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Effect of dairy manure-based fertilizers on nitrous oxide emissions in a semi-arid climate

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Abstract

Manure treatment technologies are of interest to dairy operations to improve nutrient management, although there are little data related to nutrient availability and environmental impacts of these manure-based fertilizer products. This field trial experiment investigated the impact of two manure-based fertilizer sources (phosphorus enriched solids [PE] and mechanical vapor recompression solids [VR]) on soil nutrients, crop yields, and N_2O emissions in a forage rotation. The study was a factorial random complete block design, with two main factors: manure history (with [M]; without [NM]) and manure-based fertilizer product (control [Con], PE, VR), under a continuous corn and triticale rotation. M had greater soil organic carbon, total carbon, total nitrogen, and M3-P (30%–128%) and reduced NH_4-N (15%) than NM, with no other treatment differences. Corn silage yields were greater in NM versus M (7%) treatments only in 2021, while in 2022 VRNM was 17% greater than ConNM only. Triticale yields were 14% greater in M plots versus NM treatments only in 2021. In 2022, triticale yields were 1.7 times lower in ConNM versus all other treatments, and PENM was 71% greater than ConM. The greatest N_2O fluxes occurred in May, June, and July with M having 69% greater average cumulative fluxes than NM, while average VR cumulative fluxes were 102% greater than PE and Con. Over both years, net loss of $N_{applied}$ as N_2O-N was 1.9%–2.2% for VR and 0.4%–0.8% for PE solids. While manure-based fertilizers performed well as a nutrient source, their susceptibility to N_2O loss needs to be considered in management strategies.

Plain Language Summary

Manure treatment technologies can improve nutrient management, though there is little data related to crop and environmental impacts of manure byproducts. We investigated two manure-based fertilizer sources (Phosphorus Enriched Solids [PE] and Mechanical Vapor Recompression Solids [VR]), and application of solid dairy

Abbreviations: EF, emission factor; MAP, monoammonium phosphate; SOC, soil organic carbon.

manure, on soil nutrients, crop yields and N_2O emissions. Application of solid dairy manure had greater soil carbon, nitrogen and phosphorus in the topsoil compared to manure-based fertilizers. There were slight differences in corn silage and triticale yields which were greater in treatments with previous manure application. Over two years, net loss of N applied as N_2O-N was 1.9–2.2% for VR and 0.4–0.8% for PE solids. Nutrient extraction technologies produce manure-based fertilizer products that are beneficial for crops but may be susceptible to N_2O losses, which need to be considered when managing these products.

1 | INTRODUCTION

Environmental sustainability of agricultural systems has become a focus for many consumers, producers, and corporations. This has led many national organizations to set sustainability goals to lessen the environmental impact of production. The Innovation Center for U.S. Dairy has set environmental sustainability goals to achieve greenhouse gas neutrality, optimize water usage, and improve water quality by optimizing utilization of manure and nutrients by 2050 (usdairy.com/sustainability).

Although dairy production systems vary across the United States and exist in many different climatic zones, the greatest concerns facing the industry are related to water quality degradation from nitrate leaching and phosphorus (P) runoff, air quality degradation due to emissions of ammonia, and climate impacts resulting from methane and nitrous oxide (N_2O) emissions (M. Holly et al., 2018). Idaho is one of the top three dairy-producing states in the United States, with the majority of milk cows (74.8%) located in the south-central region (USDA-NASS, 2017). Dairy production is characterized by a high animal density at both the farm (4–20 AU ha^{-1}) as well as the regional (~2 AU ha^{-1}) level resulting in on-farm surpluses of both nitrogen (N) and P (Hristov et al., 2006; Spears et al., 2003). These farm gate P surpluses have led to a buildup of soil P on many producer fields resulting in restricted application rates of manure based on P removal of crops.

In response to these challenges, both established and newly developed manure technologies have started to gain interest as a means of generating more environmentally friendly manure-based fertilizers that stabilize and improve N and P capture. Two systems that have been deployed on dairies across the United States are the Livestock Water Recycling System and the Sedron Varcor system. The Livestock Water Recycling System utilizes mechanical separation in conjunction with chemical treatment (addition of polymers) to capture and concentrate nutrients from a liquid manure stream resulting in clean water and a P-enriched manure-based fertilizer byproduct (PE). Similar systems, such as dissolved air flotation, can enhance nutrient recovery as a secondary solid-liquid separation technology by producing polymer-stabilized solid fractions from fine suspended solids. Studies report nutrient capture efficiencies of 36%–50% total N, 85%–95% total P, and 11%–41% total K for dissolved air flotation and other similar systems (Katers & Pelegrin, 2012; Porterfield et al., 2020). The Sedron Varcor System, which uses mechanical vapor recompression (VR), has proven to be effective in distilling high-salinity wastewater while also allowing for minimizing energy consumption (Zhou et al., 2014). Recently, the adoption of VR with manure treatment has gained interest to create dried, nutrient-rich solids along with a clean distilled water byproduct. While these systems have been deployed at multiple dairies, there is little information regarding the performance of the manure-based fertilizer byproduct as a crop nutrient and how best to manage these products for reducing potential losses to the environment.

While manures and manure-based fertilizers provide a wide array of nutrients, they also supply carbon which can increase soil organic carbon (SOC) stocks, an important driver of N_2O emissions (Hansen et al., 2019). In the dairy production region of Idaho, SOC stocks are naturally low (~1%), but the addition of manure can raise these levels significantly (Baxter et al., 2023; Bierer et al., 2021; Leytem et al., 2024). It has been demonstrated that degradable carbon (C) applied to a low SOC soil will trigger greater microbial activity and denitrification than when applied to a higher SOC soil (Chantigny et al., 2010; Pelster et al., 2012). Therefore, manure and manure-based fertilizers may have an enhanced loss of N_2O when applied to the arid low SOC soils of southern Idaho. Increasing rates of manure application have been shown to increase annual N_2O emissions with the effect of past manure application persisting even after cessation of manure addition (Chang et al., 1998; Leytem et al., 2019, Dungan et al., 2023). Therefore, evaluating new manure-based fertilizers on N_2O emissions should consider past manure application history which will be common in the intense dairy region of southern Idaho.

