Published February 21, 2019

Soil Biology & Biochemistry

Greenhouse Gas Emissions from an Irrigated Crop Rotation Utilizing Dairy Manure

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Information on greenhouse gas (GHG) emissions from manure application in cropping systems of the irrigated mountain west region is needed. The objectives of this study were to (i) determine the effect of manure application rate and frequency (annual vs. biennial) on GHG losses compared to synthetic fertilizer, (ii) determine the effect of irrigation on GHG losses and (iii) determine the overall global warming potential (GWP) of using manure vs. synthetic fertilizer. Treatments included dry manure rates of 18 or 52 Mg ha^{-1} applied annually or 36 Mg ha^{-1} applied biennially as well as synthetic fertilizer and control treatments. Cumulative losses of N_2O-N over the rotation ranged from 1.4 to 8.4 kg ha^{-1} with the 52 Mg ha^{-1} manure application losing the greatest amount of N_2O-N. Emission factors for the growing season indicated that 0.13 to 0.24% of total N applied was lost as N_2O-N. Cumulative CO_2–C losses were greatest in the manure treatments, with approximately 7% of carbon added lost as CO_2–C. Maximum N_2O-N fluxes occurred at soil moisture contents of 0.3 to 0.4 m^3 m^{-3} and temperature near 25°C, while CO_2–C emissions occurred over broader soil moisture and temperature conditions. The overall GWP associated with manure application indicated a net negative GWP for manure treatments while the synthetic fertilizer treatment was near neutral. Including manure in cropping system rotations can lead to enhanced GHG emission, however the benefits of enhanced SOC can outweigh these losses leading to lower GWP than use of synthetic fertilizer alone.

Abbreviations: DM, dry matter; GHG, greenhouse gas; GWP, global warming potential; IC, inorganic carbon; MAP, monoammonium phosphate; SOC, soil organic carbon; TC, total carbon; TN, total nitrogen.

Core Ideas

- **Manure addition enhanced N_2O losses.**
- **0.13 to 0.24% of total N added was lost as N_2O.**
- **Overall, global warming potential was lower in manure treatments than in fertilizer treatments.**

The application of manure to cropland soils can influence the generation of greenhouse gasses (GHGs), namely carbon dioxide (CO_2) and nitrous oxide (N_2O). The addition of dairy manure to croplands can also have the added benefit of increasing soil organic carbon (SOC). The net losses of GHG emissions vs. SOC accumulation determine the overall global warming potential (GWP) of manure utilization in cropping systems. The 1990–2013 US Agriculture and Greenhouse Gas Inventory estimated that 28% (168 million Mg CO_2eq) of agricultural sources of GHG emissions in 2013 were from N_2O losses from cropland soils, while there was a net gain of 1.4 million Mg CO_2eq due to soil carbon (C) storage (USDA, 2016).

The potential for losses of GHG following manure application to cropland soils is dependent on a combination of manure properties and environmental conditions. Soils can lose C as CO_2 via organic matter decomposition, which can be stimulated with manure additions (Halvorson et al., 2016; Dungan et al., 2017). Research has suggested that temperature and soil moisture are the two main factors controlling CO_2 flux from soils (Yuste et al., 2007; Hynšt et al., 2007; Hao, 2015). The addition of C with manures stimulates microbial activity, which utilizes oxy-

Soil Sci. Soc. Am. J. 83:137–152
doi:10.2136/sssaj2018.06.0216
Received 5 June 2018.
Accepted 15 Oct. 2018.
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gen (O_2), generates CO_2, and subsequently can create anaerobic zones in soils which allow denitrification and N_2O production to occur (Thangarajan et al., 2013). Incomplete conversion of ammonium to nitrate through the microbial driven process of nitrification can also result in the release of N_2O (Dalal et al., 2010; Kool et al., 2011). The ratio of C to N in manures is thought to affect N_2O emissions with lower ratios promoting greater denitrification (Akiyama et al., 2004). Zhou et al. (2017) found that N_2O emissions were stimulated by increasing temperature, acidic soil conditions (pH < 6.5), and soil texture classes of sandy loam and clay loam soils. The amount of C in the soil is also of importance, as it was demonstrated that slurry application resulted in higher N_2O emissions compared with fertilizers in soils where organic C was limiting (Velthof et al., 1997).

The effects of manure additions on emissions of N_2O, compared with synthetic fertilizer additions have been unclear, with some studies reporting increased emissions with manure application (Baggs et al., 2000; Rochette et al., 2004; Zhou et al., 2014) and other studies reporting decreased emissions with manure addition compared with synthetic fertilizer N (Ball et al., 2004; Meijide et al., 2007; Ding et al., 2013) or no effect (Halvorson et al., 2016). Global meta-analysis evaluating the impact of manure applications in agricultural soils have found that, compared to use of synthetic fertilizer alone, manure application increased N_2O emissions by 32.7% (Zhou et al., 2017) or had no effect on emissions (Xia et al., 2017). Soil CO_2 emissions were increased by 26.4% with the addition of manure relative to synthetic fertilizer (Xia et al., 2017). Both studies reported that substituting manure for synthetic fertilizer had the benefit of increasing SOC stocks (33.3% increase), however it should be mentioned that these benefits were often offset by the stimulation of N_2O emissions for upland soils.

There have been few studies evaluating the impact of manure application on GHG emissions from irrigated cropping systems in semiarid regions (Haile-Mariam et al., 2008; Halvorson et al., 2016; Dungan et al., 2017). As GHG emissions from agriculture have garnered more interest and mitigation strategies to reduce these emissions are becoming increasingly important, it is necessary to have a better understanding of these emissions in relation to differences in manure composition, climate and soils. Therefore, the objectives of this research were to (i) determine the effect of manure application rate and application frequency (annual vs. biennial) on GHG losses from an irrigated cropping system over the growing season and compare to losses from use of synthetic fertilizer alone, (ii) evaluate the effect of irrigation on GHG losses, and (iii) evaluate the overall global warming potential (GHG loss vs. SOC increases) of using manure vs. synthetic fertilizer in a cropping rotation.

MATERIALS AND METHODS

Field Site and Treatments

The field site was located at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID, at 42°33′4.5″ N, 114°21′14.7″ W. The climate is semiarid with an average annual precipitation of 284 mm and a mean annual temperature of 8.7°C. The predominant soil type is a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) with the following average properties in the A_p horizon (0–15 cm depth), which were determined 1 wk prior to the first fall manure application in 2012: clay, 125 g kg^{-1}; silt, 692 g kg^{-1}; sand, 183 g kg^{-1}; pH, 8.0; electrical conductivity, 0.99 dS m^{-1}; NO_3–N, 24 mg kg^{-1}; NH_4–N, 5.0 mg kg^{-1}; organic C, 8.2 g kg^{-1} and bulk density, 1.4 g cm^{-3}. Prior to the start of the study (fall 2012) this field had a cropping history of malt barley (2008 and 2009), pinto beans (2010), corn silage (2011), and pinto beans (2012) with no history of manure application.

This study was initiated in the fall of 2012 and consisted of a 4-yr rotation: spring wheat (*Triticum aestivum* L.) (2013)–potato (*Solanum tuberosum* L.) (2014)–spring barley (*Hordeum vulgare* L.) (2015)–sugar beet (*Beta vulgaris* L.) (2016). The experimental design was a randomized complete block with four replications and individual plot sizes of 18.3 m by 12.2 m. The treatments included (i) no synthetic fertilizer or manure (control), (ii) synthetic fertilizer (hereafter “Fert”), (iii) dairy manure applied annually at a rate of 18 Mg ha^{-1} (“18A”), (iv) dairy manure applied biennially at a rate of 36 Mg ha^{-1} (“36B”) and (v) dairy manure applied annually at a rate of 52 Mg ha^{-1} (“52A”). Manure applications were made on a dry weight basis. Synthetic fertilizer applications (N, P, K, and S) were determined each spring for wheat, barley and sugar beet based on pre-plant soil sampling nutrient concentrations following the University of Idaho Fertilizer Guidelines for each crop. For potato, synthetic fertilizer applications were determined based on pre-plant soil sampling nutrient concentrations following recommendations from the University of Idaho Fertilizer Guidelines as well as in season petiole sampling. The goal was to meet all necessary nutrient requirements to maximize yield as would be done by a commercial grower which resulted in application of synthetic fertilizer to some of the manure plots in some years.

The manure treatments were applied at rates that would be considered low (18 Mg ha^{-1}) and standard (52 Mg ha^{-1}) for the region. The biennial manure treatment was included to determine the effects of taking a year off from manure application while matching the cumulative 18A manure application rate over the course of the rotation. Applying manure once every two, three, or four years is a common practice before root crops such as potato and sugar beet. Manure was applied each fall (October or November) by weighing the appropriate amount of manure per plot (based on manure moisture) and spreading with a manure spreader. Manure was immediately incorporated through disking to a 15-cm depth to minimize ammonia and P runoff losses over the winter; the Fert and control plots were disked at this time as well for consistency purposes. The quantity of N and C applied as manure and synthetic fertilizer over the 4-yr rotation is summarized in Table 1. Irrigation application rates each year were determined based on crop evapotranspiration potential using the Washington State University Irrigation Scheduler, irrigation date, set time and total amount of water applied over each irrigation season is listed in Supplemental Table S1. Details regarding pesticide applications are listed in Supplemental Table S2.

In 2013, a hard red spring wheat ('Jefferson') was planted (2 April) at a seeding rate of 118 kg ha^{-1} (3,248,762 seeds ha^{-1}). Preplant synthetic fertilizer applications consisted of 43.5 kg ha^{-1} of urea-N on all plots except the controls (12 March) and 40 kg P ha^{-1} and 19 kg N ha^{-1} applied as monoammonium phosphate (MAP [11–52–0]; 26 March) to the Fert plots. Following fertilizer application, the field was roller harrowed prior to planting. The field was irrigated from 13 May to 15 July with 2.5 to 5.0 cm of water applied at each irrigation event (see Supplemental Table S1 for detailed information). On 13 August, plots were harvested for yield (26 m^2) with an Almaco plot harvester (1.5-m header) followed by bulk harvesting of the field. On 22 August, the straw was swathed and baled and removed from the field.

