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Graig W. Reicks

David E. Clay

Sharon A. Clay

Deepak R. Joshi

Janet Moriles-Miller

See next page for additional authors

Authors

Graig W. Reicks, David E. Clay, Sharon A. Clay, Deepak R. Joshi, Janet Moriles-Miller, Shaina Westhoff, Aaron Lee M. Daigh, and Stephanie A. Bruggeman

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Graig W. Reicks[1] | David E. Clay[1] | Sharon A. Clay[1] | Deepak R. Joshi[1] | Janet Moriles-Miller[1] | Shaina Westhoff[1] | Aaron Lee M. Daigh[2] | Stephanie A. Bruggeman[3]

[1] Dep. of Agronomy, Horticulture, and Plant Science, SD State Univ., Brookings, SD, 57007, USA

[2] Soil Science Dep., ND State Univ., Fargo, ND, 58108-6050, USA

[3] Biology Dep., Augustana Univ., Sioux Falls, SD, 57197, USA

Correspondence

D.E. Clay, Dep. of Agronomy, Horticulture, and Plant Science, South Dakota State Univ., Brookings, SD, 57007, USA

Email: david.clay@sdstate.edu

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Abstract

Despite differences between the cover crop growth and decomposition phases, few greenhouse gas (GHG) studies have separated these phases from each other. This study's hypothesis was that a living cover crop reduces soil inorganic N concentrations and soil water, thereby reducing N_2O emissions. We quantified the effects of a fall-planted living cereal rye (*Secale cereale* L.) cover crop (2017, 2018, 2019) on the following spring's soil temperature, soil water, water-filled porosity (WFP), inorganic N, and GHG (N_2O-N and CO_2–C) emissions and compared these measurements to bare soil. The experimental design was a randomized complete block, where years were treated as blocks. Rye was fall planted in 2017, 2018, and 2019, but mostly emerged the following spring. The GHG emissions were near-continuously measured from early spring through June. Rye biomass was 1,049, 428, and 2,647 kg ha^{-1} in 2018, 2019, and 2020, respectively. Compared to the bare soil, rye reduced WFP in the surface 5 cm by 29, 15, and 26% in 2018, 2019, and 2020 and reduced soil NO_3–N in surface 30 cm by 53% in 2019 (p = .04) and 65% in 2020 (p = .07), respectively. Rye changed the N_2O and CO_2 frequency emission signatures. It also reduced N_2O emissions by 66% but did not influence CO_2–C emissions during the period prior to corn (*Zea mays* L.) emergence (VE). After VE, rye and bare soils N_2O emissions were similar. These results suggest that nitrous oxide (N_2O-N) sampling protocols must account for early season impacts of the living cover.

1 | INTRODUCTION

Cover crops can have many positive effects on soil health (SARE, 2007; Smeltekop et al., 2002), and mixed impacts on greenhouse gas (GHG) emissions (Antosh et al., 2020; Basche et al., 2016; Çerçioğlu et al., 2019) and soil productivity (Bich et al., 2014; Reese et al., 2014). The mixed effect of cover crops on GHG emissions is difficult to assess because early-season emissions are often undersampled and many experiments do not provide critical information, such as bulk density, NO_3–N and NH_4–N concentrations, and soil water contents (Abdalla, et al., 2014; Mitchell et al., 2013; Ruis et al., 2018; Sanz-Cobena et al., 2014; Wegner, et al., 2018).

Interpreting conflicting results can result in mixed messages that slows conservation practice adoption (Wang et al., 2020). To reduce this barrier, we need to improve our

Abbreviations: CO_2, carbon dioxide; FFT, fast Fourier transform; GHG, greenhouse gas; N_2O-N, nitrous oxide; WFP, water-filled porosity.

understanding of the cover crop system. One approach to accomplish this goal is to separate the growing season into two distinct phases, growth and decomposition. During cover crop growth, nutrients are scavenged from soil and water is transpired, whereas during decomposition, nutrients are returned, and the cover crop mulch can reduce evaporation. The stark differences between growth and decomposition may partially explain the mixed impacts of cover crops on GHG emissions (Johnson & Barbour, 2019; Nielsen et al., 2015; Seiz et al., 2019; Shan & Yan, 2013). However, this explanation cannot be confirmed because little research has been conducted exclusively during the cover crop growth phase (Basche et al., 2014; Han et al., 2017). Therefore, this study quantified the influence of an unfertilized growing rye (*Secale cereale* L.) cover crop on soil temperatures, soil moisture, inorganic N, the N_2O frequency emission signatures, and total nitrous oxide (N_2O-N) and CO_2–C emissions in a well-drained frigid soil from the start of growth in April/May through termination in late June.

Core Ideas

- Rye reduced N_2O-N emissions 66% during the period prior to corn emergence.
- Nitrous oxide emission reductions were attributed to a decrease in soil water and inorganic N.
- Rye changed the N_2O-N and CO_2–C frequency emissions signatures.
- These findings show that sampling protocols must account for early season growth.

2 | MATERIALS AND METHODS

2.1 | Experimental design and treatments

Rye was planted in the fall of 2017, 2018, and 2019 in field studies conducted near Aurora, SD (44°18′20.57″ N, 96°40′14.04″ W). The site was located on the border between the Bsh (semi-arid) and DFa (continental wet all seasons) Köppen climate groups and the soil had a frigid temperature regime. The soil at the site was a Brandt silty clay loam (fine-silty, mixed, superactive frigid Calcic Hapludoll), and the surface soil (15 cm) contained 280 g clay kg^{-1} (28%), 65 g silt kg^{-1} (65%), 7 g sand kg^{-1} (7%), and 36 Mg ha^{-1} (1.8%) of soil organic carbon (SOC). The no-tillage first-order rate constant and half-life of SOC for this soil were 0.00675 kg (kg C × year)$^{-1}$ and 103 yr, respectively (Clay et al., 2015). The soil $pH_{water\ 1:1}$ was 5.8, and the soil parent materials were loess (0–60 cm) over glacial outwash. The surface soil hydraulic conductivity was 0.72 m d^{-1} and the slope was between 0 and 2%. Additional information about the study site is available in Thies et al. (2020) . Rainfall was determined based on data collected at the site. Our study was not irrigated and following cover crop seeding it was not cultivated. Prior to the study, the long-term rotation was corn (*Zea mays* L.) followed by soybean [*Glycine max* (L.) Merr.].