As part of the US Dairy's Net Zero Initiative, the Dairy Soil and Water Regeneration project (DSWR) was developed to address knowledge gaps associated with dairy feed production and manure-based fertilizers on greenhouse gas (GHG) emissions, soil health, SOC stocks, and water quality. The DSWR project consists of multiple research sites and participating dairy farms located in four major dairy-producing regions of the United States. As part of this study, a cross location comparison of the use of both PE and VR manure-based fertilizer products was initiated to evaluate these manure-based fertilizers on soil health and N_2O emissions as well as agronomic and environmental outcomes. The objectives of the current study were to investigate the impact of PE and VR solids, with and without a previous application of solid dairy manure on soil nutrients, crop yields, and N_2O emissions in an irrigated forage rotation common in southern Idaho. These data will contribute to the larger group effort to identify how manure-based fertilizers impact soil health, forage production and quality, and the environment.

Core Ideas

- Solid manure application had greater effect on soil C and N and crop yields compared to manure-based fertilizers.
- Annual cumulative N_2O emissions from mechanical recompression solids were 53%–153% greater than other treatments.
- Average N_2O emission factor was greater for mechanical recompression solids (>1.6%) versus P-enriched solids (<1.0%).

2 | MATERIALS AND METHODS

2.1 | Site description and setup

This study was conducted from 2020 to 2022 at the USDA Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho (42°15′0″ N, 114°30′0″ W). This region has a semi-arid climate with hot, dry summers and cool, wet winters with most of the precipitation occurring between October and May. Therefore, irrigation is necessary for crop production and is tailored based on evapotranspiration rates throughout the season. From May to October, the average weekly irrigation water application ranged from 9 to 68 mm, with annual totals ranging from 585 to 758 mm. Mean daily temperatures ranged from 17 to 23°C from June to September (corn growing season) and −1.6 to 13°C from October to May (triticale growing season). Annual precipitation ranged from 167 to 208 mm. More detailed information on growing degree days and temperature is reported in Figure 1. The soil is a Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid) with 0%–2% slopes (Soil Survey Staff, 2019). The average cation exchange capacity (0–15 cm) is reported at 13.1 meq per 100 g (Soil Survey Staff, 2019), with a pH of 7.9 and bulk density of 1.30 g cm^3.

Starting in the fall of 2020, plots (12.2 × 12.2 m) were arranged in a factorial randomized complete block design, with four blocks and two main treatment factors, under a continuous corn (*Zea mays*)-triticale (x *Triticosecale*) crop rotation. The first treatment factor pertains to the applied product and consists of three levels: control (Con), P-enriched solids (PE), and mechanical vapor recompression solids (VR). To investigate potential additive and interactive effects between untreated manure and the manure-based fertilizers, a second treatment factor was included to better represent soils that have had previous manure application. The second treatment factor consists of two levels: previous manure application (M) and no manure application (NM). Prior to the start of the study (2013–2019), the field site was used for alfalfa production and had no history of manure application. Manured treatments (M) received a single application (44.6 Mg ha^{-1} dry wt.) of solid dairy manure scraped from an open lot in the fall of 2020. Manure application rate was chosen based on common rates used in the region where the study took place. Manure was incorporated via disking into the top 15.2 cm of soil immediately following application, and all treatments received the same tillage for consistency.

2.2 | Agronomic practices

2.2.1 | Organic amendment applications and analyses

Nutrient concentrations and product application rates are reported in Tables 1 and 2. PE and VR solids were surface applied by hand each spring prior to corn silage planting (May 25–27 for 2021 and 2022). In 2021, all products were incorporated via disking into the top 15.2 cm of soil

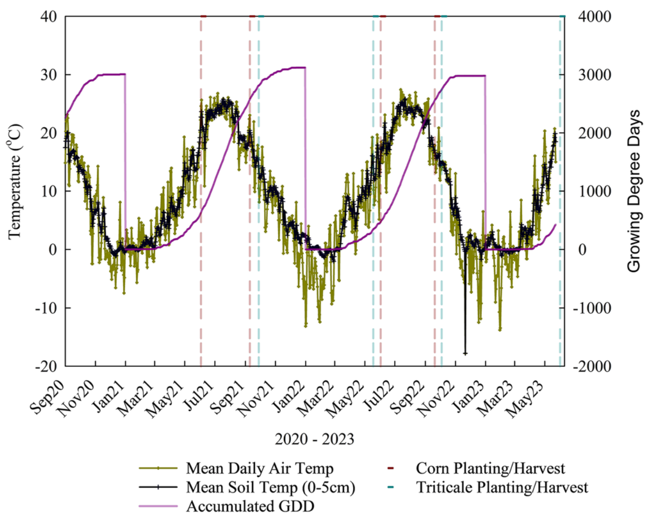

FIGURE 1 Mean daily soil and air temperatures and cumulative growing degree days (GDD) for September 2020–May 2023.

TABLE 1 Amendment nutrient concentrations.

Year	Source[a]	Total C (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})	C:N (g kg^{-1})	N:P (g kg^{-1})
2020	Dairy manure	320.9	20.3	6.7	15.8	3.0
2021	PE	284.5	31.4	15.3	9.1	2.1
	VR	420.0	37.9	8.3	11.1	4.6
2022	PE	256.4	28.7	16.4	8.9	1.8
	VR	384.2	37.5	11.3	10.2	3.3

[a]Dairy manure was a solid manure scraped from an open lot dairy, P-enriched solids (PE), mechanical vapor recompression solids (VR).

TABLE 2 Annual nitrogen (N) and phosphorus (P) application rates from 2020 to 2022.