In 2014, potato ('Russet Burbank') was planted 29 April. The field was moldboard plowed the previous fall following manure application and roller harrowed on 18 April. Seeds were planted at a rate of 2153 kg ha^{-1} (average seed piece size was 56.6 g). Preplant synthetic fertilizer applications (16 and 17 April) consisted of 112 kg ha^{-1} of urea-N (18A, 36B), 84 kg ha^{-1} of urea-N (52A, Fert), 4.7 kg ha^{-1} of MAP-N (18A), 42 kg ha^{-1} of MAP-N (Fert), 9.8 kg ha^{-1} of MAP-P (18A), 87 kg ha^{-1} of MAP-P (Fert), 198 kg ha^{-1} KCl-K (Fert), and 13 kg ha^{-1} of S as gypsum on all the plots, excluding the control treatment. Fertilizer was incorporated on the same day with a roller harrow. The field was irrigated from 21 May to 19 September with 0.43 to 4.3 cm of water applied (see Supplemental Table S1 for detailed information). In season synthetic fertilizer applications consisted of 90 (52A), 112 (18A), and 135 (36B, Fert) kg ha^{-1} of polymer coated urea on 20 May which was incorporated immediately with a rolling cultivator (Lilliston by Bigham, Lubbock, TX). A final application of granular urea N at a rate of 45 kg ha^{-1} was applied to all treatments excluding the control treatment (24 July) with a hand spreader. Tuber yield was determined on 25 September for each plot using a single row potato digger (Grimme, Lincolnshire, UK) with 33.5 m of row within each plot. The field was bulk harvested on 8 October by a commercial operator.

In 2015, spring malt barley ('Moravian 69', MillerCoors) was planted 31 March at a seeding rate of 123 kg ha^{-1}. Preplant synthetic fertilizer was applied (31 March) to the Fert treatments at rates of 9 kg ha^{-1} of urea-N, 9.5 kg ha^{-1} of MAP-N, and 20 kg ha^{-1} of MAP-P; preplant synthetic fertilizer was not applied to any manure treatments. Fertilizer was incorporated on the same day with a roller harrow. In season application of 45 kg ha^{-1} of urea-N occurred on 22 May on the Fert plots only via hand spreader and incorporation with irrigation. The field was irrigated from 5 May to 11 July with 2.5 to 5 cm of water applied at each irrigation event (see Supplemental Table S1 for detailed information). Plot harvest for yield (26 m^2) was done on 29 July using an Almaco plot harvester (1.5 m head). Field was bulk harvested on 4 August and straw was swathed and baled on 18 August.

Table 1. Average amount of manure N and C and synthetic fertilizer N added, by treatment, and total nutrients added over the 4-yr period. Treatments included: no synthetic fertilizer or manure (control), synthetic fertilizer ("Fertilizer"), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), and dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"). All rates on a dry weight basis.

Year	Control	Fertilizer	18A	36B	52A
	kg ha^{-1}				
			Manure N		
2012	–	–	300	568	875
2013	–	–	426	–	1,315
2014	–	–	242	456	668
2015	–	–	293	–	883
			Manure C		
2012	–	–	13,076	24,812	37,150
2013	–	–	16,400	–	48,056
2014	–	–	8,585	16,089	23,810
2015	–	–	9,396	–	28,390
			Synthetic fertilizer N		
2013	–	63	43	43	43
2014	–	305	274	291	219
2015	–	63	–	–	–
2016	–	142	31	40	–
	Cumulative nutrients added over study period (2012–2016)				
Total N	–	573	1,609	1,398	4,003
Total C	–	–	47,457	40,901	137,406

In 2016, sugar beets ('BTS-21RR25') were planted on 9 May at a rate of 128,097 seed ha^{-1}. Field was moldboard plowed the previous fall and roller harrowed prior to planting. Preplant synthetic fertilizer applications (20 April) consisted of 31 (18A), 40 (36B), and 124 (Fert) kg ha^{-1} urea-N; 19 kg ha^{-1} MAP-N and 40 kg ha^{-1} MAP-P on the Fert plots only; 414 kg ha^{-1} sulfur as gypsum on all but the control plots. Fertilizer was incorporated on the same day with a roller harrow. The field was irrigated from 11 May to 18 September with 2.5 to 5 cm of water (see Supplemental Table S1 for detailed information). Plots were mechanically harvested for yield (21 m of row) with a two-row beet harvester on 11 October. Bulk harvest of the field was done on 9 Nov. 2016.

Soil and Manure Collection and Analysis

Pre-plant soil samples were collected in late March of 2013, 2014, 2015, and 2016, with ten subsamples collected and composited by plot for the 0- to 30-cm depth, and five subsamples collected and composited for the 30- to 61-cm depth. Soils were collected with a 5.7-cm bucket soil auger (Signature Mud Auger part no. 350.20, AMS Inc. American Falls, ID). Soils were thoroughly mixed and subsampled for analysis. Subsamples were stored in a cooler overnight and then shipped to the University of Idaho Analytical Sciences Laboratory (Moscow, ID) the following day for analysis of organic matter (Sims and Haby, 1971), total N (TN; combustion of 0.15 g; Leco CN 628, Leco Corporation, St. Joseph, MI) and nitrate N (NO_3–N; 2 N KCl extraction with analysis via flow injection with OI Flow Solution

3000 FIA, Xylem Inc., Rye Brook, NY). Post-harvest soil samples were collected in September (prior to manure applications) at depths of 0 to 15, 15 to 30, 30 to 61, and 61 to 91 cm with an AMS 9110-AG probe (AMS Inc. American Falls, ID). After collection, the bulk soil samples were air dried, sieved through a 7-mm screen, and analyzed for total C (TC) by combustion of a 50-mg sample in a FlashEA1112 (CE Elantech, Lakewood, NJ) and inorganic C (IC) by the method of Sherrod et al. (2002). Soil organic C was determined by subtracting the IC from TC.

Manure samples were collected from each plot by placing three trays (0.5 m by 0.6 m) within the plots during manure application. Following application, samples from trays were composited and a subsample was taken from each plot. Three composite samples were made from subsamples of each of the individual plots. Samples were stored in a refrigerator until shipping to Soiltest Laboratory (Moses Lake, WA) for analysis. Manure water content was determined gravimetrically on a 100-g subsample by drying at 105°C for 8 h; total C and N content were determined via combustion of moist manure samples with the CHN 628 analyzer (LECO, St. Joseph, MN). The initial inorganic N concentration of the manure was measured (ratio of 5 g manure to 25 mL extractant) with 2 mol L^{-1} KCl extraction (Gavlek et al., 2005). The supernatant was analyzed via an automated flow injection analyzer for NO_3–N concentration via cadmium reduction (Lachat Method 12-107-04-1-B) and NH_4–N concentration via the salicylate-hypochlorite method (Lachat Method 12-107-06-2-A; Lachat Instruments, Loveland, CO). Manure pH and EC were measured in a 1:5 (manure to distilled water) slurry. Total P was determined via digestion of 0.5 g manure with nitric/perchloric acid and measurement of P via inductively coupled plasma optical emission spectrometry (PerkinElmer Optima 7300 DV, PerkinElmer, Waltham, MA). Manure properties measured over the study period are listed in Table 2.

Gas Flux Measurements

Nitrous oxide and CO_2 flux measurements were conducted using a vented, non-steady state, closed chamber technique. The gas chambers were built according to USDA-ARS GRACEnet sampling protocols (Parkin and Venterea, 2010). In brief, a rectangular chamber (78.5 cm by 40.5 cm by 10 cm) was manufactured from an aluminum sheet of 3.2-mm thickness and fitted with a sampling port and vent on the top. To insulate the chamber, a layer of corkboard was applied to the surface, which was then coated with a layer of Mylar tape. In the field, each chamber was placed onto an aluminum anchor that was set 10 cm into the soil and sealed using a water channel. Duplicate anchors were placed about 1 m apart in each plot and were set parallel to the crop row to cover the row and inter-row space (17.8 cm for wheat, 91 cm for potato, 17.8 cm for barley, and 55.9 cm for sugar beet row spacing). The anchors were temporarily removed during soil tillage, fertilizer and/or manure application, and harvest but otherwise remained in the plots at all times. Plant material within the anchor area was cut so that it did not extend above the water channel.

An air sample from within the chamber was collected at 0, 15, and 30 min using a 30-mL polypropylene syringe with a stopcock. Afterward, the syringes were stored in a cooler (without ice) until transported to the laboratory. Twenty-five-mL air samples were then injected into evacuated 12-mL Exetainer vials with gray butyl rubber septa (Labco Limited, Lampeter, UK), which were then analyzed via gas chromatography. The gas chromatograph (model 7890A, Agilent Technologies, Santa Clara, CA) was equipped with a GC 120 autosampler and electron capture and thermal conductivity detectors to quantify N_2O and CO_2, respectively. Gas fluxes were determined from a linear or nonlinear increase in the concentration within the chamber headspace over time (Hutchinson and Mosier, 1981). Estimates of daily gas emissions between sampling days over the growing season (April through October) were generated using the adjacent sampling dates and the FORECAST function in Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA). Gas samples were collected during the following periods each year: 2013, 14 March to 26 November (DOY 73–330); 2014, 3 March to 17 December (DOY 62–351); 2015, 2 February to 8 December (DOY 33–342); and 2016, 22 January to 12 October (DOY 22–285). Gas samples were collected either two or three times per week during the spring, summer, and fall, and on an irregular basis during the winter when temperatures were above freezing.

Net Global Warming Potential Estimates

The N_2O emissions and SOC change data were used to derive net GWP of the different treatments (Ghimire et al., 2017). Soil inorganic C (SIC) was not included as there was no significant effect of treatment on SIC. The GWP of N_2O was calculated using the CO_2eq of 264.5 (IPCC, 2014). The CO_2eq of SOC change was calculated by using the annual rate of SOC accrual or loss from the soil compared with the control over the 4-yr rotation and converting the number into CO_2eq (Robertson et al., 2000). Net GWP (Mg CO_2eq ha^{-1}) for each treatment was calculated using the following equation:

Table 2. Physical and chemical properties of the dairy manure sources, by year. Concentrations are reported on a dry weight basis.

