9.4	11.0	20.6	20.4	17.8
	p-value	0.003	NS	NS	NS	NS
20–30	Control	1.89 a	10.5	36.4	0.80 a	8.00 a
	Broadcast	2.13 a	12.2	34.8	1.00 a	9.65 a
	Vertical Till	1.81 a	10.6	38.4	1.03 a	9.61 a
	Chisel Plow	1.20 b	8.74	39.8	0.34 b	4.14 b
	CV	34.2	21.4	12.6	66.4	52.3
	p-value	0.01	NS	NS	0.03	0.02

[†] OM = soil organic matter; P = Bray-1 extractable phosphorus; K = Bray-1 extractable potassium N = total soil nitrogen; C = total soil carbon; [‡] NS = not soil significant; [§] treatments with the same letter are not different at $p = 0.05$.

3.3. Ammonia Fluxes

An average of 4753 kg DM ha^{-1}, 200 kg TN ha^{-1}, 40.6 kg TP ha^{-1}, 116 kg NH_4-N ha^{-1}, and 9.8 kg WEP ha^{-1} was applied in manure. Emissions of NH_3-N were generally greatest immediately after manure was applied (Figure 1, left panels). In both years broadcast lost the greatest amount of cumulative NH_3-N (Fig 1, right panels) but there were some differences in effectiveness of incorporation on N conservation. In both years, CP NH_3 losses were statistically similar to the control.

Differences between years is likely related to the manure quantity and quality applied as has been seen elsewhere [6,8]. The solids content was one fifth and NH_4-N content was 50% lower in the manure applied in 2018 than 2019. The lower solids content manure was likely able to move into the soil more easily, leaving less on the surface where NH_3 volatilization rates are far greater [49,50]. Greater solids application in 2019 likely kept manure on the soil surface and on the cover crop biomass for longer allowing for greater losses. Residue coverage measurements show 26% more manure on the surface for broadcast and 24% for VT in 2019 than 2018 emphasizing overall less incorporation/absorption into the soil.

The overall amounts of NH_3-N loss were much lower than what has been cited elsewhere [6,51,52] and could be partly due to delayed sampling for NH_3 to permit FTIR measurements, since large NH_3 volatilization losses can occur within hours after manure application [6,7,53]. Dell et al. [6] reported >50% of NH_4-N applied was lost with broadcast application during this short timeframe.

Our methodology quantified fluxes days after manure application based on linear relationships, thus more rapid changes in NH_3 fluxes after manure application may not be captured accurately. Other methods, such as passive diffusion sampling [54], can track NH_3-N loss in the hours after application but is extremely labor intensive. Notwithstanding, relationships in our study still reflect overall field scale loss patterns as treatment impacts indicative of other studies showing CP can reduce NH_3 by 90% vs. broadcast, while lower disturbance methods are less effective and more variable [6,7].