Treatment		2020	2021			2022		
		Manure (kg ha^{-1})	PE/VR[a] (kg ha^{-1})	Synthetic (kg ha^{-1})	Total (kg ha^{-1})	PE/VR (kg ha^{-1})	Synthetic (kg ha^{-1})	Total (kg ha^{-1})
ConM	N	905.6	–	–	–	–	–	–
	P	29.9	–	–	–	–	–	–
PEM	N	905.6	133.8	–	133.8	140.0	110.5	250.5
	P	29.9	72.8	–	72.8	79.8	–	79.8
VRM	N	905.6	340.9	–	340.9	265.3	67.1	332.4
	P	29.9	74.2	–	74.2	79.9	–	79.9
ConNM	N	–	–	–	–	–	–	–
	P	–	–	–	–	–	–	–
PENM	N	–	133.8	13.4	147.2	140.0	179.5	319.6
	P	–	72.8	27.9	100.7	79.8	–	79.8
VRNM	N	–	340.9	13.4	354.3	265.3	192.7	458.0
	P	–	74.2	27.9	102.1	79.9	–	79.9

Note: Treatment codes are as follows: control (Con), P-enriched solids (PE), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM).
[a]P enriched solids were applied only to PEM/PENM, and mechanical vapor recompression solids were applied to only VRM/VRNM.

immediately following application. In 2022, no-till practices were followed, and products remained on the soil surface. Application rates were determined using a P-banking method based on total anticipated crop P removal over the 5 years of the study, with no manure applied during the last year of the trial on alfalfa (USDA-NRCS, 2013). For all organic amendments (M, PE, and VR), total C and total N were determined via combustion with a FlashEA1112 (CE Elantech). Total P was determined via microwave digestion of 0.5 g manure/manure-based amendment with nitric/hydrochloric acid and measured via inductively coupled plasma optical emission spectrometry (Perkin Elmer Optima 7300 DV; Perkin Elmer).

Starting in 2021, control treatments received no fertilizer applications, regardless of previous manure application. Due to low soil P concentrations, ammonium phosphate (MAP) was applied at a rate of 122 kg ha^{-1} to non-manured PE and VR plots in 2021. Plots were then disked to 15.2 cm and roller harrowed on June 1, 2021. In 2022, all PE and VR treatments received urea applications based on soil test recommendations to meet crop N needs. All fertilizer recommendations were determined using the Pacific Northwest Publishing's Guidelines for corn silage (Brown et al., 2010).

2.2.2 | Planting and harvesting

Corn (Northup King NK 8005 GTA/LL) was planted using a four-row, Monosem NG+ planter with 76.2-cm row spacing and 15.2 cm between seed placement on June 2–3 for both years. Corn silage yield was determined with a research plot harvester (Haldrup M-63) on September 10 2021, and September 20 2022, using a two-row cutting width and average yield lengths of 10.5 m. Triticale (TriCal 719) was planted at a seeding rate of 112 kg ha^{-1} and 19.1-cm row spacing on September 28 2021, and October 4 2022. Triticale silage yield was determined using a research plot harvester (RCI Engineering 36A) on May 18, 2022, and Jun 1, 2023 using a 0.9-m cutting width and average yield lengths of 9.5 m. Fields were bulk harvested by a commercial operator on September 10, 2021, and October 1, 2022 for corn silage and May 29, 2022, and June 15, 2023 for triticale.

2.3 | Gas flux measurements

Nitrous oxide fluxes were measured using a LI-COR Smart Chamber (LI-COR Biosciences 8200-01S) and LI-7820 N_2O/H_2O Trace Gas Analyzer (LI-COR Biosciences) system. Within each plot, two LI-COR soil collars (one in-row and one between row) were installed so that the top of the collars were within 2–5 cm above the soil surface. Sampling was conducted throughout the year, with increased sampling frequency throughout the primary growing season to better capture related pulse events. Following corn planting and initial irrigation, gas samples were collected twice per week (1 day after irrigation and 2–3 days after irrigation) during the growing season. In the off-season months (October–March), sampling was reduced to once per week as weather permitted. Increased sampling events were implemented based on precipitation events and potential freeze/thaw pulse events. For each flux measurement, air was sampled for either 90 s (during the primary growing season) or 120 s (during the off-season). To capture potential variability in emissions on each sampling day, due to diurnal changes in temperature, gas sampling occurred between ~10:00 a.m. 3:00 p.m. MST, with blocks being sampled in numerical order (1–4) throughout the course of the day. Within each block, plot sampling was randomized during each sampling event. Gas sampling files were merged to calculate gas fluxes using the SoilFluxPro software (v 5.2.0). Both the LI-COR Smart Chamber and the SoilFluxPro software estimate soil gas fluxes using Equation (1):

$$F_c = \frac{10VP_0\left(1-\frac{W_0}{1000}\right)}{RS\left(T_0+273.15\right)} \times \frac{\partial C'}{\partial t}, \quad (1)$$

where F_c is soil gas flux rate (µmol m^{-2} s^{-1}), V is total system volume (cm^3), P_o is initial pressure (kPa), W_0 is initial water vapor mole fraction (mmol mol^{-1}), R is the gas constant (8.314 Pa m^3 K^{-1}), S is soil surface area (cm^2), T_0 is initial air temperature (˚C), and $\frac{\partial C'}{\partial t}$ is the initial rate of change in vapor dilution corrected CO_2 mole fraction (µmol mol^{-1} s^{-1}).

All gas sampling and flux data underwent QAQC processes to ensure data quality. Flux calculations were checked for linearity, initial gas concentrations, start/stop times, and r^2 trends. Deviations were flagged for further investigation or removal, depending on the source and degree of deviation. Only data that had successfully passed the QAQC process were included for analysis. Cumulative annual and monthly emissions were estimated through linear forecast modeling in Microsoft Excel 2016. The FORECAST function was used to estimate daily gas fluxes between measurements using the adjacent sampling dates as reference points. A total of 40 gas sampling events (June–December) were used for 2021, and a total of 49 gas sampling events (February–November) were used for 2022. The $\%N_{applied}$ lost as N_2O-N was calculated by dividing the total annual N_2O-N by the total applied N for each treatment. The emission factors (EF) for N_2O-N were calculated for each treatment by subtracting the cumulative N_2O-N of the control from the cumulative N_2O-N of each treatment and then dividing by the appropriate total N-applied.