Year	Dry matter	pH	Electrical conductivity	Total N	Total C	Ammonium N	Nitrate N	C to N	Total P
	g kg^{-1}		mmhos cm^{-1}	g kg^{-1}		mg kg^{-1}			g kg^{-1}
2012	586 ± 155	9.0 ± 0.2	19.4 ± 1.8	17.8 ± 2.1	303 ± 34	2238 ± 1573	14.9 ± 3.7	17	6.2 ± 1.3
2013	357 ± 61	8.9 ± 0.1	23.0 ± 2.7	28.7 ± 5.0	371 ± 31	2836 ± 1365	14.7 ± 2.2	13	8.1 ± 0.9
2014	620 ± 113	8.7 ± 0.1	14.3 ± 2.5	14.7 ± 2.1	220 ± 32	3621 ± 905	9.6 ± 0.5	15	5.6 ± 0.7
2015	515 ± 7	8.7 ± 0.1	12.6 ± 0.7	15.9 ± 0.1	233 ± 17	3079 ± 590	6.8 ± 5.4	15	5.6 ± 0.1

$$\text{Net GWP} = \text{GWP}_{N2O} + \text{GWP}_{SOC}$$

As irrigation and farm management were the same for all plots, the CO_2eq for these were not included. Any germinating plants inside the chamber bases were clipped and removed before each sampling. Therefore, the Net GWP calculation did not include plant CO_2 exchange.

Statistical Analysis

Estimated cumulative N_2O and CO_2 emissions, average fluxes, cumulative N and C losses as a percentage of total N and C added, crop yield, and emissions intensities were statistically analyzed using one-way analysis of variance using the General Linear Model procedure of SAS (SAS Institute Inc., Cary, NC). All experimental error variances were tested for homogeneity using Bartlett's test, and values were transformed (either log or square root) when needed to achieve normality. Mean comparisons were performed using the Ryan–Einot–Gabriel–Welsch multiple range test at $\alpha = 0.05$. Pearson correlations were performed to determine relationships between variables. Statements of statistical significance were based on p-value < 0.05.

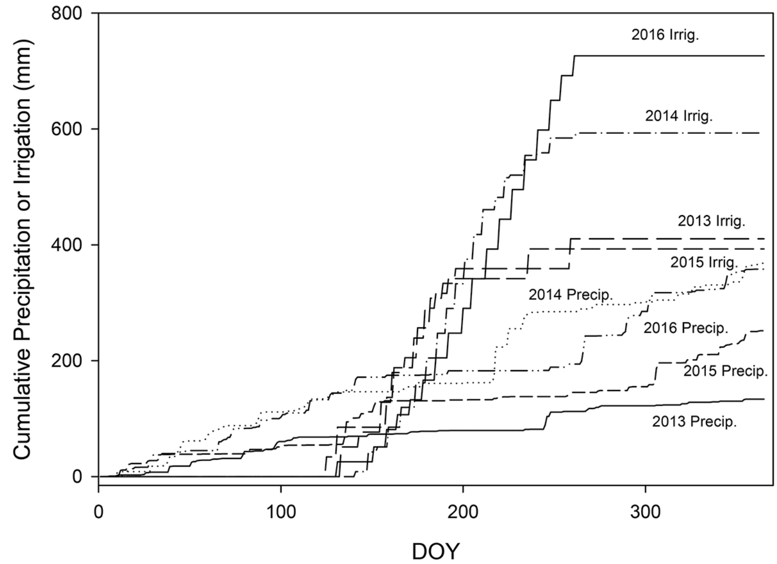

Fig. 1. Cumulative precipitation and irrigation amounts during the monitoring periods over the study period. DOY, day of year.

RESULTS

Environmental Conditions, Soil Nutrient Status and Crop Yields

In 2013, 2014, 2015, and 2016, the total precipitation accumulations were 134, 368, 252, and 358 mm, respectively, with total irrigation additions of 410, 593, 393, and 726 mm, respectively (Fig. 1). Average daily air temperature over the monitoring periods for each of the 4 yr ranged from 0.5 to 31°C. The soil volumetric water content at 0- to 15-cm depth was similar for all treatments and fluctuated between 0.04 and 0.40 m^3 m^{-3} and was driven by irrigation events during the growing season.

Pre-plant soil nutrients for each year of the rotation at the 0- to 30-cm depth are listed in Table 3. Soil organic matter content was significantly greater in the 52A manure treatments (17.8 to 35.0 g kg^{-1}) compared with the control (13.3 to 14.9 g kg^{-1}) and Fert (13.5 to 15.3 g kg^{-1}) treatments for all 4 yr of the study. In 2014, there were no significant differences in SOM content between the control, Fert, 18A, or 36B treatments, while in 2015 and 2016, both the 18A and 36B manure treatments were lower than the high manure rate but greater than the control and Fert treatments. Total N also accumulated with increasing manure application rates. In both 2015 and 2016 the 52A manure plots had greater total N than the other treatments (1750 and 2337 mg kg^{-1}, respectively), while in previous years total N was similar between treatments. Soil NO_3–N concentrations did not differ by treatment in 2013, but in 2014 to 2016 they were higher in the 52A manure treatment (range of 31.8 to 75.4 mg kg^{-1}) than in the other treatments.

Crop yields were not significantly different among treatments in 2013 (wheat) and 2014 (potato) with an average of 6786 and 9322 kg DM ha^{-1}, respectively (Table 4). The lack of response to treatment in 2013 and 2014 is likely due to the high fertility status of the field as it recently came out of commercial production, coupled with high natural N mineralization

Table 3. Pre-plant soil test organic matter, total nitrogen, and nitrate nitrogen (0–30 cm depth).

Treatment†	2013	2014	2015	2016
	Organic matter			
	g kg^{-1}			
Control	14.0 b‡	14.3 b	13.3 c	14.9 c
Fertilizer	13.5 b	14.0 b	13.5 c	15.3 c
18A	15.8 ab	16.3 b	19.8 b	19.9 b
36B	17.0 a	16.5 b	18.8 b	20.2 b
52A	17.8 a	19.8 a	27.5 a	35.0 a
	Total N			
	mg kg^{-1}			
Control	836 ab	990 ab	961 bc	1043 c
Fertilizer	764 b	907 b	891 c	1040 c
18A	906 ab	1050 ab	1260 b	1332 bc
36B	927 a	932 b	1278 b	1443 b
52A	980 a	1225 a	1750 a	2337 a
	NO_3–N			
	mg kg^{-1}			
Control	22.8 a	8.9 bc	16.3 c	12.1 c
Fertilizer	24.8 a	7.9 c	19.0 c	12.6 c
18A	27.8 a	15.6 b	26.0 bc	27.0 b
36B	31.8 a	14.0 b	35.8 b	23.3 bc
52A	33.0 a	31.8 a	53.5 a	75.4 a

† Treatments: Control, no synthetic fertilizer or manure; Fertilizer, synthetic fertilizer; 18A, dairy manure applied annually at a rate of 18 Mg ha^{-1}; 36B, dairy manure applied biennially at a rate of 36 Mg ha^{-1}; 52A, dairy manure applied annually at a rate of 52 Mg ha^{-1}. All rates on a dry weight basis.

‡ Mean values within a column followed by the same lowercase letter are not significantly different at the 0.05 probability level.

in the soils of this region (Stanford et al., 1977; Westermann and Crothers, 1980). In 2015 (barley), the Fert (7566 kg DM ha^{-1}), 18A (7683 kg DM ha^{-1}) and 36B (7069 kg DM ha^{-1}) manure treatments had significantly higher yields than the control (5305 kg DM ha^{-1}) but did not differ from the 52A manure treatment (6559 kg DM ha^{-1}). In 2016 (sugar beet), the 52A manure (19,741 kg DM ha^{-1}) and Fert (19,345 kg DM ha^{-1}) treatments were significantly greater than the control (15,766) with no differences between remaining treatments (average of 18,132 kg DM ha^{-1}).

Nitrous Oxide Fluxes

Nitrous oxide fluxes in the spring of 2013 (14 March to 8 May), prior to the first irrigation event, were low (<12 g N_2O-N ha^{-1} d^{-1}; Fig. 2). The first irrigation event occurred on 13 May 2013, following which there was a large spike in N_2O-N emissions on 14 May 2013, with flux values increasing between 8 and 23 times compared with pre-irrigation levels for all treatments (Fig. 2). The trend in flux values on 14 May 2013 was as follows: 52A > 36B > 18A > Fert > control. Two days after irrigation, fluxes decreased between 33 and 58% compared with peak fluxes for all treatments. By day three following irrigation, fluxes had decreased by 66 to 93% compared with peak flux post irrigation for all treatments. There were small spikes in fluxes following later irrigation events, but these fluxes accounted for less than 58% (excluding control plots) of the fluxes occurring after the first irrigation event. A large proportion of total season emis-

Table 4. Crop yield data from the monitoring periods, on a dry weight basis.

Treatment†	Wheat grain (2013)	Potato tuber (2014)	Barley grain (2015)	Sugar beet root (2016)
	kg ha^{-1}			
Control	6,230 a‡	8,800 a	5,305 b	15,766 b
Fertilizer	6,172 a	10,402 a	7,566 a	19,345 a
18A	7,505 a	9,762 a	7,683 a	17,592 ab
36B	6,595 a	9,691 a	7,069 a	18,672 ab
52A	7,429 a	7,955 a	6,559 ab	19,741 a

† Treatments: Control, no synthetic fertilizer or manure; Fertilizer, synthetic fertilizer; 18A, dairy manure applied annually at a rate of 18 Mg ha^{-1}; 36B, dairy manure applied biennially at a rate of 36 Mg ha^{-1}; 52A, dairy manure applied annually at a rate of 52 Mg ha^{-1}. All rates on a dry weight basis.

‡ Mean values within a column followed by the same lowercase letter are not significantly different at the 0.05 probability level.