Four experimental units, each consisting of a PVC pipe covering 317 cm^2, were driven into the soil to a depth of 14 cm with about 6.3 cm of the pipe extending above the soil surface. The pipes were spaced about 1.5 m apart. The surface 2.5 cm was cultivated in all four pipes and rye was hand-planted inside two of them chosen at random at 56 kg ha^{-1} (39,500 seeds kg^{-1} or 220 seeds m^{-2}) on 20 Oct. 2017, 16 Oct. 2018, and 23 Oct. 2019. Planting depth was 2.5 cm. Fertilizer was not applied, residue cover was minimal, and all soils were exposed to the prevailing climatic conditions. Seed emergence was monitored in late November each year and 17, 15, and 36% of the planted seeds emerged in 2017, 2018, and 2019, respectively.

The following discussion is intended to provide a reference for the system that simulated GHG emissions prior to the emergence of the cash crop. Because a cash crop was not seeded into the study area, the changes in GHG emissions and soil properties were attributed to rye. In the region, corn is generally planted between the last week of April and the 3rd week of May. However, the date varies, and it is based on the last day of expected frost, which is between 13 and 14 May, soil temperatures, and moisture content. Cover crops and other weeds are generally killed prior to the critical weed-free period of corn (from VE to V5). However, in some situations, cover crop control may be delayed or not conducted if conditions are not conducive for planting the cash crop. Under these conditions, the cover crop biomass can be harvested for other purposes.

The cover crop growth period was separated into three sampling intervals (Table 1). At the end of each interval, the rye was clipped near the soil surface to allow the chamber lid to close and to simulate grazing. During the first interval, rye emerged, and the interval ended prior to corn emergence (VE). For most of the farmers in the region, the cover crop growth would be terminated at the completion of this interval. Emergence dates were calculated by assuming the seed would not be planted until the risk of frost damage for corn was reduced (soil temperature >10°C) and the soil moisture was <0.33 cm^3 cm^{-3}. A formula from Nleya et al. (2016) was used to calculate growing degree days (GDD) for corn (lower limit 10 and upper limit 30 °C). These authors also reported that approximately 51.7 GDD were needed for corn seeds to germinate and emerge.

During the second interval, the cover crops continued to grow and based on accumulated GDD, corn plants at the end of the second interval would have been between the V2 and

TABLE 1 The relationship between the experiment events and corn growth periods. Clip 1 provides a reference for early season greenhouse gas emissions prior to corn emergence, whereas clips 2 and 3 provide a reference for delayed control, grazing, or seeding

Reference period	Events	2018	Days of sampling	2019	Days of sampling	2020	Days of sampling
Start measurement		7 May		26 Apr.		8 Apr.	
Prior to VE	clip 1	25 May	18	13 May	17	4 May	26
VE to corn at V2	clip 2	15 June	21	29 May	16	29 May	25
V2–V5	clip 3	3 July	18	24 June	26	26 June	28

V3 growth stages. In our region, cover crop growth through the second interval would be considered delayed control and may be suitable for crops that are seeded later than corn, such as soybean. The third interval ranged from V2 or V3 to V5 or V6 and probably would not be part of a corn or soybean production system.

2.2 | Carbon dioxide and nitrous oxide emissions

Greenhouse gas emissions measurements were initiated in the spring as soon as it was physically possible to set up measuring equipment in the field. LI-COR LI-8100-104 long-term opaque chambers (8100-104 LI-COR) were used to measure emissions. Each of the four chambers covered an area of 317 cm^2. Prior to sampling, the cover pivoted over the PVC pipe, creating an enclosed volume. Gas samples were collected for 15-min six times daily (between 0000 and 0230 h, 0400 and 0630 h, 0800 and 1030 h, 1200 and 1430 h, 1600 and 1830 h, and 2000 and 2230 h). At each gas sampling event, the chambers were sampled in a designated sequence, and corrections were applied to each individual chamber to account for air volume differences. During the individual sampling event, the gas within the chamber was mixed with a pump, a vent was used to equalize the chamber and atmospheric pressures, and thermistor measured the air temperature.

Gas drawn from the chamber was analyzed for N_2O-N and CO_2–C concentrations every second, for a total of 900 measurements, using a Picarro Cavity Ringdown Spectrometer (model G2508; Picarro Inc.). Based on each chamber's volume, N_2O-N emissions were calculated with data obtained between 45 and 900 s, whereas CO_2–C emissions were determined with data obtained between 45 and 165 s, both using 4.01 LI-COR SoilFluxPro software (v. 4.01; LI-COR). To assess accuracy, standard gases were used prior to and at the completion of all experiments. Adjacent to the chambers in an identically treated area, soil moisture and temperatures for the surface 5 cm were measured using LI-COR LI-8150-205 Soil Moisture Probes (LI-COR) and LI-COR LI-8150-203 Soil Temperature Probes (LI-COR), respectively.

Emissions were measured from 7 May to 3 July 2018, 26 Apr. to 24 June 2019, and from 8 Apr. to 26 June 2020 (Table 1). When rye reached a height of 15 cm, plants were clipped to 3-cm height, which occurred three times each year. At each clipping date, rye biomass was dried, weighed, ground, and analyzed for total N and C using a stable isotope C and N analyzer (Clay et al., 2015).

2.3 | Soil sampling

In 2018, 2019, and 2020 soil samples from the 0-to-15- and 15-to-30-cm soil depths were collected with a 2-cm diam. soil probe. For each experimental unit, an area outside of the GHG chambers was sampled when GHG sampling was initiated (Table 1). When the study was completed, soil samples from within the chambers at the same depths were collected. Each composite sample consisted of eight soil cores that were frozen until analysis. A subsample was analyzed for gravimetric moisture content by drying the soil samples to a constant weight at 105 ˚C. The bulk densities for the 0-to-15- and 15-to-30-cm depths in 2018 were 1.33 and 1.32 g cm^{-3}, respectively. In 2019, the bulk densities for the 0-to-15- and 15-to-30-cm depths were 1.31 and 1.28 g cm^{-3}. In 2020, the bulk densities for those same depths were 1.33 and 1.29 g cm^{-3}. Based on the measured bulk densities and volumetric moisture contents, the percentage WFP was determined. This calculation assumed that the soil particle density was 2.65 g cm^{-3}. Soil samples were dried at 40 ˚C, ground (<2 mm) and analyzed for NH_4^+–N and NO_3^-–N (Clay et al., 2015).