2.4 | Soil sampling and analysis

Soil samples (0–15 cm) were collected approximately 1 month following corn planting for soil nutrient status. For each sampling event, six subsamples (three in row and three between row) were taken per plot using a 5.1-cm soil auger, composited by depth, and air-dried for 3–5 days prior to analysis. Soil samples were shipped to American Agriculture Laboratory, Inc (McCook, NE 69001) and analyzed for nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), SOC, inorganic carbon (IC), Mehlich 3-P, saturated paste electrical conductivity (EC), 24 h CO_2 respiration, and pH (data shown in Tables 3 and 4).

2.5 | Statistics

Daily N_2O fluxes were summed to estimate monthly and annual cumulative emissions. Cumulative (monthly and annual) N_2O emissions, crop yields, and soil characteristics were analyzed using SAS's PROC GLIMMIX (SAS Institute Inc.) function with an experimental design of a 3 × 2 randomized complete block design factorial with the model consisting of Factor A (amendments), Factor B (manure application), month (for emissions only), year (soils only), and all possible interactions. Block was treated as a random factor, and analysis was separated by year (except for soils). Significant differences were determined using Tukey's adjusted least square means. Due to homogeneity of variance violations, N_2O-N and $\%N_{applied}$ lost was ln transformed for both years for analysis. Data were back transformed for ease of discussion within the main text.

3 | RESULTS AND DISCUSSION

3.1 | Soil chemical properties

Soil chemical properties measured in spring 2021 and 2022 are reported in Table 3. Significant differences occurred almost exclusively between previous manure application status and between years. Averaged across both years, treatments

TABLE 3 Average soil chemical properties measured approximately 1 month following corn planting (0–15 cm) from 2021 to 2022.

	SOC (g kg^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})	NH_4-N (mg kg^{-1})	M3-P (mg kg^{-1})	pH (mg kg^{-1})
Con	14.9	16.9	1.9	6.5	87.8	7.98
PE	15.1	17.8	2.0	7.0	103.0	7.96
VR	15.5	17.7	2.1	6.7	99.2	7.94
M	17.5 a	19.7 a	2.3 a	6.2 b	134.4 a	8.04 a
NM	12.8 b	15.2 b	1.7 b	7.3 a	58.9 b	7.88 b
	***	***	***	**	***	***
2021	16.9 a	18.8 a	1.8 b	3.3 b	104.5	7.94
2022	13.4 b	16.1 b	2.1 a	10.2 a	88.8	7.98
	***	***	**	***	n/s	n/s

Note: Significant differences for $p < 0.05$, $p < 0.01$, and $p < 0.0001$ are denoted as *, **, and ***, respectively. Significant treatment differences are indicated by differing letters within a column. Treatment codes are as follows: control (Con), P-enriched solids (PE), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM).

TABLE 4 Soil characteristics including 24 h respired CO_2 (CO_2 respired) and electrical conductivity (EC) measured in 2021 and 2022.

	CO_2 Respired			EC		
	2021 (ppm)	2022 (ppm)	Avg. (ppm)	2021 (mS cm^{-1})	2022 (mS cm^{-1})	Avg. (mS cm^{-1})
Con	67.5	73.8	70.7	1.11	0.62	**0.86 b**
PE	78.3	66.5	72.4	1.06	0.78	**0.92 ab**
VR	78.0	87.6	82.8	1.16	0.91	**1.04 a**
M	94.6	88.3	91.5	*1.53 a*	*0.79 b*	1.16
NM	54.6	63.7	59.1	*0.69 b*	*0.75 b*	0.72
ConM	101.5	87.2	**94.4 a**	1.62	0.69	1.16
PEM	101.5	78.5	**90.0 a**	1.46	0.80	1.13
VRM	80.9	99.3	**90.1 a**	1.52	0.89	1.20
ConNM	33.5	60.4	**46.9 c**	0.60	0.55	0.57
PENM	55.2	54.6	**54.9 bc**	0.66	0.76	0.71
VRNM	75.2	76.0	**75.6 ab**	0.81	0.93	0.87
p-values	CO_2 Respired	EC				
Amendment	n/s	*				
Manure application	***	***				
Amendment × Manure application	*	n/s				
Year	n/s	***				
Amendment × Year	n/s	n/s				
Manure application × Year	n/s	***				

Note: The average (Avg.) values were pooled across years. Statistics are included for treatment effects and interactions. Treatment codes are as follows: Control (Con), P-enriched solids (PE), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM). Significant differences for $p < 0.05$, $p < 0.01$, and $p < 0.0001$ are denoted as *, **, and ***, respectively. Significant treatment differences are indicated by differing letters, with comparison groups designated by bolded/italicized text.

with previous manure application had significantly increased SOC (36%), total C (30%), total N (37%), M3-P (128%), and pH (2%) and decreased NH_4-N (15%) compared to non-manured plots. Averaged across all treatments, SOC and total C decreased from 2021 to 2022 by 20% and 14%, while total N and NH_4 increased by 14% and 215%, respectively. Soil M3-P and pH did not significantly differ between years.