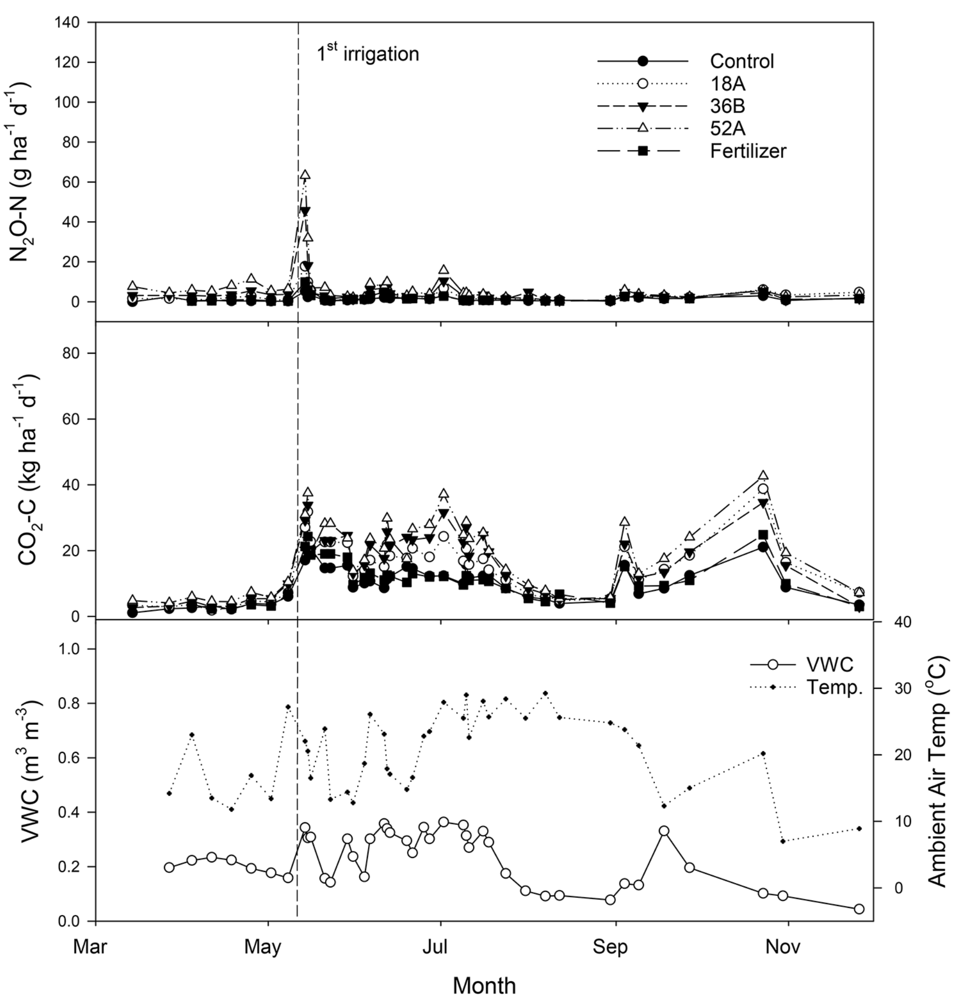

Fig. 2. Average daily N_2O-N and CO_2–C fluxes from the experimental plots, soil volumetric water content (VWC), and ambient air temperature during the 2013 monitoring period under wheat. Treatments: no synthetic fertilizer or manure (control), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"), and synthetic fertilizer ("Fertilizer"). All rates on a dry weight basis.

Table 5. Average daily fluxes of N_2O-N and CO_2–C from experimental plots over the growing season (April to October) by year.

Treatment†	N_2O-N				CO_2–C			
	2013	2014	2015	2016	2013	2014	2015	2016
	g ha^{-1} d^{-1}				kg ha^{-1} d^{-1}			
Control	1.43 e‡	1.71 d	3.77 c	1.51 c	10.61 c	12.80 d	18.48 c	10.20 d
Fertilizer	1.90 d	6.73 c	7.06 b	2.79 b	11.14 c	14.25 d	19.86 c	11.55 cd
18A‡	2.95 c	8.72 b	6.74 b	3.24 b	15.56 b	19.93 b	22.32 bc	12.82 bc
36B	4.87 b	7.54 b	7.15 b	2.91 b	17.65 b	17.57 c	24.70 b	13.12 b
52A	7.04 a	19.29 a	10.48 a	13.27 a	19.83 a	29.94 a	31.98 a	19.65 a

† Treatments: Control, no synthetic fertilizer or manure; Fertilizer, synthetic fertilizer; 18A, dairy manure applied annually at a rate of 18 Mg ha^{-1}; 36B, dairy manure applied biennially at a rate of 36 Mg ha^{-1}; 52A, dairy manure applied annually at a rate of 52 Mg ha^{-1}. All rates on a dry weight basis.
‡ Mean values within a column followed by the same lowercase letter are not significantly different at the 0.05 probability level.

sions occurred shortly after the first spike in emissions with 31, 45, and 53% of total cumulative season emissions occurring 68 d into the growing season for the 52A, 36B and 18A treatments, respectively, while only 20% of total emissions occurred during this period for the control and Fert treatments. Average daily fluxes in the 2013 growing season ranged from 1.4 to 7.0 g ha^{-1} d^{-1} and were significantly different for all treatments following the order: 52A > 36B > 18A > Fert > control (Table 5).

The 2014 early season N_2O fluxes varied (3 March to 20 May, pre-irrigation) with the largest variability seen in the 52A treatment (4.9 to 29.9 g N_2O-N ha^{-1} d^{-1}; Fig. 3) while the remaining treatments were less than 11.5 g N_2O-N ha^{-1} d^{-1}. An increase in mean air temperature on 2 May 2014 from 13 to 27°C resulted in a corresponding spike in N_2O emissions (40 to 520%) in comparison to the previous sampling event on 14 Apr. 2014 for all treatments excluding the control. The day following the first intensive irrigation event (29 May), emissions spiked again by 370

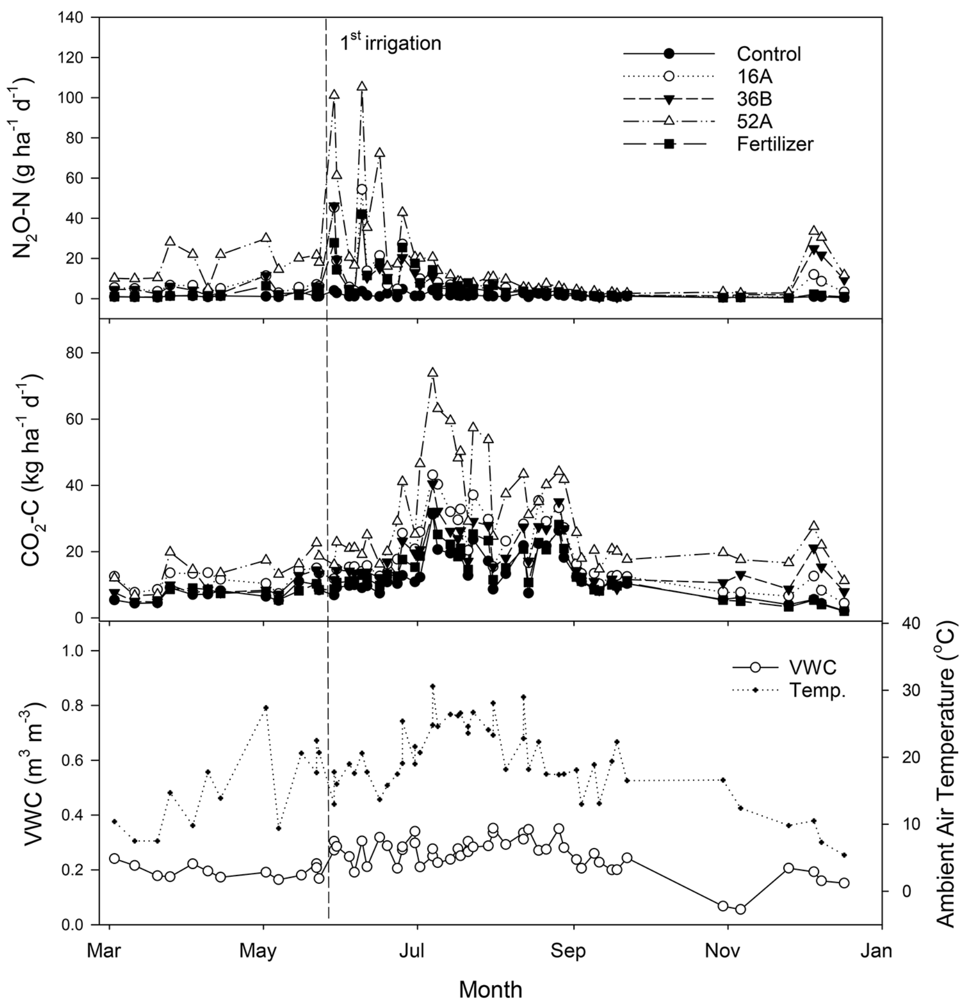

Fig. 3. Average daily N_2O-N and CO_2–C fluxes from the experimental plots, soil volumetric water content (VWC), and ambient air temperature during the 2014 monitoring period under potato. Treatments: no synthetic fertilizer or manure (control), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"), and synthetic fertilizer ("Fertilizer"). All rates on a dry weight basis.

to 472% compared with pre-irrigation emissions. As was seen in 2013, the flux rates decreased daily following irrigation reaching pre-irrigation levels within 6 d. There were additional spikes in flux rates following the next three irrigation events with the intensity of the spikes decreasing with subsequent irrigation events. Approximately 71 to 86% of growing season emissions occurred within the first 128 d of the growing season for all but the control treatments. There was also a spike in emissions in early December, which did not appear to be related to temperature or precipitation. Average daily fluxes of N_2O-N over the 2014 growing season ranged from 1.7 to 19.3 g ha^{-1} d^{-1} and followed the order: 52A > 36B = 18A > Fert > control (Table 5). It is important to keep in mind that the manure applications that occurred in 2012 applied two times the amount of manure for the 36B treatment, compared with the 18A treatment, but then did not receive manure in the fall of 2013.