2.4 | Statistical analysis

Based on 5,400 measurements from each chamber over a 24-h period, daily N_2O-N and CO_2–C emissions were determined. Due the large number of measurements, we conducted an analysis to determine the replication requirements. This analysis is available in Thies, et al. (2019). To demonstrate differences between the sampling systems we compared average daily emissions from samples collected between 0930 and 1030 h with near continuous measurement. The variances, which were different at $p < .001$ for near continuous measurement and point sampling between 0930 and 1030 h, were 0.00768 and 0.0227, respectively. This analysis

TABLE 2 The total precipitation, rye biomass produced, and growing degree days (GDD) for each sampling interval, and average water-filled porosity (WFP) of the bare soils and the rye cover crop during the sampling intervals in 2018, 2019, and 2020. The 95% confidence intervals are provided

Sampling intervals	Precipitation	Growing degree days	Dry rye biomass	C in rye biomass	N in rye biomass	Average WFP bare soil	Average WFP rye
2018	cm	°C	kg ha^{-1}			cm^3 cm^{-3}	
7 May–25 May	2.59	132	279 ± 15.67			0.74 ± 0.039	0.60 ± 0.0587
26 May–15 June	2.13	240	392 ± 25.45			0.54 ± 0.0784	0.42 ± 0.0195
16 June–3 July	10.31	225	378 ± 11.76			0.74 ± 0.0282	0.52 ± 0.0441
Total	15.03	597	1,049	452	46		
2019							
26 Apr.–13 May	7.09	25	106 ± 10.77			0.524 ± 0.021	0.583 ± 0.025
14 May–29 May	8.05	64	69 ± 11.34			0.613 ± 0.0369	0.665 ± 0.035
30 May–24 June	5.44	232	253 ± 19.38			0.511 ± 0.0103	0.435 ± 0.0306
Total	20.58	321	428	190	17.7		
2020							
8 Apr.–4 May	0.51	78	951 ± 7.7			0.441 ± 0.014	0.248 ± 0.0164
5 May–29 May	8.46	112	883 ± 24.7			0.595 ± 0.0111	0.439 ± 0.013
30 May–26 June	7.80	291	843 ± 71.1			0.423 ± 0.013	0.306 ± 0.016
Total	16.8	481	2,647	1,085	90		

showed that the daily N_2O-N variances were reduced 300% by converting from point to near continuous measurements. If the replication requirement (n) was calculated with the equation, $n = (4s^2/B^2)$, where s^2 is the variance and B is the bound of the estimation error, then the measured variances decreases would have produced a corresponding decrease in the replication (n) requirement. Based on this analysis, the experimental protocol used in this experiment was designed and tested (Thies, et al., 2020).

The experimental model was a randomized block design, where the 3 yr were treated as blocks. Each treatment within a year was replicated twice. Years (i.e., blocks) and cover crop treatments were fixed effects. The model was years, treatments, and year × treatment interaction (R Core Team, 2017). Our hypothesis was that the growing rye plant reduced soil moisture and N_2O-N emissions and increased CO_2–C emissions.

A fast Fourier transform (FFT) was conducted on soil temperatures, N_2O-N, and CO_2–C emission to determine the FFT frequency signatures (Klingenberg, 2005). The FFT frequency signature is composed of frequencies each with a magnitude and is often used to assist in interpreting repeating complex data sets (Brummell et al., 2014 ; Krijnen et al., 2013). Each frequency represents a repeating function, and the magnitude provides information on the relative importance of that frequency. Frequencies with larger magnitudes explain more of the variability. To determine the relative importance of different frequency regions, the FFT were separated into two regions, 0.75–0.85 and 0.98–1.01 cycles d^{-1}. The average value of the magnitudes for the 0.75–0.85 cycles d^{-1} was arbitrary and provided a benchmark for nondiurnal cycles and the average value of the magnitudes for the 0.99–1.01 cycles d^{-1} provided a reference for diurnal cycles. The averages and confidence intervals of the magnitudes within these frequencies were determined.

3 | RESULTS AND DISCUSSION

3.1 | Biomass production, inorganic N, precipitation, moisture, and temperature

Rye biomass production was highest in 2020 and lowest in 2019 (Table 2). The low 2019 yields were attributed to cool and wet conditions (25 GDD from 26 April to 13 May) which hampered rye growth and development. Because rye does not have the ability to fix atmospheric N_2, the N contained in the biomass was derived from N provided by the soil.

In 2018, the initial NO_3–N and NH_4–N amounts in the surface 30 cm were 3.7 and 6.68 ± 0.57 mg kg^{-1}, respectively, and when rye was terminated on 3 July 2018 the NO_3–N concentrations in the soil and rye treatments were similar but numerically lower in the rye (7.11 ± 0.91 mg kg^{-1}) than soil (9.03 ± 2.94 mg kg^{-1}) treatments. At termination, the NH_4–N concentrations in the soil and rye treatments were similar and the average concentration was 5.41 ± 0.83 mg kg^{-1}. In 2019 when the experiment was initiated the initial NO_3–N concentration (26 April) was 14.3 ± 7.3 and the initial NH_4–N concentration was 20.3 ± 4.75 mg kg^{-1}. When rye was terminated on 24 June 2019, the NO_3–N concentration in the soil was 8.66 ± 1.84 and it was 4.12 ± 0.26 mg kg^{-1} in the rye. However, rye did not influence the NH_4–N concentrations and was 10.3 ± 3.99 mg kg^{-1} in both treatments. In 2020, the NO_3–N and NH_4–N concentrations in the surface 30 cm prior to the study were 6.25 ± 1.22 and 43.6 ± 21 mg kg^{-1}, respectively. When the experiment was terminated on 26 June 2020, NO_3–N in the surface 30 cm was 7.11 ± 1.95 in the bare soil treatment and 2.5 ± 1.56 mg kg^{-1} in the rye treated soil. However, at termination rye did not influence NH_4–N concentration and was 2.8 ± 1.77 mg kg^{-1} in both treatments.

These findings show that large temporal changes in inorganic N occurred during the study. In 2018, NH_4–N concentrations were similar at the beginning and end of the study, whereas in 2019 NH_4–N concentrations decreased from 20.3 ± 4.75 to 10.3 ± 3.99. The largest decrease occurred in 2020 when NH_4–N concentrations decreased from 43.6 ± 21 to 2.82 ± 1.75. Decreases in NH_4–N concentrations over the study were attributed to nitrification and plant uptake. Nitrified N should have increased NO_3–N concentrations during the study. However, these increases would have been reduced by fixation, leaching, and plant uptake. Lower NO_3–N concentrations in the rye than soil treatments in 2019 and 2020 were attributed to plant uptake.