Significant interactions (amendment × year, manure application status × year, amendment × manure application status) occurred only for NO_3-N (Figure 2). Soil NO_3-N did not significantly differ between amendments in 2021 but was reduced by 168% on non-manured compared to manured plots. In 2022, both PE and VR treatments had 160% and 197% greater soil NO_3-N, respectively, compared to the controls. However, there was no longer a significant difference based on previous manure application status. In non-manured plots, NO_3-N was greater in 2022 compared to 2021. Pooling 2021 and 2022, the only significant difference occurred

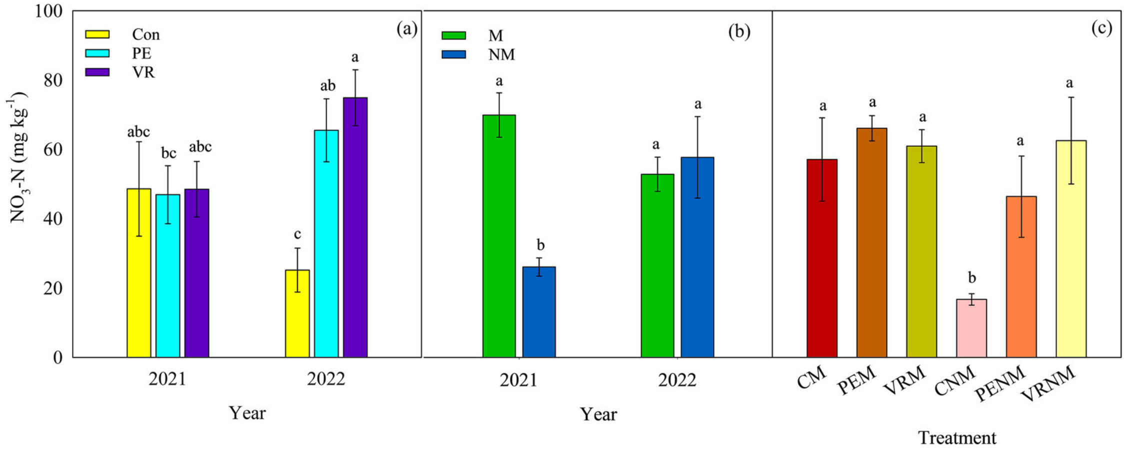

FIGURE 2 Soil NO_3-N (0–15 cm) (a) amendment and (b) manure application status compared across years. (c) Treatment averages pooled from 2021 and 2022. Treatment codes are as follows: Control (Con), P-enriched solids (PE), mechanical vapor recompression solids (V), previous manure application (M), and no manure application (NM). Samples were collected on July 1, 2021 and 2022. Significant treatment differences are indicated by differing letters within panels.

with the non-manured control plots, which had 250% less soil NO_3-N compared to all other treatments.

Significant increases in SOC, total N, NO_3-N, and P following manure application have been widely reported and are further supported by the results of this study (Bierer et al., 2022; Butler & Muir, 2006; Dungan et al., 2023; Edmeades, 2003; Ozlu et al., 2019). In the first year of the study, previous manure application acted as the primary driver of increased SOC, facilitating enhanced microbial activity and thus greater N-mineralization. This enhanced mineralization is also supported with the decrease in SOC from 2021 to 2022 as the C from the initial solid manure application was utilized by the microbial community. Dungan et al. (2022) demonstrated, on an adjacent field, that manure application increased labile C and enzyme activities related to C and N cycling (β-glucosidase and β-glycosaminidase) by two- and fourfold, respectively, compared to control or fertilizer plots. Additionally, potential ammonia oxidation increased 3.8-fold in manured versus control soils, suggesting that as manure mineralization takes place, NH_4-N is converted quickly to NO_3-N in manured plots. In the present study, this is likely reflected in the 15% decrease in NH_4-N on manured plots compared to non-manured plots due to increased rates of nitrification. Leytem et al. (2024) also reported that soils receiving eight annual applications of manure, at a similar rate to the present study (on adjacent field), that NH_4-N only increased 37%, while NO_3-N increased 242% on manure versus fertilizer plots suggesting that conversion of NH_4-N to NO_3-N occurs quickly.

Soil NO_3-N levels clearly reflect the differing treatment trends over time, with significant differences based on previous manure application occurring in the first year (2021) and amendments in the second year (2022). Lack of significant differences in total soil N between amendments may be due to high residual N from the previous alfalfa crop. Studies have shown that manure treatment technologies, particularly AD and liquid-solid separation, can slow decomposition rates compared to untreated manure (Khalil et al., 2016; Lentz & Ippolito, 2012). In this study, manured plots had 55% greater 24 h respired CO_2 compared to NM plots regardless of amendment, reflecting greater microbially available C from the manure application (Table 4). While generally greater on M plots, PE and VR solids had 5% less 24 h respired CO_2 compared to the control on manured plots, which may be due to increased salt content due to the combined application of manure and manure-based fertilizers (Yan & Marschner, 2013). On non-manured plots, respired CO_2 was 17% and 61% greater with PE and VR solids, respectively, compared to the control which may reflect the different decomposition rates between the PE and VR solids.

3.2 | Corn silage and triticale yields

Corn silage and triticale yields are reported in Table 5. In 2021, a 7% reduction in corn silage yield was observed in manured relative to non-manured plots. In 2022, significant interactions between manure application status and amendment occurred for corn silage. Significant differences only occurred between VR solids and control on non-manured plots, with VR solids having 17% greater yields. For triticale, manured plots had 13% greater yields compared to non-manured plots in 2022. In 2023, a significant interaction between manure application status and amendments did occur, with yields generally being greater on manured plots compared to non-manured plots. Control plots with manure had the greatest yields, being 1.7–3.4 times greater than non-manured PE and control plots. Both VR treatments and

TABLE 5 Average yields adjusted to standard moisture (65% for corn silage; 70% for triticale) for 2021—2023.

Crop	Treatment	2021 (Mg ha^{-1})	2022 (Mg ha^{-1})	2023 (Mg ha^{-1})
Corn silage				
	M	47.6 b	57.9	–
	NM	51.4 a	57.6	–
	p-value	**	n/s	
	ConM	46.6	58.6 ab	–
	PEM	47.3	56.7 ab	–
	VRM	48.9	58.4 ab	–
	ConNM	52.3	52.1 b	–
	PENM	51.8	59.5 ab	–
	VRNM	50.1	61.1 a	–
	p-value	n/s	*	
Triticale				
	M	–	15.0 a	14.2
	NM	–	13.2 b	9.3
	p-value		**	***
	ConM	–	14.5	16.8 a
	PEM	–	15.5	12.9 ab
	VRM	–	15.1	12.8 ab
	ConNM	–	11.7	4.9 c
	PENM	–	13.6	9.8 b
	VRNM	–	14.4	13.3 ab
	p-value		n/s	***

Note: Significant differences are denoted for $p < 0.05$, $p < 0.01$, and $p < 0.0001$ as *, **, and ***, respectively. Significant treatment differences are indicated by differing letters, with comparison grouped by crop and year. Treatment codes are as follows: control (Con), P-enriched solids (PE), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM).

manured PE treatments had 165% greater yields compared to the non-manured control.

