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SPECIAL SECTION

The Role of Conservation Agricultural Practices on Reducing Greenhouse Gas Emissions and Enhancing C Sequestration

Impacts of corn stover removal on carbon dioxide and nitrous oxide emissions

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Abstract

Harvesting corn (*Zea mays* L.) stover for production of biofuels, industrial sugars, bioproducts, and livestock bedding is increasing rapidly, but little is known of the impacts of stover removal on soil-borne greenhouse gas (GHG) emissions. This study evaluated the impacts of removing surface corn stover (0, 25, 50, 75, 100 wt. % removal) on carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from a sandy loam soil cropped to monoculture corn using conventional moldboard plow tillage (CT) and no-tillage (NT). Stover removal systematically decreased CO_2 emissions from CT, whereas stover removal had little effect on CO_2 emissions from NT. In particular, the CT 0% stover removal treatment produced 47% greater CO_2 emissions (5.75 Mg CO_2–C ha^{-1}) than the CT 100% removal (3.91 Mg CO_2–C ha^{-1}) treatment. Stover removal increased N_2O emissions from both tillage treatments, producing up to a 75% increase under CT (2.79 kg N ha^{-1} at 0% removal; 4.87 kg N ha^{-1} at 100% removal) and up to a 95% increase under NT (1.75 kg N ha^{-1} at 0% removal; 3.41 kg N ha^{-1} at 100% removal). Cumulative nitrate exposure increased in comparable patterns to N_2O emissions when stover residues were removed. There was a trade-off in GHG emissions resulting from stover removal under CT, whereby increasing stover removal reduced CO_2 emissions but increased N_2O emissions. In contrast, stover removal did not affect CO_2 emissions under NT but it increased N_2O emissions especially at the 100% removal rates.

1 | INTRODUCTION

The profitability of grain corn (*Zea mays* L.) production can be improved by selling the post-harvest stover for generation of biofuels (e.g., gasohol), industrial sugars, livestock bedding/feed, and many bioproducts (Ragauskas et al., 2006). Removal of corn stover from the field is also attractive from a residue management perspective because modern corn varieties generate substantially more stover than old varieties. Lorenz, Gustafson, Coors, and de Leon (2010) reported that breeding for increased maize yield over time in the U.S. Corn Belt also resulted in increased corn stover biomass. A comparison of maize varieties that

Abbreviations: CT, conventional tillage; GHG, greenhouse gas; NT, no-tillage; SOC, soil organic carbon; UAN, urea ammonium nitrate.

were released after 1959 and grown in 1987 and 1988 found that only 15% of the grain yield increase was due to changes in the harvest index, whereas 85% of the increases in grain yields were due to overall increases in the total dry matter production (Tollenaar, 1989). The greater stover biomass can be particularly problematic for no-till production on fine-textured soils where the surface layer of stover can cause, on average, 13% reductions in corn grain yields by keeping the soil wetter and cooler relative to moldboard plow production (Drury et al., 1999). As a consequence, farmers in many cool, humid regions are forfeiting the energy, soil health, and environmental benefits of no-till corn production and reverting back to aggressive inversion tillage (such as moldboard plow), which buries the corn stover to regain lost grain yield and alleviate problems resulting from excess surface stover.

Although the benefits (warmer and drier soils in the spring in humid regions) and opportunities (value-added product) for harvesting corn stover are compelling, there are serious concerns regarding possible negative impacts of stover removal on soil health, crop productivity, and environmental quality (Laird & Chang, 2013; Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004). Removing stover can potentially increase soil erosion (Mann, Tolbert, & Cushman, 2002) and degrade soil physical and hydraulic properties (Chalise et al., 2018). Stover removal can also reduce returns of organic matter and plant nutrients to the soil. In a simulation study, Lugato and Jones (2015) estimated that for every metric tonne (Mg) of crop residue that is removed from fields in Europe, the soil organic carbon (SOC) losses would be between 0.2 and 0.5 Mg CO_2 eq ha^{-1} yr^{-1}. However, only a few studies have examined the overall effect of this practice on soil biological communities (Lehman et al., 2014; Urra, Mijangos, Lanzén, Lloveras, & Garbisu, 2018), with no studies in the humid regions of eastern Canada.

Corn stover removal affects the complex balance of soil nitrogen (N) and C, and this may in turn affect soil-borne greenhouse gas (GHG) emissions in unexpected ways. A Minnesota study involving three residue removal rates in a strip tillage system found that N_2O emissions were not affected by residue removal, whereas CO_2 emissions were reduced (Baker, Fassbinder, & Lamb, 2014). Soils in Minnesota, however, are typically drier than soils in the Corn Belt area of the United States and Canada, and hence GHG emissions in the Minnesota study are expected to be lower than from soils in the Corn Belt. In a subsequent study in Minnesota involving three corn stover removal rates (grain only removal, grain and 50% stover removal, grain and ~81% stover removal), N_2O emissions were not affected by stover removal in either CT or NT fields (Johnson & Barbour, 2018). A tillage study involving stover removal in Ontario found that complete stover removal increased N_2O emissions especially in conventional fall moldboard plow tillage (CT) compared with no-tillage (NT) treatments (Congreves, Brown, Németh, Dunfield, & Wagner-Riddle, 2017).

Core Ideas

- CO_2 emissions decreased with increasing stover removal under conventional tillage (CT).
- CO_2 emissions were not affected by stover removal under no-tillage (NT).
- N_2O emissions increased with increasing stover removal under both CT and NT.
- N_2O emissions were 42% greater under CT than NT when averaged over 3 yr.
- There was a trade-off in CO_2 and N_2O emissions with stover removal under CT.

The objectives of this paper were to examine the impacts of varying corn stover removal rates on CO_2 and N_2O emissions from a sandy loam soil cropped to corn using CT and NT. The impacts of stover removal on other aspects of corn production (e.g., corn emergence, in-season biomass accumulation, corn grain yields, nutrient removal in the grain and stover, soil fertility) will be described in subsequent papers.

2 | MATERIALS AND METHODS

2.1 | Site description and treatments

The field site is located near Harrow, Ontario, Canada (42.025° N, 82.898° W), which has a moderate humid continental climate. The soil is a well-drained Harrow sandy loam (Brunisolic Grey-Brown Luvisol [Canadian soil classification system]; Typic Hapludalfs [USDA Soil Taxonomy]). The average soil texture is 64.0 wt. % sand, 21.6 wt. % silt, and 14.4 wt. % clay in the A horizon, and the initial (fall 2014) SOC was 20.7 g C kg^{-1} soil, total N was 1.72 g N kg^{-1} and pH was 6.9 in the top 10 cm soil. The site was cropped to a corn–soybean [*Glycine max* (L.) Merr.] rotation under moldboard plow tillage prior to initiation of the experiment. Precipitation and temperature were provided by a weather station located within 1 km of the field site.

The treatments included continuous (monoculture) corn grown under two tillage treatments (NT and fall conventional moldboard plow tillage with spring secondary tillage using a triple-K cultivator and packer [CT]) and five stover removal rates (0, 25, 50, 75, 100 wt. % removal) arranged in a two-by-five factorial randomized block design with four replicates. Statistical analysis of results used the Proc Glimmix procedure and significant interactions (α = .05) were identified via Proc LSmeans (SAS Institute, 2011). Results were also analyzed using repeated measures analysis and Proc Glimmix.

2.2 | Agronomic practices

Corn (Pioneer P096AMX) was planted (20 May 2015; 18 May 2016; 17 May 2017) at 79,707 seeds ha^{-1} in 0.762-m rows using a Kinze planter. Starter fertilizer (10–10–15 at 303 kg ha^{-1}) was applied at planting (5 cm beside and 5 cm below seed), and side-dress N (liquid urea ammonium nitrate [UAN]) was injected (150 kg N ha^{-1}) at the corn six-leaf stage (19 June 2015, 16 June 2016, 21 June 2017). Corn grain was harvested on 18 Nov. 2015, 21 Nov. 2016, and 22 Nov. 2017.