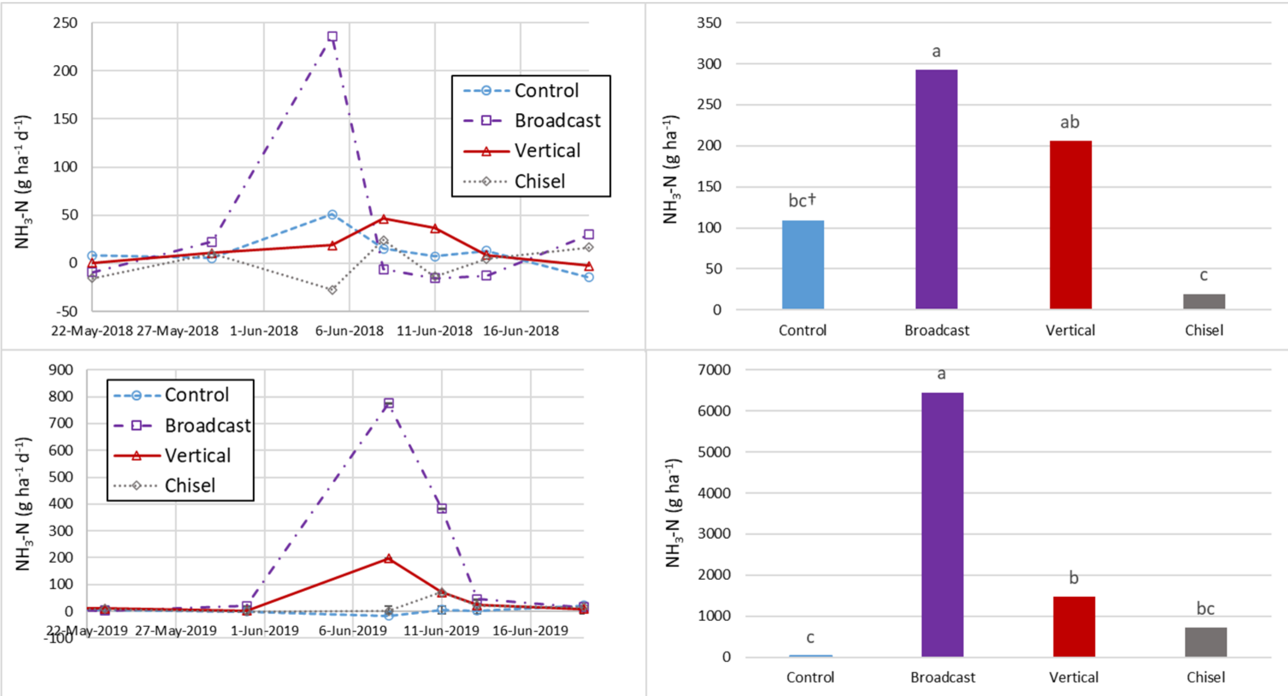

Figure 1. Seasonal (**left** panels) and cumulative (**right** panels) ammonia emissions in 2018 (**top**) and 2019 (**bottom**). † treatments with the same letter are not different at $p = 0.05$.

3.4. Nitrous Oxide Fluxes

Mean N_2O-N emissions in 2018 increased after manure application (4–7 days following) and during the fall period (September), whereas in 2019 emission increases were primarily after manure application (5–20 days following) (Figure 2). Additional peaks were evident in both years after large precipitation events. Soil moisture fluctuated to a greater extent in 2018 (average = 26.2% range: 12.4 to 40.2%) and was generally lower than 2019 (average = 33.2%; range: 24.5 to 41.8%) and may relate to the lower N_2O emissions, as greater moisture content leads to more water-filled pore space (WFPS), favoring N_2O release. Average WFPS in 2018 was only 52%, much lower than 70% in 2019; the threshold for increased denitrification is between 60 and 65% [27,28]. Overall, N_2O was not significantly correlated with moisture or temperature and could be related to the variability in weather conditions between years and at the time of manure application.

There were few significant differences among treatments within sampling dates, with only one difference in 2018 and four in 2019 (all occurring right after manure application.) Total cumulative N_2O losses represented 4.4%, 3.0%, and 8.8% of TN applications in 2018 and 4.2%, 2.9%, and 3.4% of TN applications in 2019 for broadcast, VT, and CP, respectively. Injection/incorporation of manure generally increases N_2O-N emissions [4,8,55] with reduced tillage tending to increase emissions over conventional tillage [17]. In 2018, cumulative N_2O loss for CP was significantly greater than other treatments (broadcast, VT, and control total emissions were 49%, 34%, and 26% of CP), however it was only significantly greater than the control in 2019 and similar to other manure treatments (broadcast, VT, and control total emissions were 125%, 85%, and 39% of CP). Additionally, broadcast total emissions were significantly greater than the control.