Previous manure application was the predominant source of significant differences for corn yield in 2021 and triticale yield in 2022, likely the result of increased available N from fall manure application. Yield response to manure application can be varied, with a response more likely to occur when soil N concentrations do not meet crop needs or in water-constrained environments where applied organic matter (OM) improved soil water retention and alleviated crop water stress (Arriaga & Lowery, 2003; Baxter et al., 2023; Butler & Muir, 2006; Eghball & Power, 1999; Lentz & Ippolito, 2012). While OM application can lead to increased soil nutrient concentrations and promote microbial activity, as observed in this study (Tables 3 and 4), it can also result in increased soil salinity which can negatively impact crop yields at high enough concentrations (Butler et al., 2008). In this study, soil EC ranged from 0.6 to 1.6 mS cm^{-1} in 2021 and 0.5 to 0.9 mS cm^{-1} in 2022, which is well below the recommended threshold tolerance for field corn reported for the region (3–6 mS cm^{-1}; Brown et al., 2010). However, salt stress may have differing effects at various corn growth stages. Maas et al. (1983) reported EC up to 10 mS cm^{-1} was satisfactory for corn germination, but that maximum EC thresholds for dry matter growth at 21 days were 1.0 mS cm^{-1}. In this study, manured plots had an average EC of 1.5 mS cm^{-1} in 2021, which was 123% greater than NM plots and may have slowed growth during the early growth stages resulting in the 7% decrease in corn silage yields seen that year. Additionally, the minor yield decrease may have been the result of differences in weed presence or soil moisture status; however, data were not collected for those measurements.

3.3 | Daily gas fluxes, seasonal trends, and cumulative annual emissions

Daily gas fluxes are shown in Figure 3. For both 2021 and 2022, the greatest flux events and monthly emissions occurred throughout the summer months, with peak fluxes occurring immediately following the first irrigation event after corn planting (June 7, 2021; June 28, 2022). Average summer N_2O-N emissions (June–August) were 513% greater than average spring emissions (March–May), and 1241% greater than average fall/winter emissions (September–December). In both years, VR solids had the greatest flux event for N_2O-N (354.5 and 346.0 g ha^{-1} day^{-1} for 2021 and 2022, respectively). For all but the first peak flux event, PE and VR solids had significantly greater fluxes, ranging from 193% to 540% increases, compared to the controls. Previous manure application significantly impacted N_2O-N fluxes during the first two peak events, with previous manure application resulting in 503% and 60% increases for 2021 and 2022, respectively.

The monthly percentages of applied N lost as N_2O-N were calculated by dividing the monthly cumulative emissions (kg N_2O-N ha^{-1} month^{-1}) by the annual total applied N (kg ha^{-1} year^{-1}) and are shown in Figure 4. Relative to the amount of N applied, non-manured PE and VR solids consistently had greater percent losses as N_2O-N compared to plots with previous manure application. In 2021, %$N_{applied}$ lost as N_2O-N from previously manured PE and VR solids was 64%–67% less than from plots with no previous manure application. In 2022, statistical differences were only observed in January and February due to the large amount of variability in later months. Where differences were observed, treatments that received a previous manure application had 320%–344% greater emissions than non-manured treatments, relative to total applied N.

Cumulative annual emissions are reported in Table 6. Trends in annual emissions were similar between years, with VR solids having the greatest annual N_2O-N emissions. VR solids had 52% and 153% greater N_2O-N emissions

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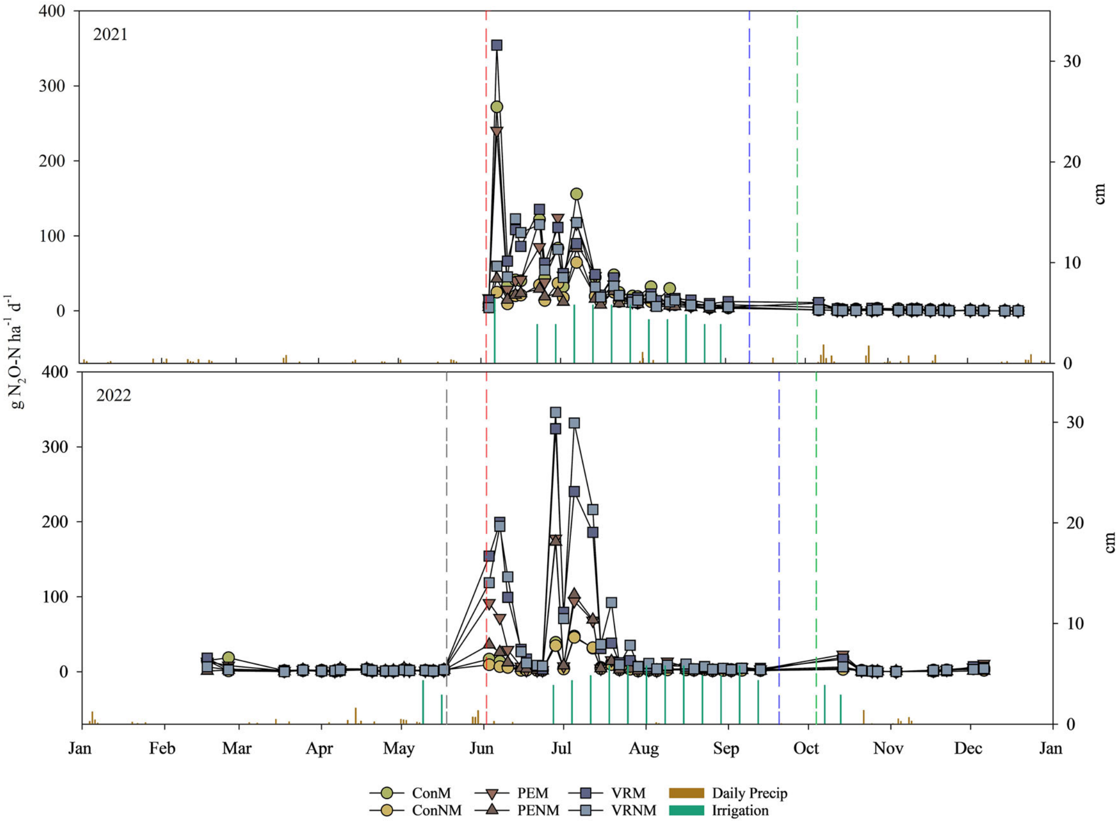

