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In-field management of corn cob and residue mix: Effect on soil greenhouse gas emissions

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ABSTRACT

In-field management practices of corn cob and residue mix (CRM) as a feedstock source for ethanol production can have potential effects on soil greenhouse gas (GHG) emissions. The objective of this study was to investigate the effects of CRM piles, storage in-field, and subsequent removal on soil CO_2 and N_2O emissions. The study was conducted in 2010–2012 at the Iowa State University, Agronomy Research Farm located near Ames, Iowa (42.0°′N; 93.8°′W). The soil type at the site is Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls). The treatments for CRM consisted of control (no CRM applied and no residue removed after harvest), early spring complete removal (CR) of CRM after application of 7.5 cm depth of CRM in the fall, 2.5 cm, and 7.5 cm depth of CRM over two tillage systems of no-till (NT) and conventional tillage (CT) and three N rates (0, 180, and 270 kg N ha^{-1}) of 32% liquid UAN (NH_4NO_3) in a randomized complete block design with split–split arrangements. The findings of the study suggest that soil CO_2 and N_2O emissions were affected by tillage, CRM treatments, and N rates. Most N_2O and CO_2 emissions peaks occurred as soil moisture or temperature increased with increase precipitation or air temperature. However, soil CO_2 emissions were increased as the CRM amount increased. On the other hand, soil N_2O emissions increased with high level of CRM as N rate increased. Also, it was observed that NT with 7.5 cm CRM produced higher CO_2 emissions in drought condition as compared to CT. Additionally, no differences in N_2O emissions were observed due to tillage system. In general, dry soil conditions caused a reduction in both CO_2 and N_2O emissions across all tillage, CRM treatments, and N rates.

1. Introduction

The dependency on fossil fuel in the United States (U.S.) has prompted the use of renewable sources of energy such as, biomass, solar, wind, geothermal, etc. Currently in the U.S., an estimated 170–256 million dry tons per year of corn (*Zea mays* L.) residue is potentially available for cellulosic ethanol production (U.S. tons; U.S. Department of Energy, 2011), which has the potential to reduce soil GHG (Dwivedi et al., 2009; Wilhelm et al., 2004; Graham et al., 2007). The cellulosic ethanol production from corn residue, which is a mixture of CRM (70% corn cob and 30% stover), has been used currently as a feedstock source by commercial ethanol plants in the U.S. (Schubert, 2006). However, field observations showed that storage and collection of CRM in the field caused detrimental effects to plant growth and development (personal observations of approximately 279 m^2 affected surface area, where CRM was piled and stored at different fields in northwest Iowa in 2009). Heavy machinery is used for piling and removing CRM, which can cause significant soil compaction, especially during wet conditions in the spring in Iowa. Therefore, piling and removal of CRM can lead to increase in soil compaction and bulk density (ρ_b), and affect soil diffusivities due to reduction in soil porosity (Wilhelm et al., 2004; Graham et al., 2007), N immobilization, plant growth, and soil GHG emissions (Chen et al., 2013).

Crop residue plays an important role in improving and maintaining adequate soil physical, biological, and chemical properties, which are essential in maintaining soil productivity (Karlen et al., 1994). Therefore, changes in management practices associated with crop residue can contribute to changes in the soil environment including soil GHG emissions (CO_2 and N_2O) (Cole et al., 1997; Smith et al., 2007). Some strategies to mitigate soil GHG emissions may include crop rotation, efficient N fertilizer management, and use of conservation tillage systems to sustain soil quality and crop yields (Paustian et al., 2000; Johnson et al., 2007). The reduction in tillage intensity by using NT is one option

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that can have a positive effect on reducing soil organic C and N mineralization, which can potentially lower soil CO_2 and N_2O emissions (Drury et al., 2006; Snyder et al., 2009). The reduction of soil GHG emissions under NT can be attributed to greater soil ρ_b at the soil surface, which reduces gas diffusivity and increases water content. These circumstances are favorable for anaerobic conditions resulting in denitrification processes and production of N_2O gas (Mosier et al., 2002). The use of NT results in less soil disturbance and increases residue cover creating wetter soil conditions. Therefore, NT is conducive to the increase of soil N_2O emissions, especially in poorly-drained soils that are susceptible to denitrification processes (Linn and Doran, 1984; MacKenzie et al., 1998; Mosier et al., 2002). In annual cropping systems such as continuous corn, which requires high N rates, the source and rate of N were significant factors in determining the severity of soil N_2O emissions (Bouwman, 1996; Pelster et al., 2011). However, the effects of N rates on soil CO_2 emissions were found to be variable (Al-Kaisi et al., 2008).