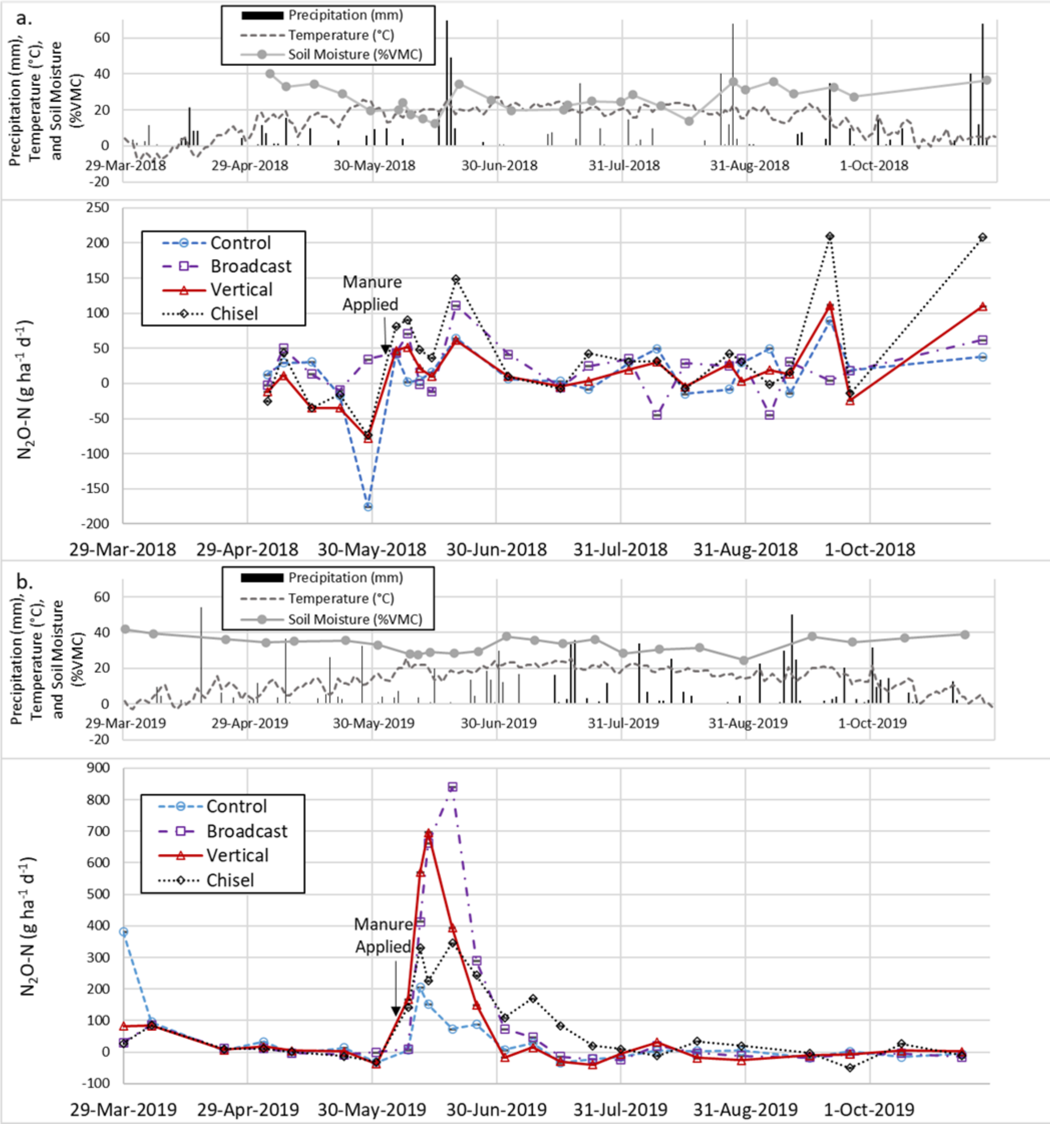

Figure 2. Nitrous oxide fluxes by treatment plotted with precipitation, temperature and average volumetric soil moisture content for the 2018 (**a**) and 2019 (**b**) seasons.

Van Kessel et al. [56] reported that N_2O fluxes for no-till or reduced tillage were only lower than conventional tillage for long-term studies compared to shorter duration experiments across 239 studies, possibly due to compaction restricting gas escape [13]. They reported similar N_2O fluxes for incorporated and surface application, hypothesizing that soil crusting/structural damage limited O_2 diffusion for both practices, confounding potential difference compared to less restrictive soil conditions [57]. It is possible that the higher emissions from untilled broadcast plots in our trial was related to variable legacy compaction in these silt loam soils from heavy manure tanker traffic over time.