FIGURE 3 Daily gas fluxes for 2021 and 2022 by treatment along with daily precipitation and irrigation events. Crop planting and harvest dates are indicated on the figures with vertical lines. Red dashed lines indicate corn planting dates, and blue dashed lines indicate corn harvest dates. Green dashed lines indicate triticale planting dates, and grey dashed lines indicate triticale harvest dates. Treatment codes are as follows: control (Con), P-enriched solids (PE), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM).

compared to both PE solids and the control in 2021 and 2022, respectively. For both years, manured plots had significantly greater N_2O-N emissions compared to non-manured plots, with differences being greater in 2021 versus 2022. Compared to non-manured treatments, manured treatments had 92% greater N_2O-N annual emissions in 2021, and 46% greater N_2O-N annual emissions in 2022.

Overall seasonal gas flux trends likely reflect seasonal changes in soil and air temperature, and soil moisture throughout the growing season. Increased temperature leads to increased soil microbial activity (Adviento-Borbe et al., 2007; Dungan et al., 2017; Leytem et al., 2013), which enhances microbial respiration and decomposition of organic matter. While N-availability and application rate are major factors in overall emissions, the main drivers in pulse event N_2O-N correspond to air and soil temperature, water-filled pore space (WFPS), and cumulative precipitation/irrigation occurring throughout the season (Adviento-Borbe et al., 2007; Sehy et al., 2003). Nitrous oxide emissions depend on a balance of nitrification and denitrification, with process dominance shifting based on soil saturation, WFPS, and increasing temperatures (Oertel et al., 2016). Previous studies have shown that while N_2O-N emissions increase following fertilizer application, the highest N_2O-N fluxes occur following an irrigation or precipitation event where soil water content increases and promotes microbial denitrification (Dungan et al., 2017; Sehy et al., 2003). A considerable proportion of cumulative annual emissions in the present study was observed after initial irrigation events each year. Across both years, VR solids produced 33%–53% of estimated annual N_2O-N within the first three irrigation events, which is an additional 15%–17% N_2O-N compared to the control. Comparatively, PE solids produced 27%–45% of estimated annual N_2O-N within the same time period, which is an additional 2%–13% compared to the control.

The shift in prevalent treatment response from previous manure application in 2021 to manure byproduct treatment in 2022 likely reflects a combination of the lag time between the initial manure application (November 5, 2020) and the subsequent gas measurement (June 6, 2021) in addition to total N applied from PE and VR solids. Applications of organic matter amendments have been associated with increased emissions of N_2O-N (Akiyama & Tsuruta, 2003; Akiyama et al., 2004; Dungan et al., 2017). However, the flux response

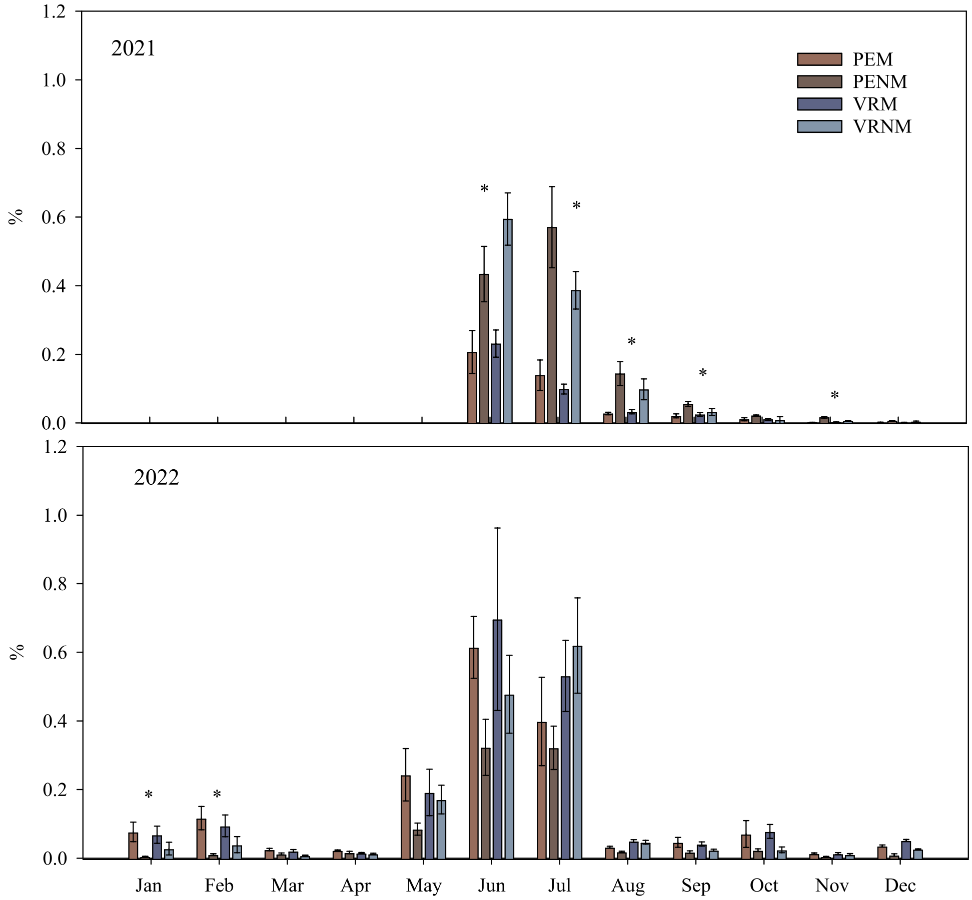

FIGURE 4 Percent of applied N lost monthly as N_2O-N for 2021 and 2022 by treatment. Treatment codes are as follows: P-enriched solids (PE), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM). Percent of applied N lost as N_2O-N was calculated as follows: [(monthly cumulative N_2O emissions)/(total applied N)] × 100. Months with significant treatment differences are denoted with "*".