Temporal changes in inorganic N concentration are important because N_2O is emitted from nitrification and denitrification and the relationship between N additions and N_2O-N emissions may follow an 'S" shaped curve which can be mathematically described using a logistic model (Kim et al. 2011). Because rye utilized inorganic N, the effect of rye on N_2O emissions may have partially resulted from changes in enzyme efficiencies. The logistic model predicts that at low and high nitrate-N levels, small changes in nitrate can have a minimal impact on N_2O-N emissions. The predication for low N levels is attributed to increased efficiency of N_2O-N reductase (more of the N_2O is further reduced to N_2). Thomas et al. (2017) suggested that N_2O-N emissions are reduced when NO_3–N level decreased below 6 ppm and Millar et al. (2010) reported that a nonlinear relationship exists between N_2O-N emissions and N rate. The predication for high N levels is attributed to respiration being C limited as opposed to N limited. This hypothesis is supported by Weier et al. (1993), who showed that in C limited systems, adding additional N will not increase denitrification. Blackmer and Bremner (1978, 1979) also showed that denitrification efficiency is influenced by NO_3–N. Findings from Senbayram et al. (2012) also showed denitrification can be limited by C availability. However, not all experiments follow the logistic model (Eagle et al. 2017). Regardless of the model, logistic, exponential, or linear, all models predict that decreasing the N rate reduces N_2O-N emissions.

Soil moisture and precipitation also should be considered when evaluating GHG emissions because as soil pores fill with water, oxygen flux into the soil decreases. Decreases in

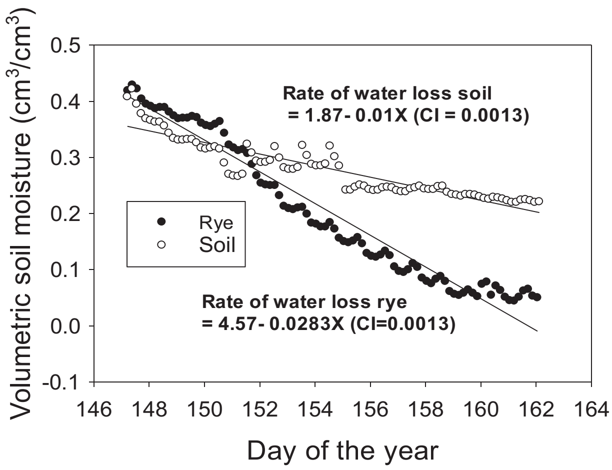

FIGURE 1 Soil moisture depletion in the surface 5 cm of soil between 26 May (146 day of the year) and 11 June (162 day of the year) in 2019. The rate of water loss [(cm^3 (cm^3×d)$^{-1}$] are shown from the bare soil and rye cover crop treatments. CI represents the 95% confidence interval

the oxygen flux can result in soil microbial communities that switch from aerobic to anaerobic respiration (Linn & Doran, 1984).

During the experiment, soil moisture was not constant and generally decreased between precipitation events. This decrease was attributed to drainage and evapotranspiration. For example, across years changes in soil moisture [*d*(soil moisture)] during the experiments could be explained by the equation, *d*(soil moisture) = −0.0116 + 0.0004 × rye biomass (kg ha^{-1}), $r = .79$, $p < .01$). Following precipitation soil moisture increased rapidly. In all 3 yr, there were intervals where the WFP was >60%. This value is the tipping point where Linn and Doran (1984) reported that respiration switches from aerobic to anaerobic. In 2018, between 7 and 25 May and between 16 June and 3 July, the WFP in the bare soil generally exceeded the 60% WFP (Table 2, Supplemental Table S1). However, rye reduced the WFP for these sampling intervals. In 2019, due to high rainfall, rye had a minimal effect on WFP between 26 April and 29 May (Supplemental Tables S1 and S2). However, as the season progressed and cover crop growth increased, and soil moisture contents decreased at a rate 2.8 times faster than bare soil (Figure 1). In 2020, the cover crop had lower WFP for all periods when compared with bare soil. These results were attributed to high biomass production and transpiration, especially from 8 Apr to 4 May.

The soil temperature in the surface 5 cm differed among years, and it was generally lower in 2019 than 2018 or 2020 (Supplemental Table S2). Across all years, the rye and bare soil treatments had similar soil temperatures. However, differences were observed at selected times. For example, between 26 April and 13 May in 2019 at 1000 and 1400 h, the soil temperatures in the rye treatment were generally higher than the

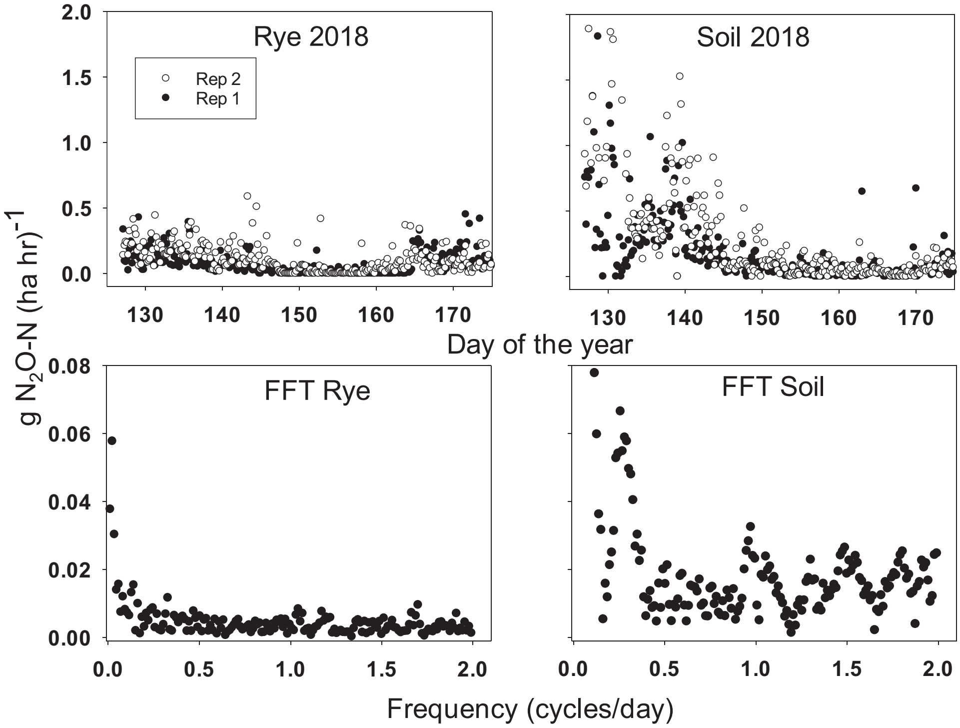

FIGURE 2 The 2018 (top) N_2O emissions) and (bottom) frequency emission signatures for the rye and bare soil treatments. For the frequency data, the magnitude is on the *y* axis and the frequency is on the *x* axis

TABLE 3 Analysis of the N_2O-N and CO_2–C frequency signatures. The average magnitudes for two frequency ranges (0.75 to 0.85 and 0.99 to 1.01 cycles d^{-1}) and the ratio between these magnitudes for the bare soil and rye treatments in 2018, 2019, and 2020. Confidence intervals for the 90% level are shown