2.3 | Stover baling and reapplication

After grains were harvested, the surface stover was mowed, leaving approximately 15 cm stubble in all plots (14 Dec. 2014; 11 Dec. 2015; 22 Nov. 2016). The cut corn stover was then baled and removed from the NT and CT plots, weighed, tagged, and reapplied to the same respective plots at 0, 25, 50, 75, and 100 wt. % of the total stover biomass based on the CT treatment with no stover removed (i.e., CT, 0% removal). The mass of the stubble (~15 cm) was left in all plots and was not included in the removal and reapplication calculations. The CT 0% removal treatment was used as the reference because (a) it is the most common tillage practice used by farmers in central Canada and (b) using one treatment as the reference (i.e., CT 0% removal) in each year ensured that stover removal rates remained comparable even though stover and grain yields differed between tillage treatments (CT, NT) and stover removal rates. The bales were reweighed, and a combination of full and partial bales based upon the target weights of each treatment were placed on each plot and distributed by hand. This approach also enabled us to treat stover removal as a rate study. The CT 0% stover biomass yields were 5.89 Mg ha^{-1} in 2014, 7.57 Mg ha^{-1} in 2015, 4.67 Mg ha^{-1} in 2016, and 4.99 Mg ha^{-1} in 2017; these became the target application rates for the subsequent years (e.g., the stover biomass yield in 2014 became the CT 0% removal rate for 2015 field season). Therefore, the 0% CT removal rates were 5.36 Mg ha^{-1} for 2015, 7.68 Mg ha^{-1} for 2016, and 4.87 Mg ha^{-1} for 2017, with a 3-yr average application rate of 5.97 Mg ha^{-1} (Table 1). Differences between the targeted and actual rates were due to differences in moisture of the bales when they were first measured and when they were reweighed prior to application. Subsamples of the stover residue from each plot were dried, ground, and analyzed on a TruMac analyzer (Leco Corporation) for total C concentration. The stover C concentration and biomass data were multiplied to obtain stover C addition rates (Supplemental Table S1). After stover reapplication, the CT plots were plowed in the late fall or early winter when soil conditions were fit (11 Feb. 2016; 9 Dec. 2016) to approximately 18 cm depth, except for fall 2014, when frost and wet conditions delayed plowing until the following spring (24 Apr. 2015). The soil and reapplied stover in the NT plots was left undisturbed except for no-till planting and side-dress N injection each June.

TABLE 1 Corn stover application rates (dry weight basis) under conventional tillage and no-tillage and 5 stover removal rates in the 2015, 2016, and 2017 growing seasons as well as the 3-yr average

Tillage	Stover removal rate wt. %	Stover application rates 2015	2016	2017	3-yr average
		Mg ha^{-1}			
Conventional tillage	0	5.36 (0.72)	7.68 (0.31)	4.87 (0.07)	5.97 (0.30)
	25	4.59 (0.51)	5.63 (0.41)	3.57 (0.11)	4.59 (0.14)
	50	2.99 (0.44)	3.83 (0.28)	2.48 (0.09)	3.10 (0.21)
	75	1.56 (0.16)	2.00 (0.13)	1.33 (0.05)	1.63 (0.06)
	100	0	0	0	0
No-tillage	0	5.74 (1.02)	7.37 (0.71)	4.74 (0.17)	5.95 (0.15)
	25	4.05 (0.57)	5.32 (0.39)	3.69 (0.24)	4.35 (0.11)
	50	2.91 (0.25)	3.79 (0.51)	2.56 (0.10)	3.09 (0.17)
	75	1.48 (0.16)	1.94 (0.10)	1.44 (0.04)	1.62 (0.08)
	100	0	0	0	0

Note. Stover application rates are based upon the fraction (i.e., 0, 25, 50, 75, or 100% removal) of the previous year's conventional tillage 0% removal corn stover biomass. The targeted application rates were 5.89, 7.57, and 4.67 Mg ha^{-1} for 2015, 2016, and 2017, respectively. The numbers in parentheses are the SE (n = 4).

2.4 | Greenhouse gas measurements

Flux densities of CO_2 and N_2O emanating from the soil were measured periodically (typically once per week) throughout the growing season (1 May–31 October) using the in situ chamber method of Drury, Yang, Reynolds, and McLaughlin (2008). In brief, collars (59.7 cm long by 24.3 cm wide by 15 cm high) were inserted into the soil every spring to approximately 8 cm depth. Gas sampling involved clamping and covering the chambers and withdrawing 20-ml gas samples at 0, 10, 20, and 30 min after closure and injecting them into 12-ml pre-evacuated exetainers (Drury et al., 2008). Gas samples were collected on the same of day at each collection event (9 a.m.–12 p.m.). The chambers were removed before planting and before sidedress and reinserted between corn rows shortly after planting and N sidedress operations. The chambers were perpendicular to the corn rows, with no plants inside the chambers. There were two chambers inserted into each of three replicates.

A total of 73 sampling events occurred during the 3-yr study, and a total of approximately 15,000 gas samples (including standards) were analyzed. The concentrations of N_2O and CO_2 were determined using a Model GC-2014 Shimadzu gas chromatograph, fitted with a Flex autosampler and a 0.5-ml sample loop attached to the 0.5-m 80/100 Haysep-T pre-columns. The pre-columns used a backflush valve and vent to prevent water vapor from contaminating the detectors. The main columns were a 1.5 m 80/100 Haysep N (CO_2 analysis) and a 2.5-m 80/100 Haysep D (N_2O analysis). The N_2O peaks were analyzed using an electron capture detector, and the CO_2 peaks were analyzed using a thermal conductivity detector. The flux rates were based upon a linear regression over 30 min using the four samples collected at 10-min intervals. Growing-season N_2O and CO_2 emissions were determined by linear interpolation between sampling events using the trapezoid rule.

Volumetric soil water contents were determined using miniTrase TDR waveguides (Hoskin Scientific) inserted into the soil at the 0- to 10-cm depth within 1 m of the chambers at every GHG sampling event. Soil temperature was measured using temperature loggers (ONSET HOBO TidbiT v2, Hoskin Scientific), which were buried in the soil in each plot within 1 m of the chambers at 10 cm depth after planting until 31 October each year.

2.5 | Inorganic nitrogen analysis and nitrate exposure

Soil core samples (0–30 cm depth) were collected at 3-wk intervals during the growing season to obtain ammonium and nitrate concentrations using a Lachat QuikChem 8500 flow injection analyzer (ATS Scientific) and following the brucite (ammonium) or cadmium reduction (nitrate) protocols. Cumulative nitrate exposure was determined using the methods of Snowdon, Zebarth, Burton, Goyer, and Rochette (2013). Nitrate exposure was calculated by multiplying the nitrate concentration by the number of days it was at that concentration; hence, the units are mg N kg^{-1} d^{-1}. The cumulative nitrate exposure over the growing season is then determined using a linear interpolation between the exposure levels over the soil sampling dates (Burton, Zebarth, Gillam, & MacLeod, 2008). Although the units are not intuitive, if nitrate is present in the soil over longer periods at significant quantities, then N_2O emissions would be greater with the increased exposure as compared to growing seasons where high nitrate concentrations in soil may be present for shorter periods of time that may or may not coincide with conditions that are favorable to denitrification losses.

3 | RESULTS AND DISCUSSION

3.1 | Growing season precipitation

Precipitation quantity and distribution varied considerably over the three growing seasons (Table 2). The total growing season (1 May–31 October) precipitation amounts in 2015 (606 mm) and 2016 (530 mm) were above the 50-yr average of 480 mm, whereas 2017 had only 430 mm precipitation. Above-normal precipitation in 2015 occurred early in the season, with 169 mm in May and 137 mm in June; the long-term average for these months was 83 and 85 mm, respectively. The 2016 growing season started out as being very dry, with only 47 mm in May and 54 mm in June, whereas August (112 mm) and September (148 mm) were wetter than the long-term average for these months (76 and 86 mm, respectively; Table 2).