The 2015 early season emissions varied for all treatments pre-irrigation, with the 52A treatment generally having greater N_2O emissions than the other treatments (Fig. 4). The first irrigation event occurred on 5 May, but unlike other years, there was little response in N_2O flux with irrigation. The average air temperature for 2 d following the first irrigation was 10°C, which was 10°C cooler than the days following the first irrigation in other years (~20°C), which may have dampened the effect of irrigation on N_2O emission flux. There was a larger response in flux to the second irrigation event on 11 May; however, the largest response in flux was not until the fifth irrigation event on 22 June, where emissions increased to their highest level for all but the Fert treatment. There was also a large spike in emissions on 26 August, which was 2 d after the final irrigation for the season. The largest spike in flux from the Fert plots occurred on 26 May, which was 4 d after an in-season fertilizer application of 45 kg N ha^{-1} of urea. By the 89th day of the growing season, 77 to 87% of growing season N_2O-N losses had occurred in all of the manure and Fert treatments, while the control had lost 67%. In the 52A treatment, there were also spikes in N_2O fluxes that occurred after harvest (30 October to 8 December), which could have been related to precipitation events that occurred during these times along with a relative increase in temperature. However, it is interesting to note that these emission spikes only occurred in the 52A treatment. There were few significant differences in average daily fluxes over the 2015 growing season which

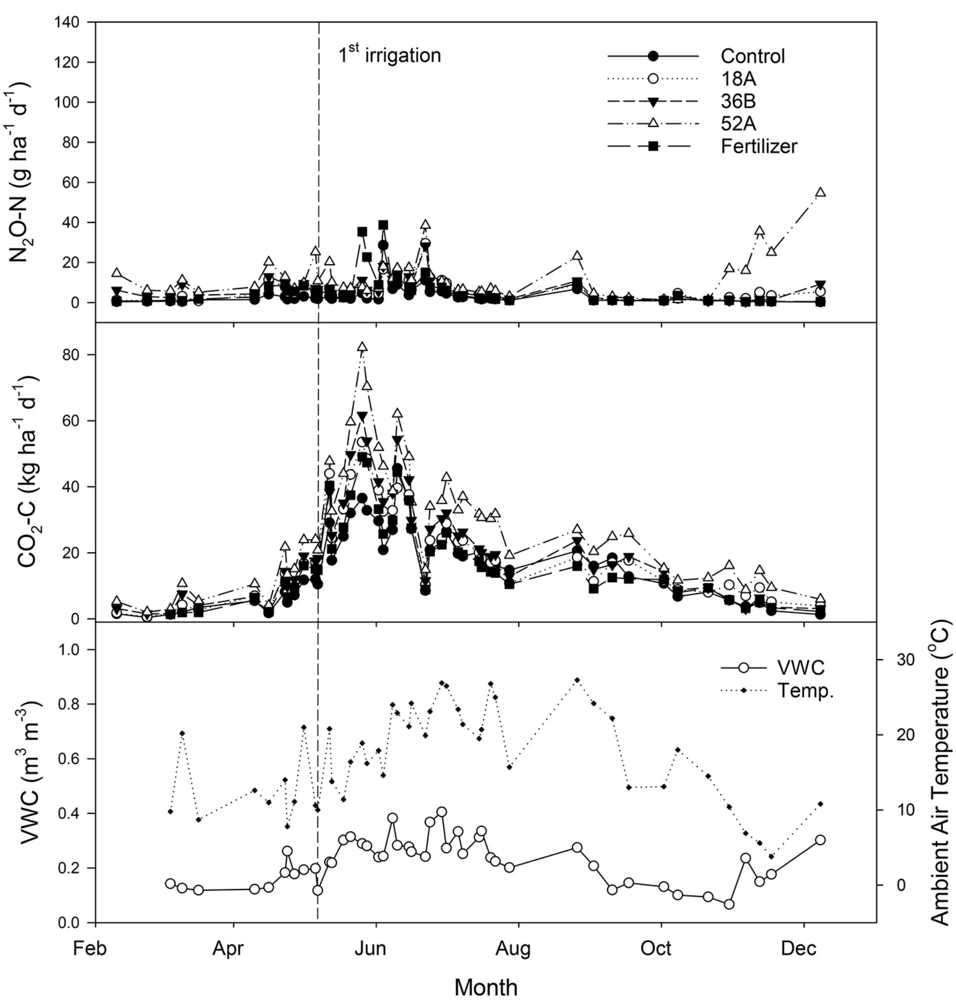

Fig. 4. Average daily N_2O-N and CO_2–C fluxes from the experimental plots, soil volumetric water content (VWC), and ambient air temperature during the 2015 monitoring period under barley. Treatments: no synthetic fertilizer or manure (control), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"), and synthetic fertilizer ("Fertilizer"). All rates on a dry weight basis.

ranged from 3.8 to 10.5 g ha^{-1} d^{-1} and followed the trend 52A > 36B = 18A = Fert > control (Table 5).

In 2016, there was a large spike in emissions prior to the growing season (before 1 April) particularly for the 52A treatment (Fig. 5). Large spikes in N_2O fluxes also occurred with the first three irrigation events (11 May, 31 May, and 7 June), comprising 44 to 69% of total growing season cumulative fluxes for all but the control treatment (38%) by the 28th day of the growing season. There was little variation in N_2O emissions following the end of July and emissions generally had a downward trend to the end of the growing season. The average daily N_2O-N fluxes ranged from 1.5 to 13.3 g ha^{-1} d^{-1} and differed by treatment as follows: 52A > 36B = 18A = Fert > control (Table 5).

Carbon Dioxide Fluxes

In two (2013 and 2015) out of the four study years, there was a response in CO_2–C fluxes to the first irrigation event (Fig. 2 and 4). In 2013, 1 d after the first irrigation, CO_2–C fluxes increased between 2.9- to 3.5-fold the previous sampling day flux rate. Two days following irrigation, fluxes peaked and then declined again but did not decrease to pre-irrigation flux levels until 12 August. Fluxes tended to increase 1 or 2 d following further irrigation events through the irrigation season (13 May to 15 July) and then decreased. In 2015, the first significant increase in CO_2–C flux followed the second irrigation. It should be noted that the first irrigation event occurred while temperatures were still low (10°C), which is likely the reason why there was not a large increase in CO_2 flux at that time. The remaining daily flux values in 2015 did not seem to trend with irrigation events as seen in 2013 and fluxes did not go back down to pre-irrigation levels until the end of the monitoring period (December) of that year. In 2014, the first irrigation event occurred on 21 May, however the first significant flux in CO_2–C emissions did not occur until 25 June, 2 d following an irrigation event. Some of the subsequent fluxes were within 2 d of irrigation events however not all of them were. In 2016, the first significant increase in CO_2–C fluxes occurred 2 d following the second irrigation event (31 May). Some of the subsequent fluxes coincided within 2 d of irrigation events but not all.

Average daily fluxes of CO_2–C in 2013 ranged from 10.6 to 19.8 kg ha^{-1} d^{-1} and were significantly greater for treatments receiving manure applications than the control and Fert treatment

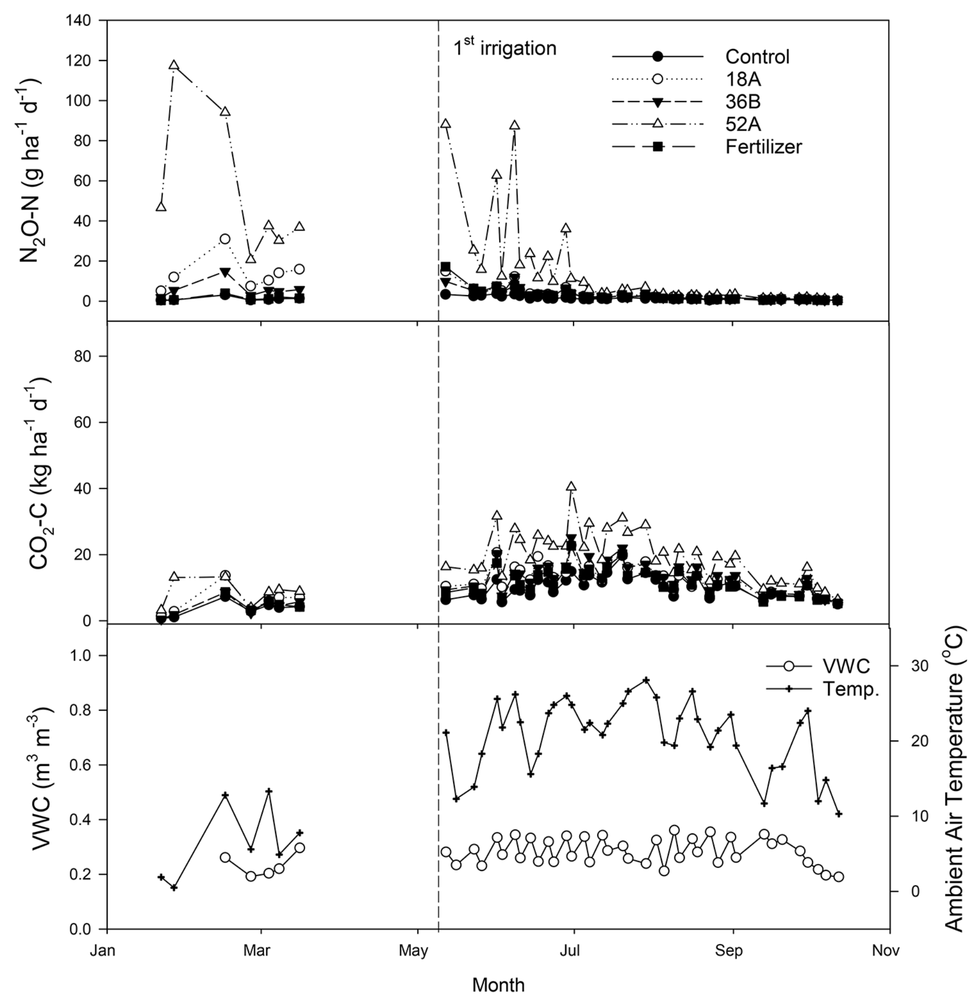

Fig. 5. Average daily N_2O-N and CO_2–C fluxes from the experimental plots, soil volumetric water content (VWC) and ambient air temperature during the 2016 monitoring period under sugar beet. Treatments: no synthetic fertilizer or manure (control), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"), and synthetic fertilizer ("Fertilizer"). All rates on a dry weight basis.

following the trend 52A > 36B = 18A > Fert = control (Table 5). This trend changed slightly in 2014 with the 36B < 18A, while the other trends stayed the same. The relative decrease in average daily CO_2–C fluxes from the 36B treatment (17.6 kg ha^{-1} d^{-1}) compared with the 18A treatment (19.9 kg ha^{-1} d^{-1}) in 2014 is not surprising as there was no manure application in the fall of 2013 on these plots. Average daily CO_2–C fluxes in 2015 and 2016 ranged from 10.2 to 32.0 kg ha^{-1} d^{-1} with few clear trends. In these years, the 52A manure treatment always had the highest average CO_2–C flux which was followed by 36B and 18A manure treatments and then the Fert and control, however there were few statistical differences between them.