		N_2O-N Frequency			CO_2–C Frequency		
		0.75-0.85	0.98 –1.01		0.75-0.85	0.98 –1.01	
Year	Treatment	g N_2O-N/ (ha×h)	g N_2O-N/ (ha ×h)	Ratio	g CO_2–C/ (ha×h)	g CO_2–C/ (ha×h)	Ratio
2018	Soil	0.011 ± 0.0019	0.031 ± 0.009	2.82	29.8 ± 6.97	99.4 ± 55.3	3.34
2018	Rye	0.0031 ± 0.00063	0.0025 ± 0.0013	0.81	27.9 ± 4.18	159.0 ± 64.8	5.7
2019	Soil	0.0071 ± 0.0019	0.0310 ± 0.0075	4.36	20.3 ± 5.72	70.4 ± 20.3	3.47
2019	Rye	0.0057 ± 0.0013	0.0081 ± 0.0044	1.39	38.5 ± 7.74	132.2 ± 59.9	3.43
2020	Soil	0.00935 ± 0.0031	0.0143 ± 0.0013	1.53	82.5 ± 23.8	85.3 ± 33.3	1.03
2020	Rye	0.0065 ± 0.00148	0.00440 ± 0.00143	0.67	67.2 ± 11.5	118 ± 2.84	1.76

bare soil, whereas in 2020 between 30 May and 26 June soil temperatures were cooler in the rye the bare soil. Temperature changes are important when evaluating GHG emissions because it influences gas solubility, equilibrium relationships, microbial activity, and plant growth.

3.2 | Nitrous oxide and carbon dioxide frequency emissions signatures

To determine if N_2O-N fluxes followed a predictable pattern, we conducted an FFT, which converts time domain data into the frequency domain. The transformation results in a series of frequencies and associated magnitudes (Figures 2, 3, 4). The size of the magnitude provides an assessment of the importance of each frequency. Across all 3 yr, rye reduced the magnitudes 80% for the frequencies between 0.98 to 1.01 cycle's d^{-1} and 42% for the frequencies between 0.75 to 0.85 cycle's d^{-1} (Table 3). In addition, across years, rye reduced the ratio 66% between the non-diurnal period (0.75 and 0.85) and the diurnal (0.98 and 1.01 cycles d^{-1}) period. The larger ratio for bare soil (2.9) than rye (0.95) indicates that bare soil had a stronger diurnal cycle for emissions than rye. We attributed these results to cover crop-induced differences in soil physical, chemical, and biological properties that were previously discussed. Others have seen

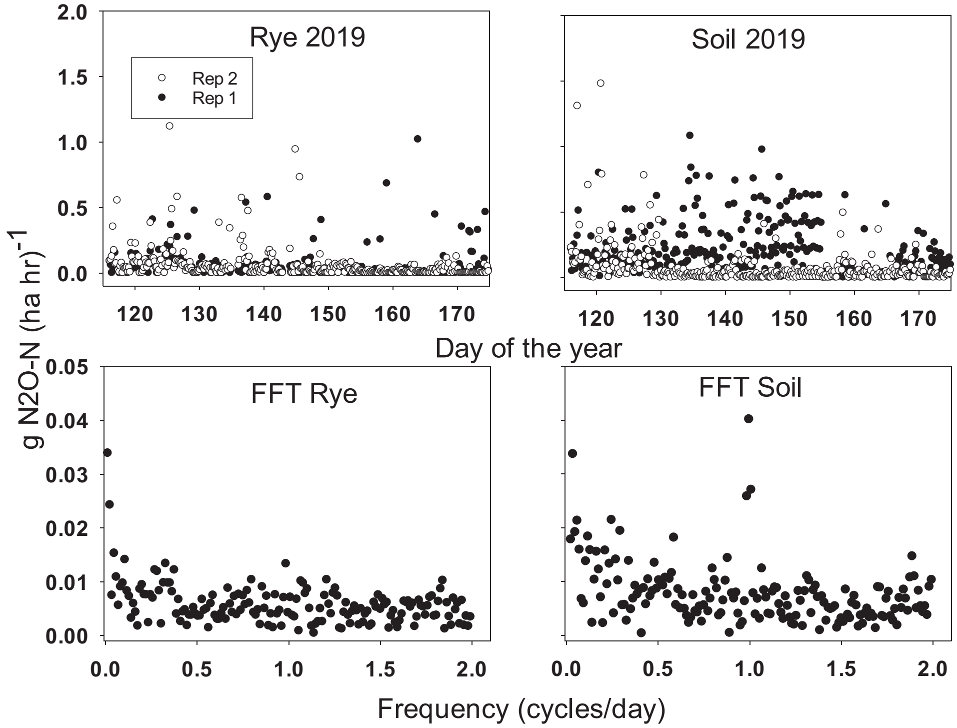

FIGURE 3 The 2019 (top) N_2O emissions and (bottom) frequency emission signatures for the rye and bare soil treatments. For the frequency data, the magnitude is on the *y* axis and the frequency is on the *x* axis

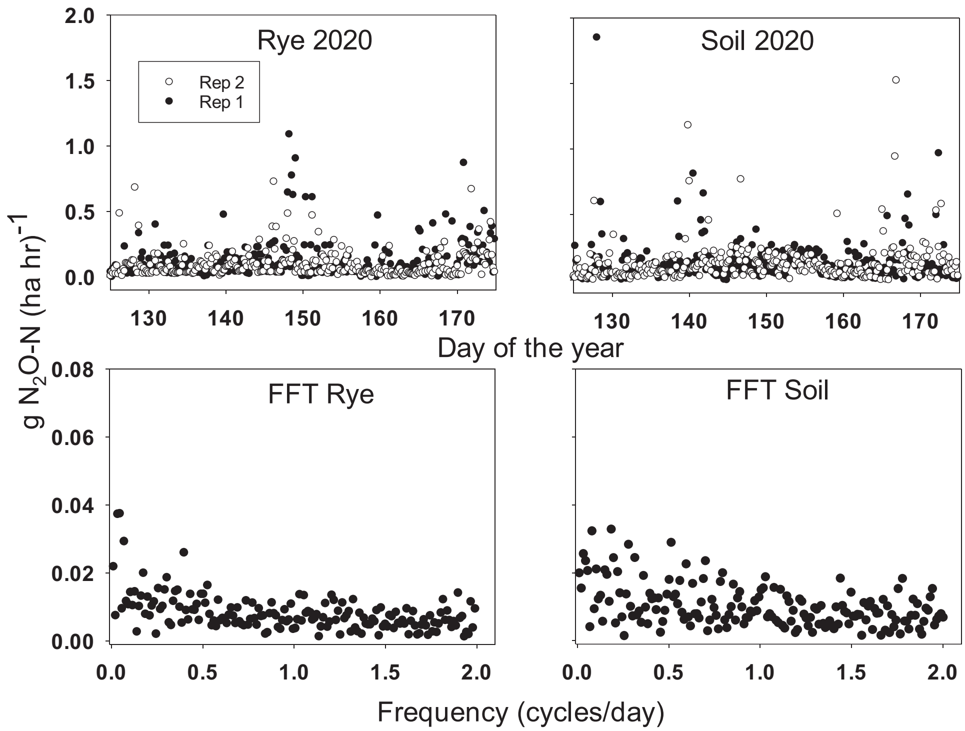

FIGURE 4 The 2020 (top) N_2O emissions and (bottom) frequency emission signature for the rye and bare soil treatments. For the frequency data, the magnitude is on the *y* axis and the frequency is on the *x* axis

similar responses. For example, Shurpali, et al. (2016) reported that when N_2O flux was low and the plant was N limited, the N_2O emission pattern switched, with emissions being higher during the night than day. This change in FFT signature has implications on the sampling requirement and suggests that near-continuous sampling may be required for precise and accurate measurement.