TABLE 2 Monthly precipitation at Woodslee, Ontario, for 2015–2017 and the 50-yr average (1961–2010)

Month	2015	2016	2017	50-yr average
	mm			
May	169	47	102	83
June	137	54	32	85
July	61	77	93	89
Aug.	61	112	71	76
Sept.	112	148	50	86
Oct.	66	92	82	60
Total	606	530	430	480

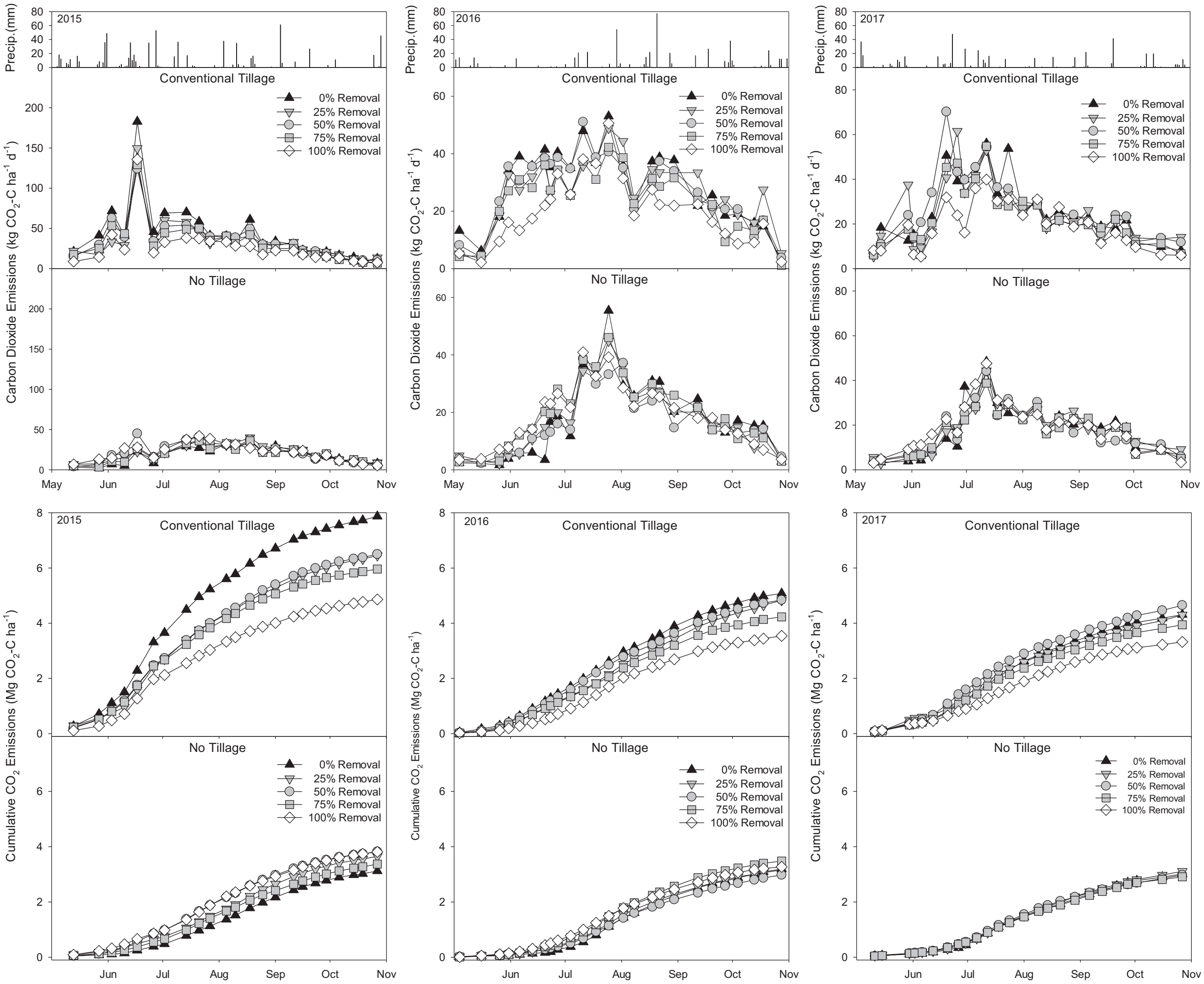

FIGURE 1 Episodic (upper graphs) and cumulative (lower graphs) CO_2 emissions under no-tillage and conventional tillage at five stover removal rates (0, 25, 50, 75, and 100%) in the 2015, 2016, and 2017 growing seasons. Note the different *y*-axis scales for the CO_2 emission data. The upper bar graph is the daily precipitation for the 2015, 2016, and 2017 growing seasons

3.2 | Carbon dioxide emissions

The CO_2 emissions in 2015 were considerably greater for the CT treatments compared with the NT treatments, especially during the period from mid-June until mid-September 2015 (Figure 1). The highest CO_2 emission flux for all CT treatments occurred on 17 June 2015. This peak event followed 5 d of precipitation delivering 77.6 mm of rainfall, which was preceded by very dry conditions (<5 mm rain d^{-1}) over the first 11 d of June. The soil temperature on 17 June 2015 was also fairly warm, with daily average temperatures of 21.2 °C for the CT treatments and 21.1 °C for the NT treatments. The above-average rainfall levels in May and June 2015 may have contributed to these higher CO_2 fluxes (Table 2). In the CT treatments, there was considerable separation in the five stover treatments in June and July, with the 0% removal treatment having greater CO_2 emissions than any of the stover removal treatments. Treatment differences were not apparent at the end of the growing season from early September until late October (Figure 1).

In 2016, the episodic CO_2 emissions had lower spikes in emissions than in 2015 (note the lower *y*-axis scale in 2016 in Figure 1). For example, the highest CO_2 emission peak in 2015 was 183 kg CO_2–C ha^{-1} d^{-1} (17 June 2015) with the 0% CT treatment compared with the highest peak in 2016 at 53 kg CO_2–C ha^{-1} d^{-1} (25 July 2016) with the 0% CT treatment. The CT treatments had greater CO_2 emissions than the NT treatment especially in June (Figure 1). The trend for greater CO_2 emissions when the entire corn stover was returned to the soil (i.e., 0% removal) was also apparent in 2016 with CO_2 emissions decreasing when more of the corn stover was removed.

TABLE 3 Cumulative growing season (1 May 1–31 October) CO_2 emissions from conventional tillage and no-till tillage at 0, 25, 50, 75, and 100% corn stover removal rates during 2015, 2016, and 2017, as well as the 3-yr average

Tillage	Stover removal rate wt. %	CO_2 emissions 2015	2016	2017	3-yr average
		Mg CO_2–C ha^{-1}			
Conventional tillage	0	7.87 (0.74)a	5.08 (0.11)a	4.31 (0.25)ab	5.75 (1.08)a
	25	6.45 (0.39)b	4.83 (0.26)ab	4.30 (0.26)ab	5.19 (0.65)b
	50	6.50 (0.50)b	4.84 (0.39)ab	4.65 (0.29)a	5.33 (0.59)ab
	75	5.96 (0.37)b	4.23 (0.50)bc	3.94 (0.24)b	4.71 (0.63)c
	100	4.86 (0.44)c	3.54 (0.21)cd	3.31 (0.13)c	3.91 (0.48)d
No-tillage	0	3.12 (0.29)d	3.19 (0.20)d	3.01 (0.13)c	3.11 (0.05)e
	25	3.65 (0.26)d	3.16 (0.23)d	3.11 (0.26)c	3.31 (0.05)e
	50	3.82 (0.03)d	2.98 (0.14)d	2.97 (0.22)c	3.26 (0.28)e
	75	3.37 (0.18)d	3.48 (0.07)d	2.91 (0.12)c	3.25 (0.17)e
	100	3.81 (0.18)d	3.27 (0.41)d	3.16 (0.14)c	3.41 (0.20)e
		F value ($P > F$)			
Tillage		166***	60***	77.5***	283***
Stover removal rate		3.9**	2.2	2.9*	7.3***
Tillage × stover removal rate		8.3***	3.9**	4.3**	12.5***

Note. Numbers in parentheses are SE ($n = 6$). Means within a column followed by the same letter are not significantly different at $P = .05$ using the least squares means procedure.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

***Significant at the .001 probability level.

In 2017, the peak CO_2 emissions were also considerably lower than they were in 2015, with a maximum CO_2 emission for the 50% removal CT treatment on 20 June 2017 and a maximum for the 25% removal CT treatment on 26 June 2017 (Figure 1). In 2017, CT generally had greater CO_2 emissions than NT, similar to 2015 and 2016.