Relationships among Fluxes, Climate, and Soil Properties

When all data were combined over year and treatment, there were weak positive relationships between N_2O average daily fluxes and pre-season soil test total N (r = 0.21) and NO_3–N (r = 0.26). Correlation analysis of the relationship between soil volumetric water content and N_2O flux by treatment was significant (P = 0.0007–0.02) for all treatments but with weak correlations (r = 0.18–0.25). The relationship between air temperature and fluxes was only significant for the control treatment (P = 0.0016) but again had a weak relationship (r = 0.23). Although the effect of soil moisture and temperature were not highly correlated with N_2O-N fluxes individually, the interaction between the two variables had a distinct impact on N_2O-N fluxes. Figure 6 illustrates the interactions of soil moisture and temperature on N_2O-N fluxes for each treatment over the 4 yr. As can be seen for all treatments, the greatest flux rates occurred at the intersection of the highest recorded soil moisture (~0.35 m^3 m^{-3}) and the highest recorded air temperature (~25°C), with additional peaks occurring at high soil moisture over a range of temperatures.

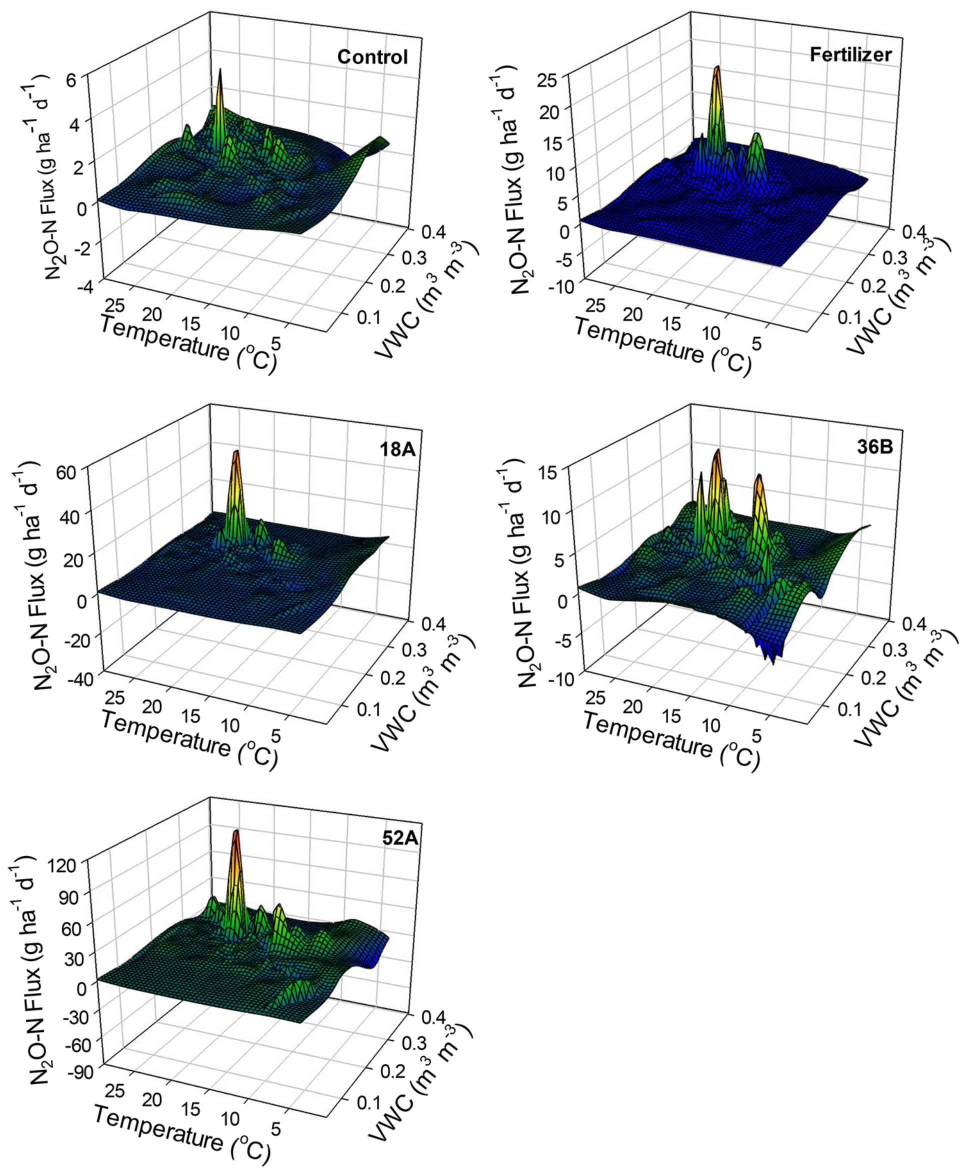

Fig. 6. Emissions of N_2O-N in relation to air temperature and soil volumetric water content (VWC). Treatments: no synthetic fertilizer or manure (control), synthetic fertilizer ("Fertilizer"), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), and dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"). All rates on a dry weight basis.

Neither average daily CO_2–C flux nor cumulative CO_2–C losses were strongly correlated with pre-season soil organic matter (r = 0.11–0.22) when data were combined over year and treatment. Correlation analysis of the relationship between soil moisture content and CO_2–C fluxes by treatment was significant (P < 0.0001) for all treatments with correlation coefficients ranging from 0.33 to 0.37 (data not shown). The relationship between temperature and CO_2–C fluxes by treatment was slightly better with correlation coefficients ranging from 0.40 to 0.44 (P < 0.0001). As with N_2O-N fluxes the interaction of soil moisture and air temperature had a large impact on CO_2–C fluxes with spikes in emissions occurring when both high soil moisture content (>0.25 m^3 m^{-3}) and higher temperatures (>15°C) were present (Fig. 7). Additionally, even at low temperatures (~5°C), there were increases in emissions with soil moisture contents above 0.25 m^3 m^{-3}.

Cumulative GHG Emissions and Emissions Intensities

Cumulative losses of both N_2O-N and CO_2–C were calculated over each growing season and summed over the 4-yr rotation and are shown in Table 6. When summed over the 4-yr rotation, the total N_2O-N losses ranged from 1.4 to 8.5 kg ha^{-1} following the trend: 52A > 36B = 18A = Fert > control. The loss of total N applied as N_2O-N ranged from 0.13 to 0.24% with the Fert treatment being significantly higher than the manure treatments, which did not differ among each other. The total CO_2–C losses summed over the 4-yr rotation ranged from 9,632 to 18,309 kg ha^{-1} and followed the trend: 52A > 36B = 18A > Fert = control. The cumulative amount of CO_2–C lost as a percentage of C applied ranged from 6.31 to 8.04 for the manure treatments with no significant differences between treatments.

Emission intensities were calculated for each season and expressed as grams of N_2O-N lost per megagram of dry matter

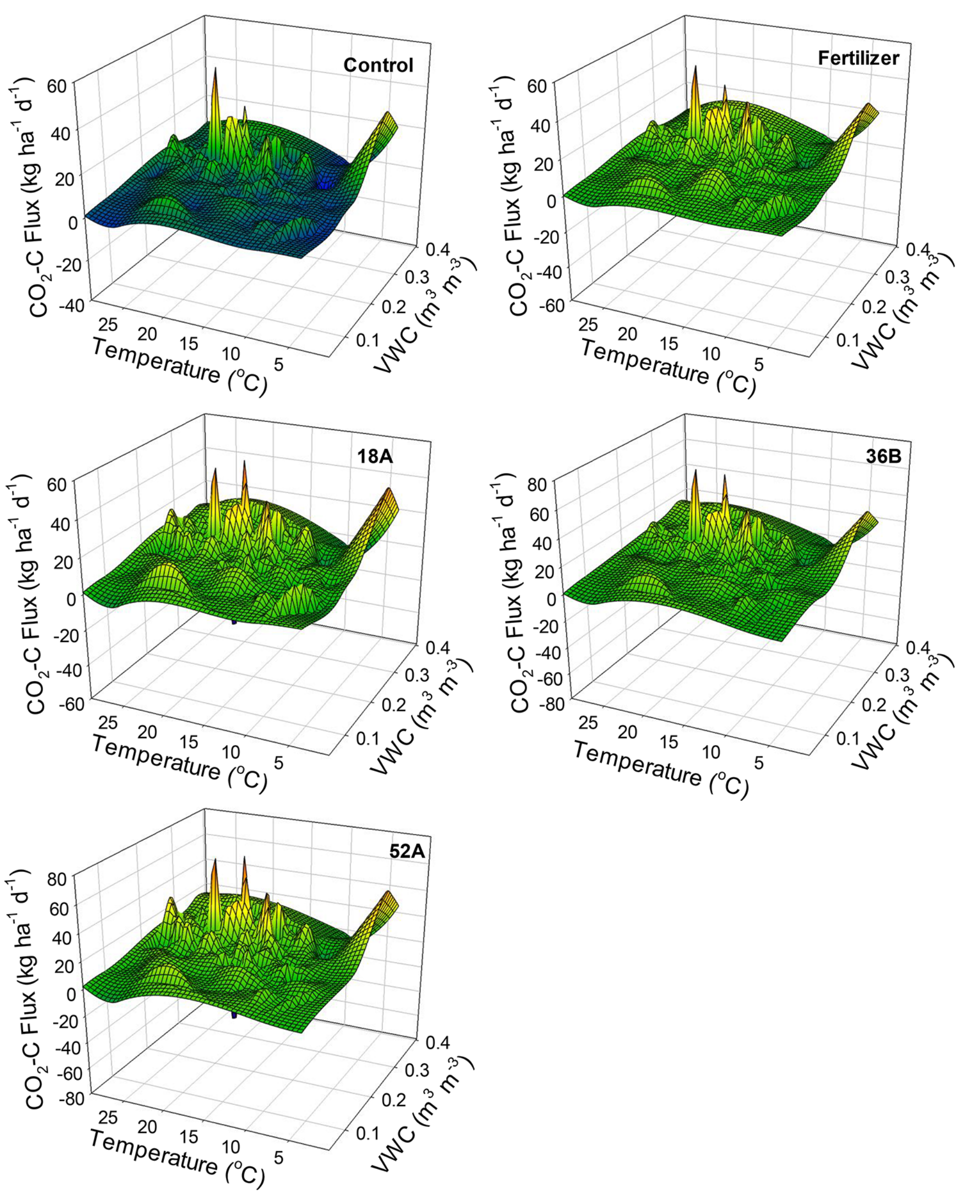

Fig. 7. Emissions of CO_2–C in relation to air temperature and soil volumetric water content (VWC). Treatments: no synthetic fertilizer or manure (control), synthetic fertilizer ("Fertilizer"), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), and dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"). All rates on a dry weight basis.