TABLE 6 Annual cumulative emissions of N_2O-N for 2021 and 2022.

Treatment	2021[a] (kg ha^{-1} year^{-1})	2022[b] (kg ha^{-1} year^{-1})
Con	3.4 b	2.2 b
PE	3.1 b	3.8 b
VR	4.9 a	7.6 a
p-value	**	**
M	5.0 a	5.4
NM	2.6 b	3.7
p-value	***	*

Note: Significant differences for $p < 0.05$, $p < 0.01$, and $p < 0.0001$ are denoted as *, **, and ***, respectively. Significant treatment differences are indicated by differing letters, with comparisons grouped by year. Treatment codes are as follows: control (Con), P-enriched solids (P), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM).
[a]Total of 40 sampling days between June 4 and December 20. [b]Total of 49 sampling days between February 17 and November 22.

often depends on a combination of environmental factors such as temperature, soil moisture and WFPS, manure nutrient concentrations and application rates, soil nutrient status, and site management practices (Adviento-Borbe et al., 2007; Asgedom et al., 2014).

In the present study, as discussed above, the addition of manure increased SOC and likely labile C which enhances microbial activity. This addition of labile C with manure, coupled with relatively fast nitrification in these soils, can lead to high rates of N_2O-N production as nitrification is usually the dominant process generating N_2O in the semi-arid, aerobic conditions of the region. Dungan et al. (2022) reported that addition of manure enhanced denitrification enzyme activity by 2.9-fold compared to control treatments on adjacent plots. In addition, irrigation events throughout the growing season can lead to temporary periods of soil saturation that promote denitrification.

To better represent the manure application rates used by producers in the region, application rates of VR and PE solids were determined using a "P-banking" method based on the estimated total crop P removal throughout the course of the study. As a result, total N applied differed between treatments (USDA-NRCS, 2013). While synthetic N was applied

TABLE 7 Average N_2O emission factors for 2021 and 2022 and 2-year total.

Treatment	2021	2022	Total
	% $N_{applied}$ lost		
PEM	−0.1	0.9	0.8
PENM	0.04	0.3	0.4
VRM	0.1	1.8	1.9
VRNM	0.6	1.6	2.2

Note: Emission factors for each treatment were calculated by subtracting the total annual N_2O-N of the control from the total annual N_2O-N of treatment, and then dividing by the total applied N. Treatment codes are as follows: P-enriched solids (PE), mechanical vapor recompression solids (VR), previous manure application (M), and no manure application (NM).

as needed to meet corn needs, VR solids had 33%–43% more total N applied compared to PE solids across both years. This increase in potentially mineralizable N is partially accountable for the additional 287%–346% N_2O-N fluxes with VR solids seen during the growing season compared to PE solids. However, despite the differences in total applied N, the percent of $N_{applied}$ lost each month as N_2O-N primarily differed based on previous manure application for both years. The greater loss of applied N from non-manure treatments in 2021 likely reflects the delay in N-availability as the organic-N from the applied manure undergoes mineralization over time.

Annual EFs, which are commonly used in GHG inventories, are shown in Table 7. The EF values were 23.2 and 2.8 times greater from VR solids compared to PE solids for 2021 and 2022, respectively. For both years, the difference between VR and PE solids was greatest on non-manured plots compared to manured plots. The use of P-based application rates resulted in different amounts of applied N from the PE and VR solids, which may have contributed to the differences in EFs. Regardless of previous manure application, VR solids applied 2.5 and 1.3 times as much N as PE solids in 2021 and 2022, respectively. All EFs were under the IPCC emission factor of 1% (Calvo Buendia et al., 2019) in 2021, but VR solids exceeded this threshold in 2022, regardless of previous manure application. For all treatments, the EFs increased substantively from 2021 to 2022 (0.31%–1.8%).

4 | SUMMARY

Addition of manure was the prominent driver of significant differences in soil nutrient concentrations, GHG emissions, and forage yields. Within the manure-based fertilizer products, VR solids consistently had the greatest N_2O-N flux events and cumulative emissions while PE solids were more consistently comparable to background emissions seen with the control treatments. Larger N_2O-N fluxes observed from the VR product may partially be related to a higher total N application rate under the P-banking fertilization approach utilized. Nevertheless, VR solids consistently had a greater emission factors (net percent of $N_{applied}$ lost as N_2O-N), with losses exceeding the IPCC emission factor of 1% following 2 years of application. In regions with nutrient imbalances where advanced manure treatment is necessary to export nutrients, nutrient extraction technologies can produce manure-based fertilizer products that are beneficial for plant growth but may have different susceptibilities to N losses, which need to be considered when managing these products.

AUTHOR CONTRIBUTIONS

Abigail E. Baxter: Data curation; formal analysis; investigation; writing—original draft. **April B. Leytem**: Conceptualization; investigation; resources; supervision; writing—review and editing. **Dan Liptzin**: Conceptualization; data curation; funding acquisition; methodology; project administration; writing—review and editing. **Andrew Bierer**: Data curation; writing—review and editing. **Reza K. Afshar**: Conceptualization; funding acquisition; project administration; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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