Rye had a mixed effect on the FFT CO_2–C emission signatures. For the non-diurnal benchmark (frequencies between 0.75 and 0.85 cycle d^{-1}) rye increased the magnitudes in 2020, reduced the magnitudes in 2019 and did not influence the magnitudes in 2018 when compared with the soil treatment. However, for the diurnal frequencies (between 0.98 and 1.01 cycles d^{-1}) rye either increased or did not influence the magnitudes. Across the 3 yr, the ratio between two frequency periods was 2.61 for soil and 3.63 for rye. These values suggest that rye increased the importance of the CO_2–C diurnal cycle.

3.3 | Vegetative rye impact on early season nitrous oxide flux and total emissions

Across the 3 yr, rye reduced N_2O-N emissions (p = .05) by 66% during the first sampling interval (Table 3). These results were attributed to rye scavenging the soil for inorganic N and water (Linn & Doran, 1984; Del Grosso, et al., 2000; Kallenback et al., 2010 ; Thies et al., 2020). However, contrary to the first sampling interval, rye did not affect emissions during the second and third sampling intervals. The temporal effect of rye on N_2O-N emissions could be attributed to treatment differences in the amount of NH_4–N that was nitrified and NO_3–N that was denitrified and that relationship between N_2O-N emissions and NO_3–N concentration most likely followed a logistic model (Kim, et al., 2011).

Across the sampling intervals, the highest emissions were observed during the first period. Higher emissions in the early spring could be the results of soil freezing–that lyses microbial cells releasing labile organic compounds into the soil solution. These compounds when mineralized result in CO_2–C emissions and higher soil NH_4–N concentration in the soil solution, which is subsequently reduced to NO_3–N and susceptible to denitrification. Increasing soil temperatures during the spring may have also released N_2O during soil thawing (Wegner-Riddle et al., 2017). Our findings differ from Ruis et al. (2018), where rye had a minimal impact on N_2O-N emissions. Differences between Ruis et al. (2018) and our study were attributed to four factors. First, Ruis et al. (2018) sampled their system 14 times from late April 2018 to June 2019 and collected point samples from the treatments biweekly between 1000 and 1400 h. In comparison, we measured emissions more than 1,100 times over 3 yr. Second, Ruis et al. (2018) applied N fertilizer, whereas in our study N was not applied. As discussed earlier, the application of N fertilizer may have placed the Ruis et al. (2018) in the high emissions portion of the S-Curve where the amount of N uptake by the cover crop was not enough to affect N_2O-N emissions. Third, Ruis et al. (2018) reported that in a dryland system, the cover crop had a minimal impact on soil moisture, whereas in our study rye reduced soil moisture. Fourth, Ruis et al. (2018) reported that between 6 March and 25 April an N_2O-N flush was not observed and changes in soil inorganic N were not reported. Whereas, in our study, rye reduced N_2O-N emissions during the first sampling period in all 3 yr.

3.4 | Vegetative rye impact on early season CO_2–C flux and total emission

For CO_2–C emissions, the soil and rye treatments had diurnal cycles in 2018, 2019, and 2020 (Table 3). The diurnal CO_2–C cycles were attributed to diurnal temperature cycles which influenced CO_2 water solubility and microbial activity. In 2018, CO_2–C emission rates were not constant during the study and increased at a rate 14.6 g CO_2–C ± 3.1 (ha × h × d)$^{-1}$ in the bare soil and 26.6 ± 3.5 g CO_2–C (ha × h × d)$^{-1}$ in the cover crop. Across years, rye only increased CO_2–C emissions in 2019. The higher rate in rye was attributed to the increased importance of non-heterotrophic respiration.

4 | SUMMARY

In this experiment, the impact of an unfertilized growing cover crop on soil moisture, inorganic N, and GHG emissions and frequency signatures were investigated. Our research showed that when compared to bare soil, rye reduced the surface soil WFP 29, 15, and 26% in 2018, 2019, and 2020, respectively. Rye also reduced the NO_3–N concentration in surface 30 cm of soil by 52 and 64% in 2019 and 2020, respectively. Associated with these reductions was a 66% decrease in N_2O-N emissions for the first sampling period across years. The study also showed that the cover crop changed the N_2O-N and CO_2–C FFT emission signatures which could complicate the interpretation of a single sample collected at a prescribed time every 2 wk.

In addition, during the cover crop first sampling period, N_2O emissions were consistently reduced, whereas during the second and third sampling interval the cover crop did not influence emissions. Temporal changes on cover crop induced differences in N_2O may be related to changes in the inorganic N during the study. Rye induced changes in soil nitrate are important because N additions (NO_3–N) and N_2O-N emissions may follow a logistic model. This model predicts that at low N and high N levels, changes in the NO_3–N concentration may result in minimal changes in N_2O-N emissions. However, at moderate N levels, N_2O emissions increase exponentially with increasing N.

Nitrified N should have increased NO_3–N concentrations during the study. However, large increases in NO_3–N were not observed and generally NO_3–N concentrations were relatively low in this unfertilized soil. In 2018, NO_3–N increased from 3.7 to 9.03 mg kg^{-1} in the soil and 7.11 mg kg^{-1} in the rye treatment. In 2019, NO_3^- concentrations decreased from 14.3 mg kg^{-1} at the start of the experiment to 8.66 mg kg^{-1} in the soil treatment and 4.1 mg kg^{-1} in the rye treatment during the study. Slightly different results were observed in 2020 where NO_3–N at initiation was 6.25 mg kg^{-1} and at termination it was 7.11 in the soil and 2.5 mg kg^{-1} in the rye treatments.