The storage of CRM in-field is a new practice, and there is limited research on the effect of CRM on soil GHG emissions. Nevertheless, in-field CRM storage can cause changes in soil organic C and N mineralization, thus, affecting soil GHG emissions (Cochran et al., 1997; Paustian et al., 2000; Mosier et al., 2002; Chen et al., 2013). Greenhouse gas emissions are mostly affected by biological processes such as, availability of C substrate, mineral N sources for nitrification or denitrification, and soil conditions including soil temperatures, soil water content, and oxygen availability (Butterbach-Bahl et al., 2013). These soil environment parameters can be influenced by type of tillage and affect soil C and N dynamics (Reicosky et al., 1997; Al-Kaisi and Yin, 2005; Al-Kaisi and Kwaw-Mensah, 2007). The effect of the storage and removal method of CRM on soil GHG emissions will depend heavily on the cropping system (Doran et al., 1984), climate, and soil type (Mu et al., 2008), which can be site specific. The objective of this study was to investigate the potential effect of storage and removal of CRM on soil GHG emissions and suitable management practices, such as tillage, N fertilization, CRM amounts left on the soil surface, and their interaction effects on soil GHG emissions. We hypothesized that changes in soil biological and physical properties during CRM storage and removal can create soil conditions that may increase soil GHG emissions.

2. Materials and methods

2.1. Experimental sites and treatments

The study was established in the fall of 2010 on a Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) and Harps loam (loam, mixed, superactive, mesic Typic Calciaquolls) soil association at the Iowa State University, Agronomy Research Farm located in Central, Iowa (42.0°′N; 93.8°′W). The average annual temperature and annual precipitation at the site for 2011 was 8.7 °C and 807 mm, respectively. In 2012, the average annual temperature was 11.4 °C and annual precipitation was 512 mm (Fig. 1). Before the study was established in the fall of 2010, the site was in a corn–soybean [*Glycine max* (L.) Merr.] rotation under conventional tillage, which was chisel plowed in the fall and disked in the spring. Source of N fertilizer used was liquid urea–ammonium nitrate 32% N (UAN), which was side-dress injected in May after planting using agronomic rates of 170 kg N ha^{-1} (Blackmeter et al., 1997). Phosphorus and potassium fertilizers were applied as needed to maintain optimum fertility