Greater crop N uptake in 2018 may have additionally contributed to fewer differences in N_2O fluxes among treatments in 2019, as soil inorganic N was not replenished to 2018 levels with manure additions in 2019 (largely due to high NH_3-N losses (Figure 1) and immediate high N_2O-N release (Figure 2)) and concentrations of both NO_3-N and NH_4-N were quite low at the end of July (Figure 3). Soil NH_4-N concentration was particularly high in 2019 for CP and broadcast (Figure 3), approximately twice 2018 levels after manure application, which may have contributed to the larger N_2O loss for those treatments immediately after application additionally contributing to low inorganic N levels by July. The high application rate may have also contributed to a sealing effect for broadcast, possibly further reducing aeration. Some studies have reported that C near the surface can stimulate N_2O production by increasing microbial activity [4,48,58], which could have also contributed to the relatively high emissions for broadcast application in our study.

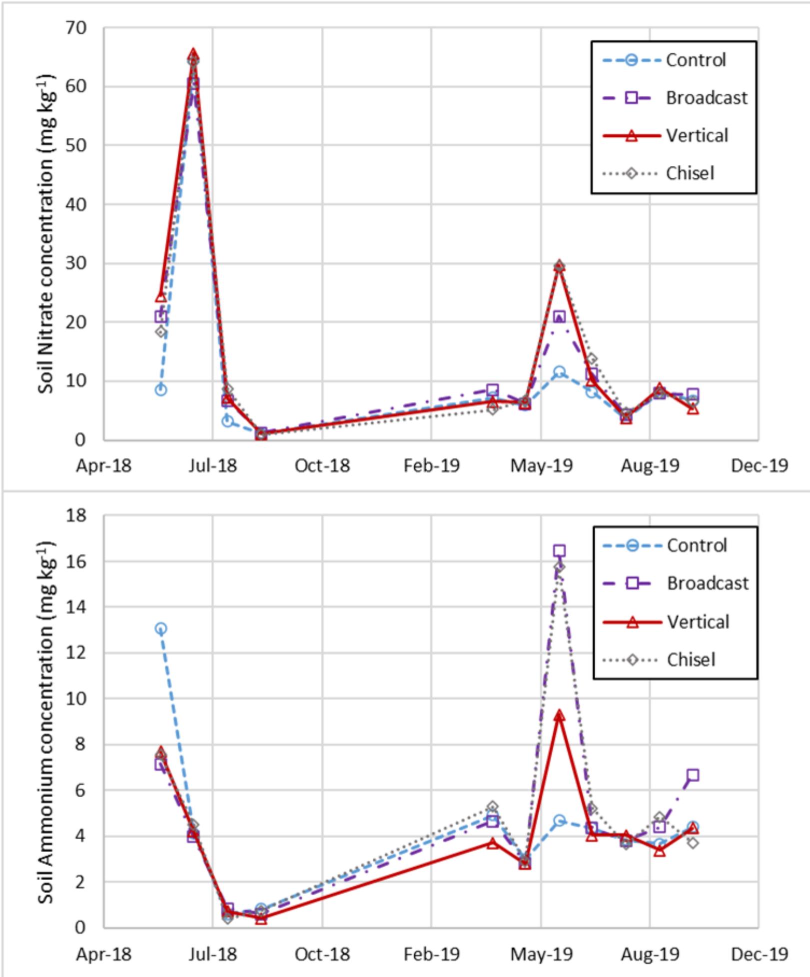

Figure 3. Soil nitrate (NO_3-N, top) and ammonium (NH_4-N, bottom) nitrogen concentrations in control and treatment plots (0–10 cm depth) from April 2018 to October 2019.

3.5. Carbon Fluxes

Methane emissions were variable in 2018 and 2019 (Figure 4), however patterns appeared to be related to changes in soil moisture and temperature and CH_4-C flux was significantly correlated to temperature (r = 0.28; p = 0.0002) on average over the two years. Fluxes were generally low in 2018, with larger emission rates after rain in mid-June and late July. Emissions were much larger in 2019, likely driven by the overall wetter season, particularly the large spike after manure application on June 6. Other research has demonstrated CH_4 flux spikes after liquid manure application [53,59,60]. Numerical differences among treatments were noted in 2018 and 2019 near the time of peak emissions, however treatment effects were variable and inconsistent, contributing to the overall lack of significance. Several other trials have also reported a lack treatment effects for tillage practice and/or amendment sources on CH_4 fluxes [2,61,62]. Greater soil moisture/lower redox status increases CH_4 release potential [2,53,61] as microbes consume oxygen. In our study, there was a weak but significant correlation between soil moisture content and CH_4-C fluxes (r = 0.24, p = 0.02) in 2019 but not in 2018.