Cumulative growing-season CO_2 emissions followed similar temporal patterns within each year (Figure 1). The greatest treatment separation was between the CT stover removal treatments in 2015, when the 0% removal treatment had considerably greater cumulative CO_2 emissions from late July until the end of the growing season, whereas the 100% removal treatment was considerably lower than all other CT stover removal treatments over this period (Figure 1). The cumulative CO_2 emissions under NT were lower, with minimal differences between the stover removal treatments. The cumulative CO_2 emission patterns were generally similar in 2016 and 2017, although the emissions were lower and the treatment spread was not as pronounced as it was in 2015. Over the 3 yr of study, CO_2 emissions were consistently higher in the CT compared with the NT treatments ($p < .001$; Table 3). There were significant tillage and stover removal interactions for the growing-season CO_2 emissions in all 3 yr as well as the 3-yr average (Table 3). In 2015, the 0% removal CT treatment had significantly greater CO_2 emissions (7.87 Mg C ha^{-1}) than all other treatments, whereas the 25, 50, and 75% removal CT treatments had significantly greater CO_2 emissions than the 100% removal treatment (4.86 Mg C ha^{-1}). In contrast, CO_2 emissions for all stover removal treatments under NT in 2015 were not statistically different but were significantly lower (3.12–3.81 Mg C ha^{-1}) than all of the CT treatments (Table 3). The pattern for stover treatments not being statistically different from each other under NT and lower than the CT treatments was similar in 2016 and 2017 with one notable exception, with the 100% removal treatment under CT having CO_2 emissions similar to all NT treatments in 2016 and 2017. In general, the greatest CO_2 emissions with the CT treatments were observed with 0% removal CT, and the lowest was observed with 100% removal CT treatment.

The 3-yr average CO_2 emissions were 47% greater with the 0% stover removal treatment (5.75 Mg ha^{-1}) compared with the 100% stover removal treatment (3.91 Mg ha^{-1}), and all CT treatments had greater CO_2 emissions than the NT treatments (range, 3.11–3.41 Mg C ha^{-1}; Table 3). In contrast, there were no differences between stover removal treatments under NT. This produced a wedge-shaped CT vs. NT pattern (i.e., going from a wider tillage treatment separation for CO_2 emissions at the 0% removal rate to a narrow separation for the CO_2 emissions at the 100% removal rate), especially in 2016 and 2017 (Figure 2).

When the growing season CO_2 emissions were analyzed using repeated measures, there was a significant

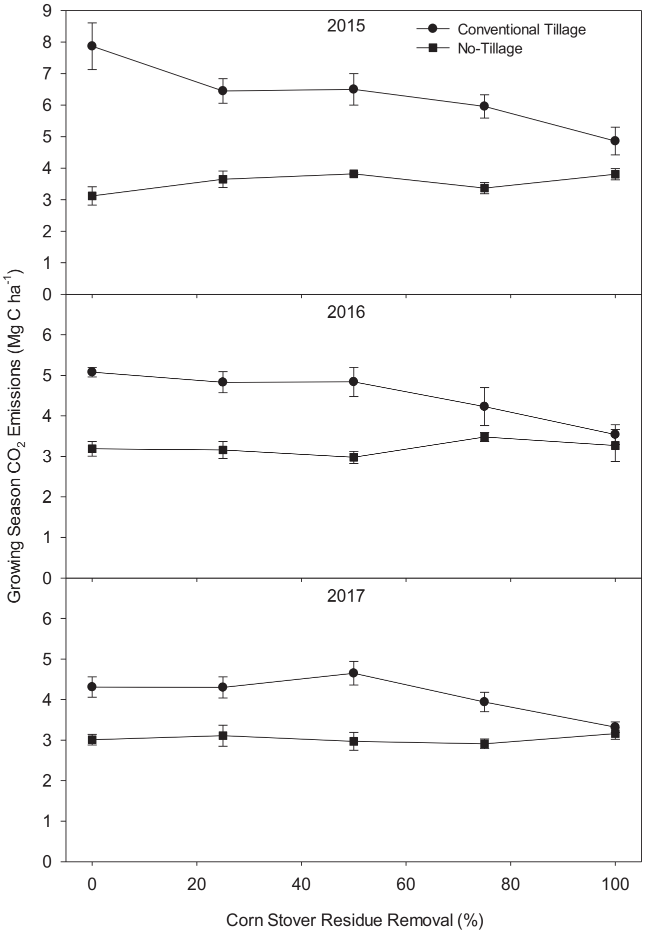

FIGURE 2 Cumulative growing season CO_2 emissions under no-tillage and moldboard plow tillage at five stover removal rates (0, 25, 50, 75, and 100% removal) in the 2015, 2016, and 2017 growing seasons

year effect, a year × tillage interaction, and a tillage × stover removal interaction (Table 4). The CO_2 emissions for the CT treatment in 2015 were statistically greater than all other treatment and years, followed by the 2016 CT treatment. No differences were found in CO_2 emissions between the 2016 and 2017 CT treatments. In contrast, no differences were observed over the 3 yr among the NT treatments. The tillage × stover residue removal interaction occurred because the average growing season CO_2 emissions for the CT treatments at the 0% removal rate were greater than at the 75 and 100% removal rates, whereas no differences were found between stover removal rates with the NT treatment (Table 4). The 100% removal rates under CT and NT were not significantly different from each other.

The average CO_2 emissions across treatments were 4.94 Mg C ha^{-1} in 2015, 3.86 Mg C ha^{-1} in 2016, and 3.57 Mg C ha^{-1} in 2017. The CO_2 emissions peaks are much broader than the N_2O emission peaks and extend over most of the growing season (Figures 1 and 3). The average growing season (1 May–31 October) volumetric water contents were 23.6% in 2015, 21.6% in 2016, and 20.6% in 2017, which follows the same time trend in growing season CO_2 emissions under CT (Table 3; Supplemental Table S2).

The CO_2 emissions decreased as corn stover was removed under CT (Table 3). The linear regression between CO_2 emissions and the amount of stover applied was positive, with an r^2 of .78 in 2015, which was the year with the greatest emissions and the highest growing-season soil water contents (Table 3; Supplemental Table S1). Both 2016 and 2017 had positive relationships between stover application and CO_2 emissions, although the r^2 values were lower ($r^2 = .4$ for both years). When the 3-yr average results were evaluated, CO_2 emissions increased with higher amounts of corn stover left in the field, and the slope of the regression was 0.79 ($r^2 = .78$). When the CO_2 emissions with the 0% removal rate (5.75 Mg C ha^{-1}) were compared with the 100% removal rate (3.91 Mg C ha^{-1}), there was 1.84 Mg C ha^{-1} more CO_2–C lost with the CT 0% removal rate, or about 72% of the 2.57 Mg C ha^{-1} of corn stover residue added to the soil (Table 3; Supplemental Table S1). Similarly, comparing the net CO_2 emissions

TABLE 4 Repeated measures analysis for CO_2 emissions, N_2O emissions, and stover biomass from 2015 until 2017

Variable	CO_2 emissions	N_2O emissions	Stover yields
	F value ($P > F$)		
Year	9.4*	15.2**	78.3***
Tillage	142***	11.9**	0.8 ns
Stover removal rate	3.6*	6.9***	0.7 ns
Tillage × stover removal rate	6.3***	0.2 ns	0.8 ns
Year × tillage	18.6***	11.9***	1.9 ns
Year × stover removal rate	0.5 ns	7.0***	0.5 ns
Year × tillage × stover removal rate	1.4 ns	0.2 ns	1.3 ns

*Significant at the .05 probability level.
**Significant at the .01 probability level.
***Significant at the .001 probability level.