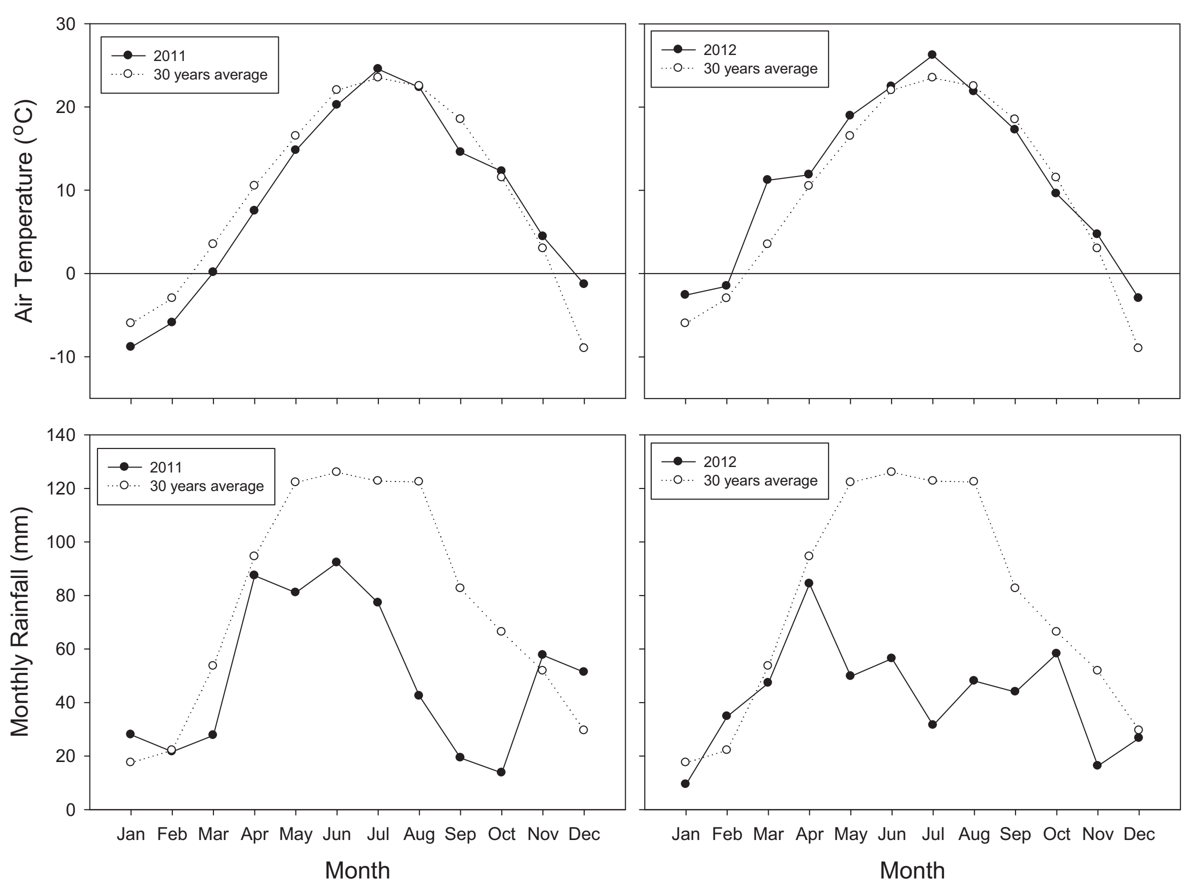

Fig. 1. Average monthly air temperature and rainfall for 2011 and 2012 growing seasons.

levels so as not to restrict corn or soybean growth. Treatments were established to monitor changes in soil GHG emissions under CRM treatments in a randomized complete block design with split–split arrangements with three replications in a continuous corn cropping system for the duration of the study. The dimension of each plot was 6.1 m wide by 7.6 m long with three meter borders between plots and replications. The site consisted of two randomized tillage systems, conventional tillage (CT) and no-tillage (NT), which represents the main treatment. Tillage system CT was conducted in the spring by using a commercially available model with straight shanks and twisted sweeps. The shanks were mounted on four tool bars in a staggering order to ensure an effective spacing of 30 cm between shanks. The depth of tillage for CT was 22–25 cm. A field cultivator was then used for secondary tillage to 10 cm deep, using a horizontal implement frame section with straight shanks and smoothing arrow. The NT system has no disturbance besides application and removal of CRM treatments, seed planting, and N fertilizer application.

Each tillage system was split into four CRM treatments including control (no CRM applied and no residue removed after harvest), early spring complete removal (CR) of CRM after application of 7.5 cm depth of CRM in the fall, 2.5 cm, and 7.5 cm CRM depths. Those treatments were randomly assigned to each tillage treatment and replication. The desired CRM treatments were based on our first field evaluations at four different sites in Emmetsburg, Iowa in 2009–2010, where CRM were piled in-field in areas of 9.1 m wide by 30.5 m long. After CRM piles were removed by farmers, noticeable amounts of CRM, ranging from 2.5 to 7.5 cm deep, were left on the soil surface. In the fall of 2010, CRM treatments were established for the 2011 growing season based on the above observations using CRM (70% corn cob and 30% corn stover) provided by POET Biorefinery from Emmetsburg, Iowa. The CRM for each treatment depth was based on spreading CRM on an experimental plot, which was weighed on a field scale to determine equivalent amounts for each designed depth. The CRM equivalent to each treatment depth was then hauled and spread, using hand hoes, on each respective plot using a field cart. For the 2012 season, the same CRM treatments were kept on the same plots, except for CR treatment, where fresh CRM was applied again in the fall of 2011 after corn harvest and removed early spring 2012.

Furthermore, each CRM treatment was split to receive three N rates of 0, 180, and 270 kg N ha^{-1} randomly assigned to each CRM treatment and replication. The N fertilizer source was 32% N liquid UAN (NH_4NO_3), which was side-dress injected in May after planting, using a spoke point injector (Baker et al., 1989). The site was planted on 6th May 2011 and 14th May 2012, using a 111 day maturity corn variety (Pioneer, P33W84) with a seeding density of 79,000 seeds ha^{-1}.