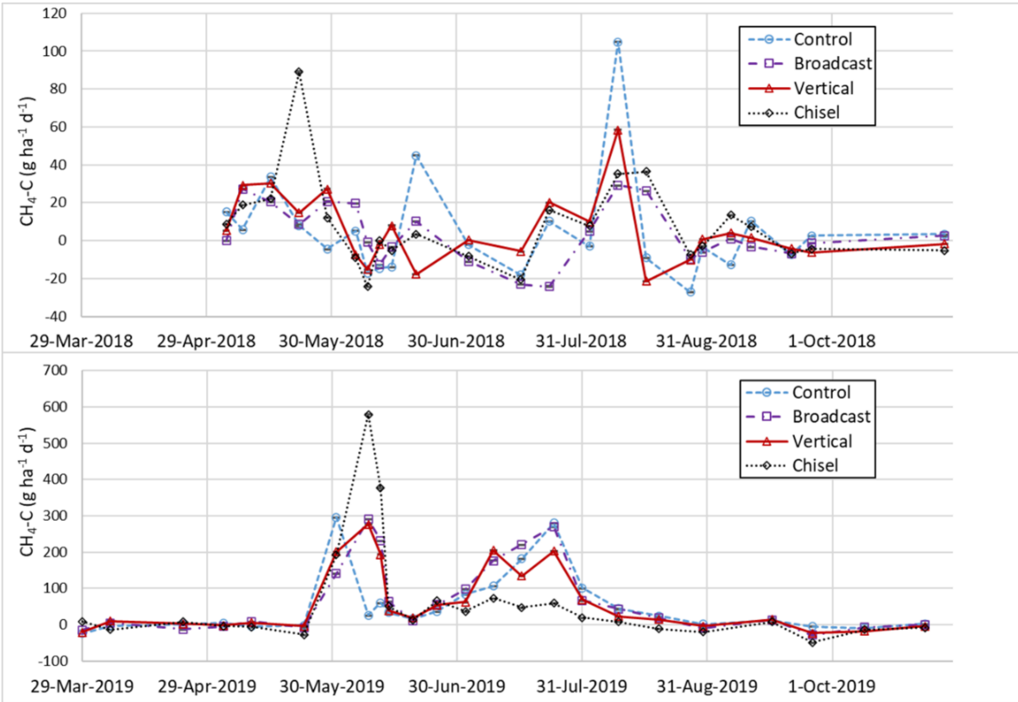

Figure 4. Methane (CH_4-C) fluxes by treatment for 2018 (**top**) and 2019 (**bottom**).

Event based and cumulative CO_2 fluxes were consistently lower for CP, with 18% lower mean cumulative CO_2-C fluxes than VT and 22% lower than broadcast (Figure 5). Not surprisingly, CO_2 fluxes were correlated with soil temperature ($r = 0.53$; $p < 0.0001$) as others have reported [3,63,64]. Soil moisture content was also weakly correlated with CO_2 fluxes ($r = -0.18$; $p = 0.02$) with generally lower CO_2 fluxes when soils were wetter.