Table 6. Cumulative losses of N_2O-N and CO_2–C over the growing season (April through October) by year and as a percentage of cumulative N and C applied over the 4-yr study period.

Treatment†	2013	2014	2015	2016	Total loss	Relative loss‡
	kg ha^{-1}					%
			N_2O-N			
Control	0.282 d§	0.297 d	0.590 c	0.231 c	1.400 c	–
Fertilizer	0.369 d	0.850 c	1.117 b	0.460 b	2.798 b	0.24 a
18A	0.576 c	1.342 b	1.133 b	0.465 b	3.518 b	0.13 b
36B	0.818 b	1.137 b	1.167 b	0.432 b	3.555 b	0.15 b
52A	1.142 a	3.546 a	1.785 a	1.996 a	8.471 a	0.18 b
			CO_2–C			
Control	2,221 c	2,421 d	3,421 c	1,567 b	9,632 c	–
Fertilizer	2,145 c	2,631 d	3,489 c	1,736 b	10,002 c	–
18A	3,200 b	3,684 b	3,943 b	1,918 b	12,747 b	6.56
36B	3,384 b	3,287 c	4,283 b	1,966 b	12,922 b	8.04
52A	4,015 a	5,627 a	5,734 a	2,931 a	18,309 a	6.31

† Treatments: Control, no synthetic fertilizer or manure; Fertilizer, synthetic fertilizer; 18A, dairy manure applied annually at a rate of 18 Mg ha^{-1}; 36B, dairy manure applied biennially at a rate of 36 Mg ha^{-1}; 52A, manure applied annually at a rate of 52 Mg ha^{-1}. Rates on a dry weight basis.

‡ Percentage of cumulative loss were calculated as follows: $[(N_2O\text{-N or }CO_2\text{–C})_{trt} - (N_2O\text{-N or }CO_2\text{–C})_{control}]/(\text{Total N or C applied})$, where $(N_2O\text{-N or }CO_2\text{–C})_{trt}$ is the N or C released as N_2O or CO_2, respectively, from the treated plots, and $(N_2O\text{-N or }CO_2\text{–C})_{control}$ is the N or C released as N_2O or CO_2, respectively, from the control plots.

§ Mean values within a column followed by the same lowercase letter are not significantly different at the 0.05 probability level.

yield for each crop (grain yield for wheat and barley; tuber yield for potato; root yield for sugar beet; Fig. 8). The emission intensity in wheat (2013) was greatest for the 52A and 36B treatments followed by the 18A, Fert, and control treatments. In potato (2014), N_2O-N emission intensity increased an average of 4.8-fold for the 52A treatment compared with the other treatments. In both barley and sugar beet, the average emission intensity of the 52A treatment was significantly greater (1.9- and 4.6-fold, respectively) than all the other treatments, which did not differ. When emission intensity (52A) in sugar beet was calculated on a sugar content basis instead of a root yield basis, the average emission intensity increases further to 5.1-fold the other treatments (data not shown), as the highest manure application rate led to lower sugar content in sugar beet.

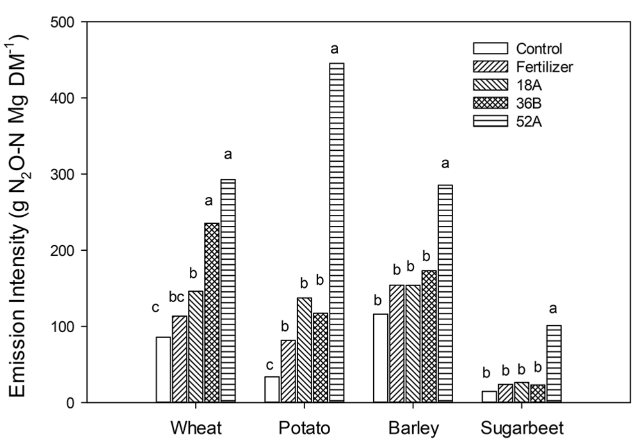

Fig. 8. N_2O-N emissions intensity for each growing season. Emission intensities were calculated for each season and expressed as grams of N_2O-N lost per megagram of dry matter yield for each crop (grain yield for wheat and barley; tuber yield for potato; root yield for sugar beet). Treatments: no synthetic fertilizer or manure (control), synthetic fertilizer ("Fertilizer"), dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), and dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"). All rates on a dry weight basis. Values within crop followed by the same lowercase letter are not significantly different at the 0.05 probability level.

Changes in Soil Organic Carbon and Net GWP

The change in post-harvest SOC (0 to 91 cm) relative to the control plots from fall 2012 to fall 2015 is shown in Fig. 9. Both the 18A and 36B treatments showed an overall increase in SOC compared with the control. Interestingly, in both of these manure treatments, SOC increased in the 0 to 30 cm depths but decreased in the 30- to 91-cm depths but with an overall increase in SOC in the soil profile. The 52A treatment showed an increase in SOC for each soil depth down to 91 cm, with

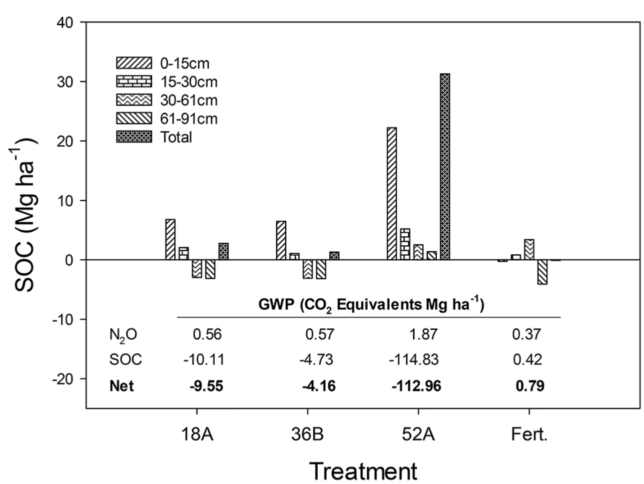

Fig. 9. Change in soil organic carbon (SOC, 0 to 91 cm) relative to control plots after 4 yr of synthetic fertilizer or manure additions. Overall global warming potential (GWP, N_2O + SOC) was calculated over the 4-yr rotation (2013 to 2016) relative to the control. Treatments: dairy manure applied annually at a rate of 18 Mg ha^{-1} ("18A"), dairy manure applied biennially at a rate of 36 Mg ha^{-1} ("36B"), dairy manure applied annually at a rate of 52 Mg ha^{-1} ("52A"), and synthetic fertilizer ("Fertilizer"). All rates on a dry weight basis.

an overall gain of 31 Mg C ha^{-1}, which is an average increase of 11-fold over the other manure treatments. Over the 4-yr rotation, the Fert treatment had a net loss of 0.22 Mg ha^{-1} of SOC. When put on a CO_2 equivalent basis the manure treatments gained between 4.2 and 112 Mg CO_{2eq} ha^{-1}, while the Fert treatment lost 0.9 Mg CO_2eq ha^{-1}. This large gain of SOC in the manure treatments outweighed the loss of CO_2eq through N_2O emissions, which ranged from 0.56 to 1.87 Mg CO_2eq-C ha^{-1}. Overall, there was a net decrease in GWP of the manure treatments while there was a slight increase for the Fert treatment.

DISCUSSION

Manure Application Increased Emissions of N_2O and CO_2

Average daily fluxes of N_2O-N and CO_2–C were within the range of those reported in the literature (Rochette et al., 2008; Bell et al., 2016; Dungan et al., 2017). In all years, average daily N_2O fluxes were significantly greater for the 52A manure application rate compared with the other treatments. During the first year following manure application (2013), there was a significant positive effect of manure application rate on both N_2O flux and cumulative emissions for all manure treatments. In subsequent years, there was no difference in either N_2O flux or cumulative emissions between the 18A and 36B manure application rates, even though the 36B rate did not receive manure applications in the fall of 2013 or 2015. At the end of the rotation, there was still no difference in the cumulative N_2O emissions between the 18A and 36B manure treatments. This suggests that there is a carryover effect of manure application in subsequent years and that adding manure either annually or biennially (with same total manure application rate) did not influence overall losses of N_2O. Dungan et al. (2017) also found that the effect of manure applications on N_2O emissions persisted for 2 yr following the last application.

In 2013 and 2015, there were two main spikes in N_2O emissions following irrigation events, with emissions remaining close to baseline for the remainder of the growing season. The exception to this was the Fert plots in 2015 which had spikes in N_2O emissions following an in-season application of synthetic N fertilizer. In 2014 and 2016, there were multiple spikes in emissions commencing with the start of the irrigation season, with the largest spikes occurring in the 52A manure treatment plots. The spikes in emissions in 2014 are likely related to the large amount of synthetic fertilizer N applied to all plots that year for potato production (219 to 305 kg N ha^{-1}), which included two in-season applications. This addition of fertilizer N to the manure plots would not only have provided additional N substrate but would also have effectively reduced the C to N ratio in the soils. Klemedtsson et al. (2005) demonstrated that N_2O emissions increase with decreasing soil C to N ratios. Huang et al. (2004) demonstrated that the addition of urea with organic amendments to soil increased N_2O emissions up to 44% compared with the organic amendment alone.