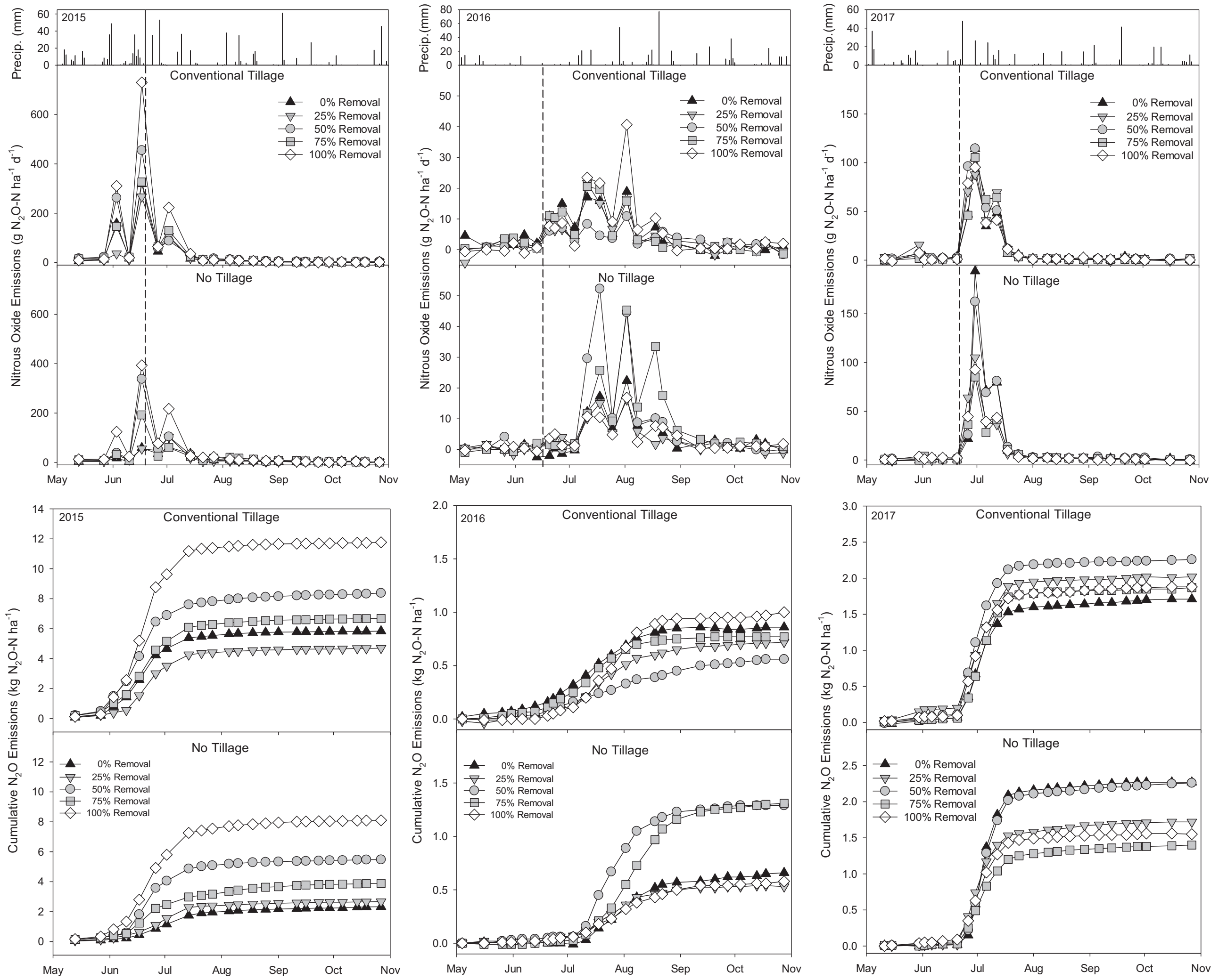

FIGURE 3 Episodic (upper graphs) and cumulative (lower graphs) N_2O emissions under no-tillage and conventional tillage at five stover removal rates (0, 25, 50, 75, and 100%) in the 2015, 2016, and 2017 growing seasons. The vertical dash line represents the sidedress N application dates. Note the different *y*-axis scales for the episodic and cumulative N_2O emission data. The upper bar graph is the daily precipitation for 2015, 2016, and 2017 growing seasons

with the CT 25% treatment (5.19 Mg C ha^{-1}) to the CT 100% stover removal treatment (3.91 Mg C ha^{-1}) resulted in a net loss of 65% of the 1.98 Mg C ha^{-1} residue C added. At lower residue removal rates, there was slightly more CO_2 emitted compared with what was added (e.g., 1.42 Mg C ha^{-1} emitted vs. 1.30 Mg C ha^{-1} added at the 50% residue removal rate and 0.8 Mg C ha^{-1} emitted as CO_2 vs. 0.71 Mg C ha^{-1} added at the CT 75% residue removal rate). This implies there may be a net loss of C from soils at high residue removal rates, whereas at low residue removal rates (0 and 25%) there may be a net gain of C to the soil under CT because net CO_2 emissions were lower than the amount of C added. In contrast to CT, the r^2 values for CO_2 emissions and stover removal under NT were all less than 0.1 for all 3 yr as well as for the 3-yr average. The 3-yr average CO_2 emissions were not affected by stover removal under NT. Hence, CO_2 emissions responded to stover addition/removal only when the corn stover was incorporated into the soil with CT.

In contrast to this study, stover removal from both phases of a corn–soybean rotation in South Dakota had no significant effect on CO_2 emissions in 2 out of 3 yr (Wegner et al., 2018). However, this study also reported that stover removal increased N_2O emissions in the two wet growing seasons, with weather apparently being the main controlling factor. On the other hand, corn stover removal (0, 50, 100 wt. %) in an Iowa study produced 12% greater CO_2 emissions from CT (18 Mg CO_2 ha^{-1} yr^{-1}) than NT (16.2 Mg CO_2 ha^{-1} yr^{-1}) in wet years, but the reverse pattern was observed in dry years (Guzman, Al-Kaisi, & Parkin, 2015). In a tillage and stover removal study in the North China Plains, CO_2 emissions followed the order CT + crop stover > CT with 100% stover removed > NT + stover > NT with 100% stover removed (Wu, Li, &