Our findings support the hypothesis that N_2O emissions would be reduced during cover crop growth. Additional research is needed to confirm these results over a range of environments and NO_3^- concentrations. For this experiment, additional information on the impact of cover crop on corn growth is available in Moriles-Miller et al. (2020, November 9-13) and the effect of the decomposing cover crop on GHG emissions are available in Joshi et al. (2020).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Graig W. Reicks https://orcid.org/0000-0002-3823-5572
David E. Clay https://orcid.org/0000-0002-5031-9744
Sharon A. Clay https://orcid.org/0000-0003-4166-6995
Deepak R. Joshi https://orcid.org/0000-0002-5142-284X
Aaron Lee M. Daigh https://orcid.org/0000-0001-5661-4800
Stephanie A. Bruggeman https://orcid.org/0000-0003-2405-6124

REFERENCES

Abadalla, M., Hastings, A., Helmy, M., Prescher, A., Osborne, B., Lanigan, G., Forristal, D., Killi, D., Maratha, P., Williams, M., Rueangritsarakul, K., Smith, P., Nolan, P., & Jones, M. B. (2014). Assessing the combined use of reduced tillage and cover crops for mitigating greenhouse gas emissions from arable ecosystems. *Geoderma*, *223–225*, 9–20. https://doi.org/10.1016/j.geoderma.2014.01.030

Antosh, E., Idowa, J., Schutte, B., & Lehnhoft, E. (2020). Winter cover crops effect soil properties and sweet corn yield in semi-irrigated systems. *Agronomy Journal*, *112*, 92–106. https://doi.org/10.1002/agj2.20055

Basche, A. D., Kaspar, T. C., Archontoulis, S. V., Jaynes, D. B., Sauer, T. J., Parkin, T. B., & Miguez, F. E. (2016). Soil water improvements with the long-term use of winter rye cover crop. *Agricultural Water Management*, *172*, 40–50. https://doi.org/10.1016/j.agwat.2016.04.006

Basche, A. D., Miguez, F. E. Kaspar, T. C., & Castellano, M. J. (2014). Do cover crops increase or decrease nitrous oxide emission? A meta-analysis. *Journal of Soil and Water Conservation*, *69*, 471–482. https://doi.org/10.2489/jswc.69.6.471

Bich, A. D., Reese, C. L., Kennedy, A. C., Clay, D. E., & Clay, S. A. (2014). Corn yield is not reduced by mid-season establishment of cover crops in northern Great Plains environment. *Crop Management*, *13*, 1–8. https://doi.org/10.2134/CM-2014-0009-RS

Blackmer, A. M., & Bremner, J. M. (1978). Inhibitory effect of nitrate on reduction of N_2O to N_2 by soil microorganisms. *Soil Biology & Biochemistry*, *10*, 187–191.

Blackmer, A. M., & Bremner, J. M. (1979). Stimulatory effect of nitrate on the reduction of N_2O to N_2 by soil microorganisms. *Soil Biology & Biochemistry*, *11*, 313–315. https://doi.org/10.1016/0038-0717(79)90078

Brummell, M. E., Farrell, R. E., Hardy, S. P., & Siciliano, S. D. (2014). Greenhouse gas production and consumption in High Arctic deserts. *Soil Biology & Biochemistry*, *68*, 158–165.

Çerçioğlu, M., Anderson, S. H., Udawatta, R. P., & Algele, S. (2019). Effect of cover crop management on soil hydraulic properties. *Geoderma*, *343*, 247–253. https://doi.org/10.1016/j.geoderma.2019.02.027

Clay, D. E., Reicks, G., Carlson, C. G., Moriles-Miller, J., Stone, J. J., & Clay, S. A. (2015). Tillage and corn residue harvesting impact surface and subsurface carbon sequestration. *Journal Environmental Quality*, *44*, 803–809. https://doi.org/10.2134/jeq2014.070322

Del Grosso, S. J., Parton, W. J., Mosier, A. R., Ojima, D. S., Kulmala, A. E., & Phongpan, S. (2000). General model for N_2O and N_2 emissions from soil due to denitrification. *Global Biogeochemical Cycles*, *14*, 1045–1060. https://doi.org/10.1029/1999GB001225

Eagle, A. J., Olander, L. P., Locklier, K. L., Heffernan, J. B., & Bernhardt, E. S. (2017). Fertilizer management and environmental factors drive N_2O and NO_3 losses in corn: A meta analysis. *Soil Science Society of America Journal*, *81*(5), 1191–1202. https://doi.org/10.2136/sssaj2016.09.0281

Han, Z., Walter, M. T., & Drinkwater, L. E. (2017). N_2O emissions from grain cropping systems: A meta-analysis of the impact of fertilizer-based and ecologically-based nutrient management strategies. *Nutrient Cycles in Agroecosystems*, *107*, 335–355. https://doi.org/10.1007/s10705-017-9836-z

Johnson, J. M. F., & Barbour, N. W. (2019). Stover harvest did not change nitrous oxide emissions in two Minnesota fields. *Agronomy Journal*, *111*, 143–155. https://doi.org/10.2134/agronj2018.09.0591

Joshi, D. R., Clay, D. E., Clay, S. A., Daigh, A. L., Miller, J., Reicks, G. & Westhoff, S. (2020). Rye Residue Effects on CO2 and N2O Emissions and Residue Mineralization. In ASA, CSSA and SSSA International Annual Meetings (2020)| VIRTUAL. ASA-CSSA-SSSA. https://scisoc.confex.com/scisoc/2020am/meetingapp.cgi/Paper/125023

Kallenback, C. M., Rolston, D. E., & Horwath, W. R. (2010). Cover cropping affects soil N_2O and CO_2 emissions differently depending on type of irrigation. *Agriculture, Ecosystem & Environment*, *137*, 251–260.

Kim, D. - G., Hernandez-Ramirez, G., & Giltrap, D. (2011). Linear and nonlinear dependency of direct nitrous oxide emission on fertilizer nitrogen input. *Agriculture, Ecosystems, and Environment*, *168*, 53–65. https://doi.org/10.1016/j.agee.2012.02.021

Klingenberg, L. (2005). *Frequency domain using Excel*. San Francisco, CA: San Francisco State University, School of Engineering.

Krijnen, F., Richman, D., Lemke, R., & Farrell, R. (2013). *Evaluation of a closed-path Fourier transform infra-Red (FTIR) multi-component gas analyzer for the simultaneous measurement of nitrous oxide, carbon dioxide and methane*. Saskatoon, SK, Canada: University of Saskatchewan. https://core.ac.uk/display/226146035

Linn, D. M., & Doran, J. W. (1984). Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. *Soil Science Society of America Journal*, *48*(6), 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x

Millar, N., Robertson, G. P., Grace, P. R., Gehl, R. L., & Hoben, J. P. (2010). Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (maize) production: An emission reduction protocol for US Midwest agriculture. *Mitigation and Adaptation Strategies for Global Change*, *15*(2), 185–204. https://doi.org/10.1007/s11027-010-9212-7

Mitchell, D. C., Castellano, M. J., Sawyer, J. E., & Pantoja, J. (2013). Cover crop effects on nitrous oxide emissions: Role of mineralizable carbon. *Soil Science Society of America Journal*, *77*(5), 1765–1773.