In addition, in 2016, soil organic matter in the 52A treatment soils increased (75% greater than the other manure treatments), but soil NO_3^- increased at a greater rate (200%) creating an effectively lower soil C to available N ratio and greater substrate for denitrification. This may have resulted in the larger cumulative N_2O emissions (142% greater) for the 52A treatment in 2016 compared with the other manure treatments. McSwiney and Robertson (2005) suggested that soil NO_3^- was the most important predictor of N_2O emissions. In fact, in the present study, there was a positive linear relationship between pre-plant soil NO_3^- and N_2O fluxes in any given year with an average r^2 of 0.89 (data not shown) even though when combined across all years this relationship was weak.

There was also a positive linear relationship between SOC and N_2O fluxes within each year with an average r^2 of 0.85 (data not shown). The greater SOC may provide more labile C for heterotrophic bacteria, creating anaerobic microsites within soil aggregates as they consume O_2, which may generate more N_2O (Smith et al., 2003; Li et al., 2016; Gu et al., 2017). Dendooven et al. (1996) suggested that denitrifier activity in soils can be limited by C availability and the C provided with manure application eliminates this as a limiting factor therefore stimulating denitrification. They also suggested that the additional C can increase N_2O emission losses during denitrification by accelerating the rate of NO_3^- reduction but not N_2O reduction.

Unlike N_2O emissions, CO_2 emissions remained higher than pre-irrigation levels throughout the growing season. The elevated CO_2 emissions are likely a result of increased root growth and exudation as well as enhanced decomposition of soil OM under warmer conditions (Adviento-Borbe et al., 2010). As expected, the 52A treatment had the greatest loss of CO_2 over the growing season as well as cumulative total losses over the rotation, due to the decomposition of added C with manure treatment. Cumulative CO_2 losses were 28 to 83% greater from manure treatments compared with the Fert treatment. In a meta-analysis, Xia et al. (2017) reported an increase of 26% in CO_2 emissions when substituting synthetic fertilizer with manure.

Climate Interactions and Irrigation Effects on Emissions of N_2O and CO_2

The largest spikes in N_2O emissions during the growing season were related to the first few irrigation events, except in 2015 where there was also a large spike in the Fert treatment following an in-season synthetic N application at a rate of 45 kg N ha^{-1}. Spikes in N_2O emissions have been found early in the growing season following N applications when soil moisture becomes elevated due to rainfall (Adviento-Borbe et al., 2010; Westphal et al., 2018) or irrigation (Liu et al., 2010; Gu et al., 2017; Dungan et al., 2017). Although irrigation water was applied continuously throughout the growing season, the effect of subsequent irrigations on N_2O emissions was diminished. The initial emission spikes occurred quickly, with an immediate return to near baseline emissions following the first few irrigation events. This emissions trend has been reported to be associated with extreme soil moisture cycling events (Mosier et al., 2006; Hernandez-Ramirez et al., 2009) which would be similar to changes in soil moisture with irrigation events.

The largest spikes in N_2O emissions in the present study occurred at soil moisture between 0.3 to 0.4 $m^3 m^{-3}$ (equivalent to 57 to 75% water-filled pore space assuming a bulk density of 1.4 g cm^{-3} and particle density of 2.65 g cm^{-3}) with temperatures near 25°C. Hu et al. (2013) also reported the greatest N_2O fluxes at a WFPS of ~70% and temperatures of 25°C from a wheat-maize system on a calcareous soil in China. At these soil moisture contents, it would be expected that denitrification was the driving force for N_2O production. Akiyama et al. (2004) found that in soils treated with cattle manure, nitrification was the dominant form of N_2O production at WFPS less than 58% and that denitrification was the driving process at WFPS greater than that. Although these are not necessarily highly saturated conditions, it has been shown that excessive rainfall can decrease gaseous connectivity among micropores within soil aggregates, therefore enhancing N_2O emissions by reducing O_2 diffusion into and through the soil (Sexstone et al., 1985). These same effects would likely be seen with irrigation as the soils are temporarily saturated near the surface during irrigation, and then decrease sharply in moisture content until the next irrigation event.

In 2013 and 2015, a spike in N_2O emissions was accompanied by a spike in CO_2 emissions, however in 2014 and 2016, this was not the case. In both 2014 and 2016, there was greater early season precipitation (pre-irrigation) than in 2013 and 2015. It is possible that this early season moisture reduced the response in microbial respiration with the first irrigation. In general, there was a poor relationship between N_2O and CO_2 emissions with $r < 0.2$ (data not shown). This may indicate that the effect of water saturation due to irrigation on O_2 diffusion into the soil may be a larger factor in creating anaerobic microsites within soil aggregates than O_2 depletion due to microbial activity. Large fluxes of CO_2 occurred at high soil moisture (0.3–0.4 $m^3 m^{-3}$) and temperature (20 to 25°C) as seen with N_2O emissions (Fig. 7). In contrast to N_2O emissions, CO_2 fluxes occurred across a much larger range of soil temperature and moisture conditions including large fluxes at low temperatures (<5°C) and high soil moisture contents (0.25 $m^3 m^{-3}$), indicating that microbial activity is prevalent across a broad range of conditions.

Non-Growing Season N_2O Fluxes

Following the second manure application (fall 2013), fluxes of N_2O during the non-growing season (October to April) became prevalent, particularly for the 52A treatment. In particular, there were high spikes of N_2O emission in the winter of 2015 and spring of 2016 for the 52A treatment that coincided with increases in soil moisture and/or soil temperature. Several researchers have reported significant non-growing season N_2O emissions, which may account for more than 50% of annual emissions (Wagner-Riddle and Thurtell, 1998; Syväsalo et al., 2004; Virkajärvi et al., 2010). While we were not able to calculate the contribution of these emissions to annual emissions, as we did not have a complete annual dataset, based on the magnitude of the spikes in N_2O emissions in the non-growing season of 2015 and 2016, it is likely that these emissions would constitute a large fraction of total annual emissions. Future research quantifying the contribution of non-growing season emissions to annual emissions is needed to assess the impact of these emissions on the overall GWP in the semiarid irrigated systems of the mountain west region.

Emission Factors, Intensities, and GWP as Affected by Manure Application

Nitrous oxide emission factors during the growing season (computed as the difference between N_2O lost from the treated plot minus the N_2O loss from the control plot, divided by the total N that was added with the treatment) ranged from 0.13 to 0.24% over the 4-yr rotation. This finding was comparable to data for cattle farmyard manure (0.27%) published by Bell et al. (2016) and to data from Webb et al. (2014) (0.09 to 0.55%). The cumulative percentage of N lost as N_2O was, on average, 39% lower from manure vs. synthetic fertilizer applications which is lower than that reported elsewhere in the literature (Bouwman et al., 2002). As the majority of N added with the manure in the present study was in the form of organic N, the lower availability of N substrate for denitrification may have resulted in the lower emission factors for these manure additions compared with synthetic fertilizer. Manure N is released over the growing season through mineralization and therefore a greater fraction may be taken up by the growing crop compared with synthetic fertilizer N which is available shortly after application.

To account for effects of manure applications on crop growth, emissions intensities were calculated. The N_2O emission intensities ranged from 5 to 445 g N_2O-N Mg DM^{-1} and were similar to those reported by Westphal et al. (2018) for soybean, wheat and alfalfa. The largest emissions intensities each year occurred with the 52A treatment. When one considers crop quality in addition to yield, the emission intensities were more unfavorable at high manure application rates in some instances. For example, at high manure application rate, sugar yield in sugar beets decreased. Therefore, emission intensities on a sugar basis were even greater for the 52A treatment (411%) compared with the other treatments. This illustrates that not only yield should be considered when evaluating emission intensity but in some cases crop quality needs to be included as well.

The effects of manure application on overall GWP were calculated using the changes in SOC and N_2O emissions of the different treatments. Gu et al. (2017) found that increases in SOC could be offset by increased N_2O emissions with manure application, leading to overall higher GWP, however this trend was not evident in the present study. When measured to a depth of 91 cm, there was an overall increase in SOC for all of the manure treatments, however, the largest increase was seen with the 52A treatment. These increases in SOC represent a net decrease in GWP. Although there was a larger amount of N_2O lost from the manure treatments in some instances, it was not enough to offset the overall gain in CO_2eq through increased SOC. While the lower manure application rates of 18A and 36B as well as the Fert treatment were near C neutral, the 52A rate had a negative GWP of 112, due to increased SOC throughout the soil profile. Gu et al. (2017) only measured SOC to a depth of 20 cm, where in the present study we found changes in SOC down to 91 cm, highlighting the importance of considering the effects of SOC beyond just the surface soils when calculating overall GWP. Baker et al. (2007) suggested that soil sampling to depths greater than 30 cm is necessary when calculating overall changes in SOC as surface sampling alone may miscalculate overall changes of SOC in the soil profile.

In summary, at the highest manure application rate, both cumulative N_2O-N and CO_2–C losses increased above that of synthetic fertilizer treatments and moderate manure application rates applied either annually or biennially. Fluxes of N_2O-N were greatest when both soil moisture and temperature were high (0.35 m^3 m^{-3} and 25°C), with a few large spikes in emissions accounting for the majority of growing season N_2O losses. Emissions of N_2O-N in the NGS were high (up to 117 g ha^{-1} d^{-1}) for the 52A manure application rate following the third manure application, suggesting that NGS emissions need to be accounted for when determining annual cumulative emissions. As increasing rates of repeated manure applications had negative impacts on yield and in some cases crop quality, emission intensities of the 52A manure application rate were greater than those of synthetic fertilizer and moderate manure applications. This finding suggests that not only yield but crop quality should be considered when evaluating the effects of manure treatment on emission intensities. Although manure application increased N_2O-N emissions relative to fertilizer, there was a net gain in SOC offsetting these emissions which led to a net negative GWP of manure application. Therefore, a more holistic evaluation of manure application in cropping systems should be accounted for to determine the overall C footprint of these systems.

SUPPLEMENTAL MATERIAL

A supplemental file is available with the online version of this article. The supplemental file contains two tables: Table S1, Irrigation date, hour and amount over each growing season; and Table S2, Pesticide and other chemical applications over the four-year rotation.

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