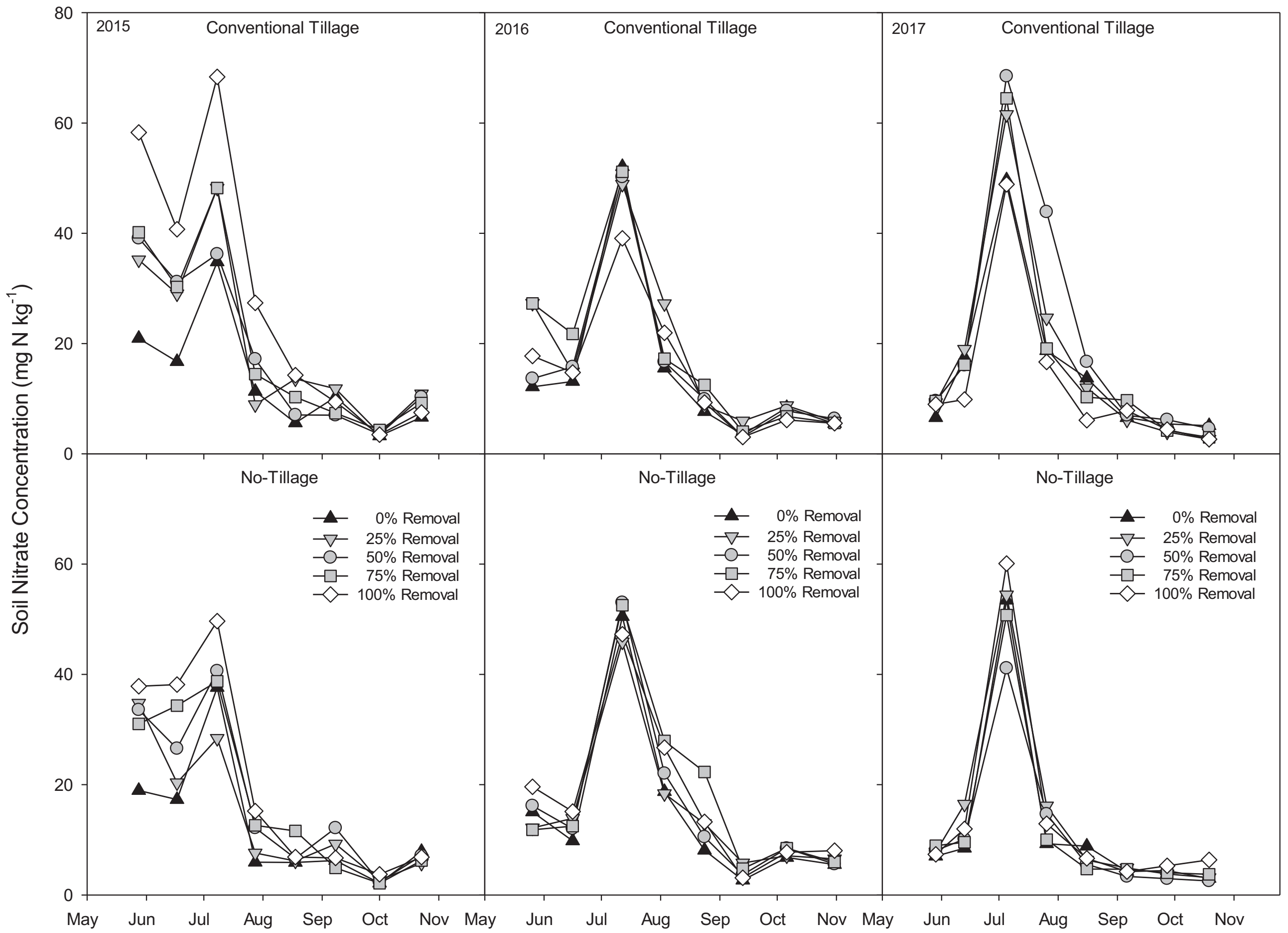

FIGURE 4 Nitrate concentrations at the 0- to 30-cm depth over the growing season under conventional tillage and no-tillage at five stover removal rates (0, 25, 50, 75, and 100% removal)

Gregorich, 2017), whereas increasing removal of sugarcane stover in Brazil (Vasconcelos et al., 2018) gave CO_2 results that were similar to our results.

3.3 | Nitrous oxide emissions

The spring of 2015 was fairly wet, and there were three high N_2O fluxes observed in early June, mid-June, and early July (Table 2; Figure 3). The early-season nitrate concentrations were also fairly high in 2015 even before side-dress N was applied (Figure 4). Perhaps the spring plowing and subsequent mineralization of the previous corn residue contributed to these early season N_2O emissions. The CT treatments had greater N_2O emissions than the corresponding NT treatments, especially in June and July (Figure 3). The greatest N_2O emissions of 730 g N_2O–N ha^{-1} d^{-1} (17 June 2015) occurred with the CT 100% removal treatment, followed by 455 g N_2O–N ha^{-1} d^{-1} with the CT 50% removal treatment, whereas the 25% removal CT treatment had an emission rate of 267 g N_2O–N ha^{-1} d^{-1}. The N_2O emissions were very low from mid-July until the end of the growing season, probably as a result of less frequent rain events and crop N uptake (Figure 3).

The N_2O emissions in 2016 were considerably lower than 2015 as a result of a drought at the beginning of the growing season (Table 2; Figure 3). There were three main emission fluxes, with the first occurring on 18–22 July following several rain events, on 2 August following one major rain event, and on 18 August following one major and several smaller rain events (Figure 3). The highest N_2O emission peak in the CT treatments occurred when 100% of the stover was removed (40.6 g N ha^{-1} d^{-1}), which was an order of magnitude lower than the 100% removal CT peak from 2015 (Figure 3). In 2016, NT had greater peak N_2O emissions than the CT treatment. The 50% NT treatment had the two greatest fluxes at 52.2 and 44.6 g N ha^{-1} d^{-1} on 18 July and 2 Aug. 2016. The 75% removal NT treatment had a similar peak as the 50% removal NT treatment on 2 Aug. 2016 at 45.3 g N ha^{-1} d^{-1}. The second largest peak for the 75% removal treatment occurred on 18 Aug. 2016 at 33.5 g N ha^{-1} d^{-1}.

The N_2O emissions fluxes were intermediate in 2017 to those in 2015 and 2016, with three major fluxes

TABLE 5 Cumulative growing season (1 May–31 October) N_2O emissions from conventional tillage and no-till at 0, 25, 50, 75 and 100% corn stover removal rates during 2015, 2016 and 2017, as well as the 3-yr average

Tillage	Stover removal rate wt. %	N_2O emissions 2015	2016	2017	3-yr average
		kg N_2O–N ha^{-1}			
Conventional tillage	0	5.84 (1.8)bcd	0.81 (0.16)bc	1.71 (0.14)	2.79 (0.68)bcde
	25	4.70 (1.0)cde	0.72 (0.13)bc	2.02 (0.16)	2.48 (0.34)cdef
	50	8.38 (2.2)b	0.55 (0.13)c	2.26 (0.43)	3.73 (0.70)b
	75	6.68 (1.5)bc	0.77 (0.15)bc	1.87 (0.18)	3.10 (0.54)bcd
	100	11.8 (2.0)a	0.96 (0.22)abc	1.88 (0.16)	4.87 (0.67)a
No-tillage	0	2.33 (0.6)e	0.66 (0.17)c	2.27 (0.26)	1.75 (0.20)ef
	25	2.67 (0.3)de	0.53 (0.10)c	1.72 (0.21)	1.64 (0.10)f
	50	5.48 (0.9)bcde	1.15 (0.13)ab	2.26 (0.21)	2.96 (0.25)bcd
	75	3.89 (0.6)cde	1.31 (0.23)a	1.40 (0.22)	2.20 (0.23)def
	100	8.10 (1.1)b	0.58 (0.18)c	1.55 (0.19)	3.41 (0.32)bc
		F value ($P > F$)			
Tillage		17.6***	0.7	0.5	17.2***
Stover removal rate		10.3***	1.9	2.3	10.0***
Tillage × stover removal rate		0.2	4.1**	1.6	0.3

Note. Numbers in parentheses are SE ($n = 6$). Means within a column followed by the same letter are not significantly different at $P = .05$ using the least squares means procedure.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

***Significant at the .001 probability level.

occurring on 30 June, 6 July, and 12 July (Figure 3). The NT treatments had greater N_2O emission fluxes than the CT treatments, especially on 30 June, 9 d after sidedress N application, with the 0 and 50% removal NT treatments having fluxes of 194 and 162 g N ha^{-1} d^{-1}, respectively. In contrast, the 50 and 0% removal CT treatments had emission fluxes of 115 and 114 g N ha^{-1} d^{-1} on the same date (Figure 3).

The patterns for the cumulative growing-season N_2O emissions were similar for CT and NT, and N_2O emissions tended to increase with increasing corn stover removal rate on a monthly basis, an annual basis, and as 3-yr averages (Figure 3; Table 5). The cumulative N_2O emissions for the CT treatments in 2015 from mid-June until the end of the growing season were greatest for the 100% removal treatment, with total growing season (1 May–31 October) emissions at 11.8 kg N ha^{-1}, followed by the 50% removal treatment at 8.38 kg N ha^{-1} with the 0% removal CT treatment at 5.84 kg N ha^{-1} or approximately 50% of the 100% removal treatment (Figure 3; Table 5). In the NT treatments, the 100% removal treatment also had the greatest cumulative N_2O emissions from mid-June until the end of October. The total N_2O emissions were greater with the 100% removal treatment under NT (8.1 kg N ha^{-1}), followed by the 50% removal at 5.48 kg N ha^{-1}, whereas the 0% removal treatment had 71% lower N_2O emissions than the 100% removal treatment at 2.33 kg N ha^{-1} (Table 5). The cumulative N_2O emissions were lower in 2016 than in 2015, and the treatment differences were not as pronounced for the CT treatments, whereas the 50 and 75% stover removal treatments had the greatest N_2O emissions among the NT treatments in 2016 (Figure 3).

There was a significant tillage effect and a significant stover removal effect, with no interactions for the 2015 and 3-yr average cumulative N_2O emissions. The CT treatment on average (7.48 kg N ha^{-1}) had 67% greater N_2O emissions than the NT treatment at 4.49 kg N ha^{-1} in 2015 (Table 5). There was a significant tillage × stover removal interaction in 2016, with the NT treatment at 75% removal rate having significantly greater N_2O emissions than all other treatments except for the NT 50% removal treatment and the CT 100% removal treatment. No significant differences occurred for the stover removal treatments under CT in 2016. In 2017, tillage, stover removal rate, or their interaction were not significant. When averaged over the 3 yr, the N_2O emissions under CT (3.39 kg N ha^{-1}) were 42% greater than the N_2O emissions under NT (2.39 kg N ha^{-1}). Stover removal had significantly greater N_2O emissions for 100% removal under CT (4.87 kg N ha^{-1}) than all other stover treatments. The 100% removal NT treatment had significantly greater N_2O emissions than the 0, 25, and 75% removal treatment under NT.