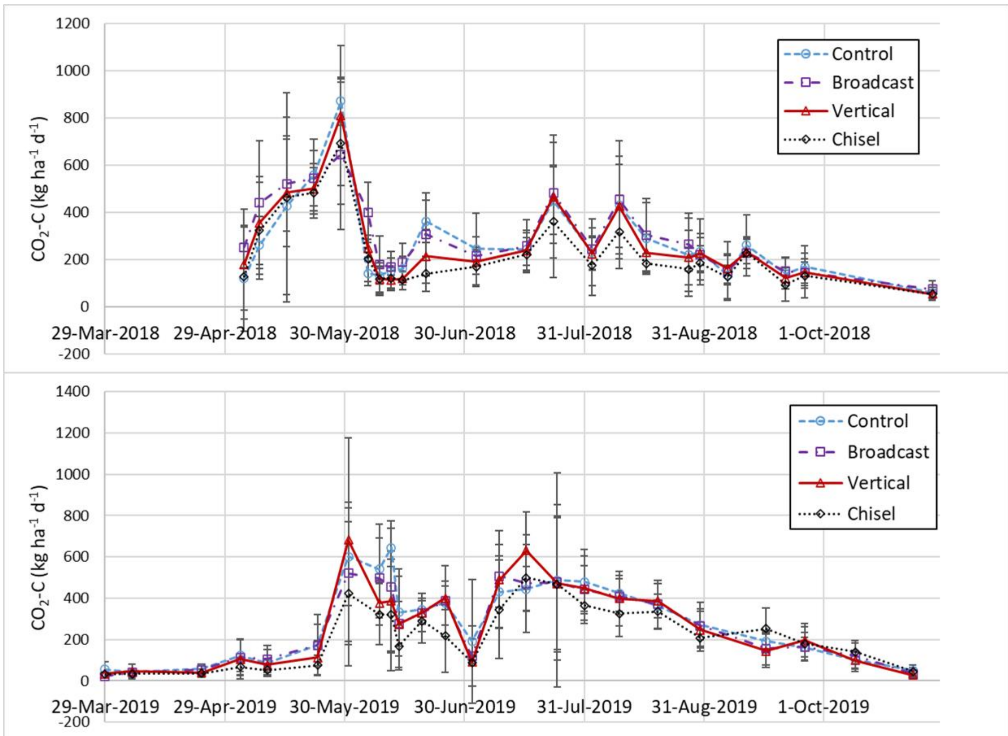

Figure 5. Carbon dioxide (CO_2-C) fluxes by treatment for 2018 (**top**) and 2019 (**bottom**).

Higher C and N as well as larger bacterial biomass near the surface in reduced or no tillage soils has been linked with greater CO_2 fluxes compared to conventional tillage [28]. Some studies have reported higher CO_2-C emissions with manure incorporation, suggesting C substrates are readily decomposed and that mechanical aeration further aids this process [1,13,65]. In contrast, tillage has also been reported to reduce respiration and CO_2 production [17,66] by burying residues in deeper layers, effectively slowing down decomposition/respiration. We hypothesize that CP likely had a similar effect in our study, diluting labile C and reducing respiration. Disruption of soil structure and crusting at the surface in these silt loam soils may have also contributed, since a lack of macroporosity has been linked to lower CO_2 emissions [13,52]. The incorporation of live biomass when planting green may have additionally reduced CO_2-C emissions by being more recalcitrant to rapid decomposition than dead residue [1,13,65].

3.6. Global Warming Potential

Global warming potential (GWP) was calculated by multiplying cumulative emissions for each GHG for the sampling season by its AR5 100-year GWP value (using 265 for N_2O plus 1% of NH_3-N as N_2O and 28 for CH_4 [67]) to calculate CO_2-equivalents. Incorporating manure led to significantly lower overall GWP for CP (16% lower than broadcast; data not shown) in both years, primarily because of lower CO_2 flux. On average, VT had a 4% lower GWP than broadcast and was similar to the control. Because of the large contribution of CO_2 to the GWP, we made estimates for just N_2O and CH_4 equivalents due to their potency as GHG's. On average across the two years, broadcast and CP had significantly greater GWP than the control. Additionally, VT was not statistically different than the control, showing mitigation of N_2O and CH_4 emissions with VT is possible. It should also be noted, however, that in the context of IPCC GHG estimates [67], particularly in the case of N_2O, the amount of N_2O lost as a percentage of total N applied for all treatments in both years was far above the 0.4% emission factor assigned to organic manure amendments, especially under the wet study conditions.

4. Conclusions

Our results suggest that while incorporating manure significantly decreased NH_3-N losses by an average of 54% for VT and 92% for CP, it increased N_2O-N emission potential, particularly for CP. The VT treatment showed potential to decrease N_2O-N emissions over CP, while also decreasing NH_3-N losses and maintaining yields similar to CP under wet post-plant conditions. Incorporating manure into a live cover crop has promise for reducing overall GHG emissions, particularly when considering GWP, and at the same time, conserving N and increasing yield compared to broadcast manure application. Minimal tillage with VT has the added benefit of maintaining low disturbance designed to enhance drainage/aeration, minimize soil structure damage and mitigate nutrient loss risk in general. More research is warranted to better understand the environmental and yield benefits of incorporating manure into a live cover crop and associated impacts on nutrient cycling and GHG dynamics over multiple seasons in different regions.

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