Moriles-Miller, J., Clay, S. A., Clay, D. E., Joshi, D. R., Reicks, G., Westhoff, S., & Daigh, A. L. (2020). Fall Planted Cover Crop Influence Early Corn Growth and Development. In ASA, CSSA and SSSA International Annual Meeting (Virtual), 9–13 Nov. 2020. https://scisoc.confex.com/scisoc/2020am/prelim.cgi/Paper/125536

Nielsen, D. C., Lyon, D. J., Hergert, G. W., Higgins, R. K., & Holman, J. D. (2015). Cover crop biomass production and water use in the central Great Plains. *Agronomy Journal*, *107*, 2047–2058. https://doi.org/10.2134/agronj15.0186

Nleya, T., Chungu, C., & Kleinjan, J., (2016). Corn growth and development. In D. E. Clay, C. G. Carlson, S. A. Clay, & E. Byamukama (Eds.), *iGrow corn: Best management practices*. Brookings: South Dakota State University.

R Core Team. (2017). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org, Accessed 20 Feb. 2020.

Reese, C. L., Clay, D. E., Clay, S. A., Bich, A. D., Kennedy, A. C., Hansen, S. A., & Moriles, J. (2014). Winter cover crops impact on corn production in semi-arid regions. *Agronomy Journal*, *106*, 1479–1488. https://doi.org/10.2134/agronj13.0540

Ruis, S. J., Blanco-Canqui, H., Jasa, P. J., Ferguson, R. B., & Slater, G. (2018). Impacts of early- and late- terminated cover crop on gas fluxes. *Journal of Environmental Quality*, *47*(6), 1426-1435. https://doi.org/10.2134/jeq2018.02.0066

Sanz-Cobena, A., Garcia-Marco, S., Quemada, M., Gabriel, J. L., Almendros, P., & Vallejo, A. (2014). Do cover crops enhance N_2O, CO_2, or CH_4 from soil in Mediterranean arable systems? *Science of the Total Environment*, *466–467*, 164–174. https://doi.org/10.1016/j.scitotenv.2013.07.023

SARE. (2007). *Managing cover crops profitably* (3rd ed.) Sustainable Agriculture Network, Beltsville, MD. https://www.sare.org/resources/managing-cover-crops-profitably-3rd-edition (Accessed 16 Oct. 2020)

Seiz, P., Guzman-Bustamante, I., Schulz, R., Müller, T., & Ruser, R. (2019). Effect of crop residue removal on nitrous oxide emissions from a horticulturally used soil in South Germany. *Soil Science Society of America Journal*, *83*, 1399–1409. https://doi.org/10.2136/sssaj2018.11.0448

Senbayram, M., Chen, R., Budai, A., Bakken, L., & Dittect, K. (2012). N_2O emissions and $N_2O/(N_2O+N_2)$ product ratio of denitrification as controlled by available carbon substrate and nitrate concentration. *Agriculture, Ecosystem, and Environment*, *147*, 4–12.

Shan, J., & Yan, X. (2013). Effects of crop residue returning on nitrous oxide emissions in agricultural soils. *Atmospheric Environment*, *71*, 170–175. https://doi.org/10.1016/j.atmosenv.2013.02.009

Shurpali, N. J., Rannik, U., Jokinen, S., Lind, S., Biasi, C. X., Mammarella, I., Peltola, O., Pihlatie, M., Hyvőnen, N., Raty, M., Haapanala, S., Zahniser, M., Virkajärvi, P., Vesala, T., & Martikainen, P. J. (2016). Neglecting diurnal variation leads to uncertainties in terrestrial nitrous oxide emissions. *Scientific Reports*, *6*, 25739. https://doi.org/10.1038/srep25739

Smeltekop, H., Clay, D. E., & Clay, S. A. (2002). The impact if intercropping annual "sava" snail medic on corn production. *Agronomy Journal*, *94*, 917–924. https://doi.org/10.2134/agronj2002.9170

Thies, S., Bruggeman, S. A., Clay, S. A., Mishra, U., Hatfield, S. G., Kumar, S., & Clay, D. E. (2019). Midmorning point sampling may not accurately represent nitrous oxide emissions following fertilizer applications. *Soil Science Society of America Journal*, *83*, 339–347. https://doi.org/10.2136/sssaj2018.08.0313

Thies, S., Joshi, D. R., Bruggeman, S. A., Clay, S. A., Mishra, U., Moriles-Miller, J., & Clay, D. E. (2020). Fertilizer timing affects nitrous oxide, carbon dioxide, and ammonia emissions from soil. *Soil Science Society of America Journal*, *84*, 115–130. https://doi.org/10.1002/saj2.20010

Thomas, B. W., Hao, X., Larney, F. J., Goyer, C., Catigny, M. H., & Charles, A. (2017). Non-legume cover crops can increase nongrowing season nitrous oxide emissions. *Soil Science Society of America Journal*, *81*, 189–199. https://doi.org/10.2136/sssaj2016.08.0269

Wang, T., Xu, Z., Kolady, D., Ulrich-Schad, J. D., & Clay, D. E. (2020). Cover Crops Usage in South Dakota: Farmer Perceived Profitability and Future Adoption Decisions. *Journal of Agricultural and Resource Economics, Western Agricultural Economics Association*, In press. *0*(Preprints) 2327–8285. https://doi.org/10.22004/ag.econ.304768

Wegner, B. R., Chalise, K. S., Lai, S. S., Abagandura, G. O., Kumar, S. Osborne, S. L., Lehman, R. M., & Jagadamma, S. (2018). Response of soil surface greenhouse gas fluxes to crop residue removal and cover crops under corn-soybean rotation. *Journal of Environmental Quality*, *47*, 1146–1154. https://doi.org/10.2134/jeq2018.03.0093

Wegner-Riddle, C., Congreves, K. A., Abalos, D., Berg, A. A., Brown, S. E., Ambadan, J. T., Gao, X., & Tenuta, M. (2017). Globally important nitrous oxide emissions form croplands induced by freeze-thaw cycles. *Nature Geoscience*, *10*, 279–283. https://doi.org/10.1038/ngeo2907

Weier, K. L., Doran, J. W., Powers, J. F., & Walters, D. T. (1993). Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. *Soil Science Society Journal*, *57*, 66–72. https://doi.org/10.2136/sssaj1993.03615995005700010013x

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