When the cumulative N_2O emission data for 2015, 2016 and 2017 were analyzed using repeated measures analysis, there was a significant year, tillage, and stover removal effect as well as significant interactions between year and tillage and year and stover removal (Table 4). The year × tillage interaction was the result of higher cumulative N_2O emissions under CT compared with NT in 2015, whereas no differences were observed between these two tillage treatments in 2016 and 2017. The cumulative N_2O emissions in 2015 were also greater than in 2016 and 2017 as a combined result of higher nitrate levels in the early growing season of 2015 as well as early-season rains, which were associated with the highest fluxes in the three growing seasons (Table 2; Figures 3 and 4). The year × stover removal rate interaction was due to the differences in N_2O emissions between stover removal treatments in 2015 compared with no significant difference in N_2O emissions between stover removal rates in 2016 and 2017 when averaged over the tillage treatments. In particular, the 100% removal rate had the highest N_2O emission in 2015 at 9.95 kg N ha^{-1}, followed by the 50% removal rate at 6.93 kg N ha^{-1}, which was significantly greater than the 0, 25, and the 75% removal rate. The 75% removal rate also had significantly greater N_2O emissions than the 25% removal treatment in 2015.

The N_2O emissions data were greatest in 2015, with an overall average of 5.99 kg N ha^{-1}, whereas the average emissions were 1.89 kg N ha^{-1} in 2017 and 0.80 kg N ha^{-1} in 2016. In 2015, the average volumetric water content of the 0- to 10-cm soils in June and July (the period with the highest N_2O emissions), was 24.3%, whereas the next highest emission year was 2017, with a 20.7% moisture content. In 2016, the soil water content averaged only 16.9% during this period (Table 5; Supplemental Table S2). Hence, the frequency of anaerobic microsites that contributed to peak N_2O emissions was also greatest in 2015 and lowest in 2016, which followed the pattern in N_2O emissions.

In an Iowa residue removal study, N_2O emissions were greater with CT than NT at the 0 and 50% removal rates, but they were similar at the 100% removal rates (Guzman et al., 2015). Yuan, Greer, Nafziger, Villamil, and Pittelkow (2018) reported lower N_2O emissions under NT compared with CT in 2 out of 3 yr in a recent corn study. Elevated N_2O emissions under CT were observed in a study on the same soil type under a winter wheat–corn–soybean rotation, whereby 3-yr N_2O emissions with CT were on average 4.19 kg N ha^{-1} compared with 3.50 kg N ha^{-1} under NT (Drury et al., 2012). In an earlier study comparing zone tillage, CT, and NT with deep and shallow UAN injection, CT (4.81 kg N ha^{-1}) had 30% greater growing season N_2O emissions than the NT treatment at 3.71 kg N ha^{-1}, whereas zone tillage had the lowest emissions at 2.98 kg N ha^{-1} with deep UAN injection (Drury et al., 2006).

The average N_2O emission for the 100% removal rate in 2015 when averaged over the two tillage treatments was 9.95 kg N ha^{-1}, or 2.4 to 2.7 times greater than the 25 and 0% stover removal treatments at 3.69 and 4.09 kg N ha^{-1} (Table 5). Similarly, the 3-yr average N_2O emissions for the 100% removal treatment were 4.14 kg N ha^{-1} or 1.8 times the average emissions (2.27 kg N ha^{-1}) for the 0% removal treatments. In a study in Minnesota, Baker et al. (2014) found no differences in N_2O emissions among 0, 50, and 100% stover removal treatments, although they did report that CO_2 emissions were slightly lower from the 100% removal treatment compared with the 0% removal treatment. Congreves et al. (2017) compared stover removal (0 or 100%) under CT and NT, and, similar to this study, they found higher N_2O emissions with complete stover removal under CT compared with no stover removal, especially during the over-winter period. In contrast with this study, a stover removal study (with/without) under CT and NT in the Loess Plateau in northwestern China reported that stover retention increased N_2O emissions compared with stover removal (Fan et al., 2018). The China study was considerably drier, with annual precipitation of 578 mm, which is comparable to the 6-mo growing season precipitation in the Ontario study, and their annual emissions (0.40–0.74 kg N ha^{-1}) were lower than the growing season emissions in the Ontario study (0.53–11.8 kg N ha^{-1}). Adler et al. (2015) studied the impact of 50% corn stover removal on N_2O emissions and soil C levels across three sites in the United States with varying climatic conditions using the Daycent model and found that SOC levels decreased with stover removal in all three locations, but the decrease was greater in the colder climates. They also predicted that N_2O emissions would increase when residue was removed and N fertilizer was applied especially in colder regions. The decrease in soil C and the increase in N_2O emissions from stover removal could, however, be offset if a high-lignin fermentation production was added back to the soils following cellulosic ethanol production (Adler et al., 2015). Furthermore, the optimal N rate may be lower when residue is removed, which may also offset the subsequent N_2O emissions.

Jin et al. (2014) reported that corn stover removal decreased total GHG emissions by 5% across nine sites in the U.S. Corn Belt. They attributed these reductions to lower inputs of C and N in the residue removal treatments. A study comparing 0 and 55% corn stover removal from a corn–soybean rotation in Brookings, SD, found that N_2O fluxes were generally greater and CO_2 fluxes generally lower with corn stover removal (Lehman & Osborne, 2016). However, in their study, treatment differences were not significant in the corn phase of the rotation, but N_2O fluxes were significantly greater in the soybean phase of the rotation.

TABLE 6 Stover biomass (dry weight basis) from conventional tillage and no-till tillage treatments at 0, 25, 50, 75, and 100% corn stover removal rates in the fall of 2015, 2016, and 2017, as well as the 3-yr average

Tillage	Stover removal rate wt. %	Stover biomass 2015	2016	2017	3-yr average
		Mg ha^{-1}			
Conventional tillage	0	7.57 (0.53)	4.67 (0.64)	4.99 (0.61)bc	5.74 (0.22)
	25	7.72 (0.48)	4.33 (0.32)	5.39 (0.67)bc	5.81 (0.34)
	50	7.62 (0.42)	3.48 (0.85)	6.18 (0.97)abc	5.76 (0.36)
	75	8.06 (0.41)	4.92 (0.98)	5.74 (0.73)abc	6.24 (0.46)
	100	8.12 (0.48)	4.93 (0.79)	5.56 (0.80)bc	6.20 (0.36)
No-tillage	0	7.49 (0.39)	3.93 (0.57)	7.11 (0.99)a	6.18 (0.47)
	25	6.73 (0.42)	4.11 (0.53)	5.78 (0.19)abc	5.54 (0.12)
	50	7.77 (1.27)	3.76 (0.75)	4.87 (0.76)c	5.47 (0.73)
	75	6.94 (0.59)	3.54 (0.55)	5.60 (0.31)bc	5.36 (0.36)
	100	8.92 (1.10)	3.30 (0.38)	6.42 (0.66)ab	6.22 (0.23)
		F Value ($P > F$)			
Tillage		1.4	0.4	0.4	1.2
Stover removal rate		0.4	3.6	1.4	1.0
Tillage × stover removal rate		1.0	0.8	3.0*	1.2

Note. Numbers in parentheses are SE ($n = 4$). Means within a column followed by the same letter are not significantly different at $P = .05$.
*Significant at the .05 probability level.

3.4 | Stover aboveground biomass

The aboveground (stover) biomass was determined following grain harvest (Table 6). There were no significant effects of tillage, stover removal rate, or their interaction on stover biomass in 2015 and 2016. In 2017, there was a significant interaction between tillage and stover removal. When no stover was removed (0% stover removal rate) under NT, the stover biomass (7.11 Mg ha^{-1}) was significantly greater than the CT 0% stover removal treatment (4.99 Mg ha^{-1}) as well as the 50 and 75% removal rates under NT (Table 6). In contrast, no significant differences were found between NT and CT at all other stover removal rates. When the stover yield data were analyzed using repeated measures, there was a significant year effect, but no other treatment effects or interactions were significant (Table 4). The average stover yields in 2015 (7.7 Mg ha^{-1}) were significantly greater than the yields in 2017 (5.8 Mg ha^{-1}), which in turn had significantly greater yields than in 2016 (4.1 Mg ha^{-1}). The above-normal precipitation, which was fairly evenly distributed in 2015, probably contributed to increased plant biomass, whereas the lowest yields occurred in the 2016 growing season, which had below-average precipitation for a summer that went from below-average precipitation in May and June compared with the 50-yr average followed by above normal precipitation in both August and September. The stover yields also followed the June and July volumetric water content trend, with 2015 > 2017 > 2016 (Table 6; Supplemental Table S2).

3.5 | Soil inorganic nitrogen dynamics and cumulative nitrate exposure

Soil inorganic N concentrations followed the typical rise-and-fall pattern following fertilization and crop N uptake (Figure 4). In 2015, the year with the highest N_2O emissions, the highest inorganic N concentrations for both the CT and NT treatments occurred with the 100% removal rates, whereas the lowest soil nitrate concentrations generally occurred with the 0% removal rate in June and July. This pattern of increased cumulative nitrate exposure (Snowdon et al., 2013) with the 100% removal CT and NT treatments compared with the lower stover removal rates also tracked cumulative N_2O emissions very well (Figures 3 and 5). These nitrate exposure results may be due to enhanced net immobilization in the 0% stover removal treatment, whereas less residue may have resulted in lower net immobilization rates, which in turn affect the level and time period that nitrate is present in the soil. The high early season N_2O fluxes with the 100% removal treatment may be due to multiple factors resulting from the removal of the previous corn stover biomass, including high nitrate exposure rates, lower labile C as observed with the lower CO_2 fluxes, and soil physical factors such as soil moisture. In a review paper, Saggar et al. (2013) indicated that complete denitrification of N_2O to N_2 may be enhanced when there is labile C, high soil water contents, and low oxygen diffusion rates, all of which are characteristic of the 0 and 25% stover removal treatments that had lower N_2O

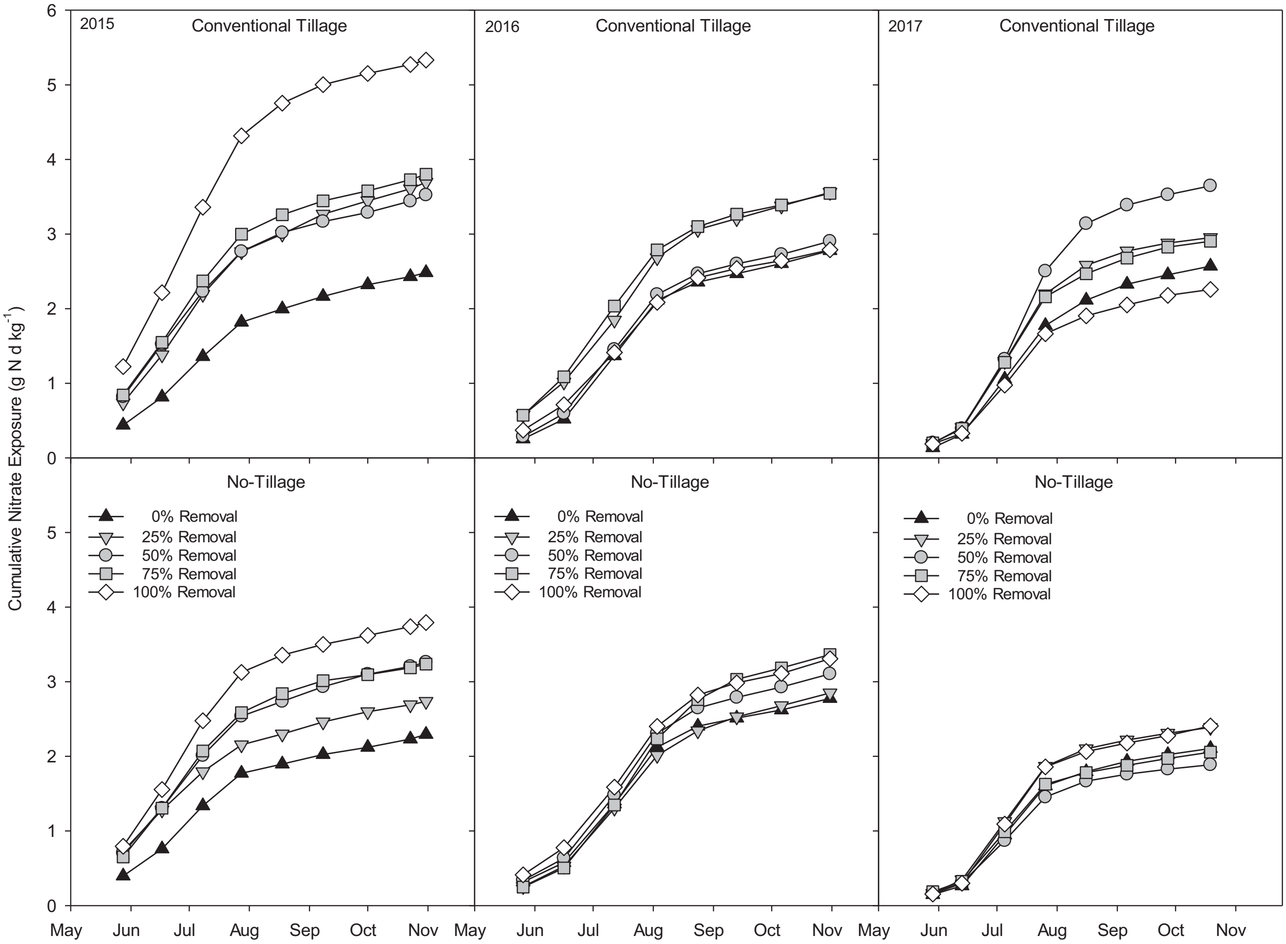

FIGURE 5 Soil nitrate exposure in the 0- to 30-cm depth under conventional tillage and no-tillage under no-tillage at five stover removal rates (0, 25, 50, 75, and 100% removal) in the 2015, 2016, and 2017 growing seasons

emissions than the 100% stover removal treatments in the Brookston clay loam soil. Treatment differences in nitrate exposure levels were less evident in the 2016 and 2017 growing seasons, although the rise and fall of nitrate did occur following fertilizer application (Figures 4 and 5).

4 | CONCLUSIONS

Stover removal had minimal impact on stover production and the direct CO_2 emissions in the NT treatments, but it was associated with reduced emissions in the CT treatment. The similar level of CO_2 emissions between the 100% removal treatment under CT compared with all other NT treatments in 2 of 3 yr implies that the CO_2 emissions from NT soils are primarily due to the decomposition of the corn stover root material and native SOC, whereas stover incorporation in CT treatments enhanced the CO_2 emissions from the corn stover, the corn roots, and the SOC, as expected. The N_2O emissions followed the opposite pattern to CO_2 especially in 2015 (the wetter year), when increased stover removal increased N_2O emissions. In the CT treatment there was a trade-off in the GHG emissions, with increasing stover removal resulting in lower CO_2 emissions and higher N_2O emissions. The 25% stover removal rate did, however, allow for reduced CO_2 emissions, with no significant impact on N_2O emissions. One explanation for the N_2O results is that the decomposition of the incorporated stover in the 0% removal treatment may have resulted in a short-term immobilization of the inorganic N in the soil at the beginning of the season when N_2O emissions occurred prior to crop growth and that uptake and/or the higher labile C may have contributed to complete conversion of N_2O to N_2. The higher N_2O emissions at the higher stover removal rates corresponded to the increases in cumulative nitrate exposure, especially in 2015. Hence, stover removal reduced CO_2 emissions under CT but increased N_2O emissions under both CT and NT, especially with high removal rates. Partial stover removal provides a balance by reducing soil CO_2 emissions while minimizing N_2O emissions from corn production.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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