2.2. Soil greenhouse gas emissions, soil temperature, and water content measurements

During the growing season from April to October in both years, soil CO_2 and N_2O emissions measurements were taken in 7–10 days intervals coupled with soil moisture (TRIME-FM Time Domain Reflectometry, Mesa Corp., Medfield, MA) and soil temperature (Digital Thermometer, Fisher Scientific, Waltham, MA) measurements at 7.5 cm soil depth at each experimental plot following the GHG sampling protocol of GRACEnet Chamber-based Trace Gas Flux Measurement (Parkin and Venterea, 2010). The intervals of 7–10 days for the soil GHG emissions measurements were commonly used (Wilson and Al-Kaisi, 2008), due to time constraints in large experiments with many plots as in this study and the lack of an automated system availability to cover a large experimental area. It may have some limitation forecasting annual soil GHG emissions, but an effort was made to monitor and collect soil GHG measurements during critical periods such as before and after rain events. Our goal was to establish soil GHG emissions trends during the growing season as influenced by CRM treatments, tillage, and N rates. In each plot, one PVC ring (30 cm diameter and 10 cm high) was placed on the soil surface to a depth of approximately 7.5 cm. All rings were placed directly on top of the UAN band between plant rows. The flux measurements were performed by placing matching vented chambers on top of the PVC rings, and then gas samples were taken at 0, 20, and 40 min intervals after chamber deployment. During these intervals, a 10 mL gas sample was collected using a polypropylene syringe and immediately injected into evacuated glass vials (10 mL) fit with plastic caps and septa rubber stoppers. Measurements were taken between 8:00 am and 2:00 pm to approximate the 24 h mean soil CO_2 and N_2O emissions. Gas sample concentrations were determined by gas chromatography instrument (GC system Model 7890A, Agilent Technologies, Santa Clara, CA).

Cumulative soil CO_2 and N_2O emissions for the growing season were calculated using the following equation (Grote and Al-Kaisi, 2007):

$$\text{Cumulative}CO_2(\text{kg}\,\text{ha}^{-1})\text{or}N_2O(\text{g}\,\text{ha}^{-1}) = \sum_{i}^{n}\frac{(X_i + X_{i+1})}{2}\times(t_{i+1} - t_1) \quad (1)$$

where X_i is the first CO_2 or N_2O emissions (kg ha^{-1} d^{-1} or g ha^{-1} d^{-1}, respectively) reading, and X_{i+1} is the following reading at times t_i and $t_{i+1,}$ respectively; n is the last soil CO_2 or N_2O emissions reading during the growing season and, i is the first soil CO_2 or N_2O emissions reading in the growing season.

2.3. Soil mineral nitrogen measurements

Soil samples for mineral N (NO_3^- and NH_4^+) analysis were collected at the same time soil GHG emissions measurements were conducted. Six 1.7 cm diameter soil cores were taken at each treatment plot for the top 15 cm depth in the same vicinity of each PVC ring. Soil samples were then taken to the lab and immediately sieved through 4 mm sieves at field moisture condition. Then, 10 g of soil sample was placed in a 125 mL Nalgene bottle, where 50 mL of 2 M KCl was added to each soil sample bottle and shaken for 30 min (Mulvaney, 1996). The extracted solution was then filtered through a Whatman No. 42 110 mm filter paper into a 20 mL scintillation vial. The filtered solution was stored at −4 °C in a freezer until ready to be analyzed for NO_3^- and NH_4^+ with the Lachat QuickChem 8000FIA+ (Lachat Instruments, Milwaukee, WI) at the soil testing laboratory at the Agronomy Department, Iowa State University.

2.4. Statistical analysis

Data for GHG emissions, soil temperature, water content, and mineral N were analyzed using repeated measures analysis procedure with Proc Mixed model (SAS Institute, 2011). A compound symmetry covariance structure was used for repeated measures. Type of tillage was considered as a main plot, CRM treatments as the split plot, N rates as split–split-plot, and date of measurements as the repeated measure variable. Mean separation was determined using the PDIFF procedure and significance was declared at $P \leq 0.05$.

3. Results and discussion

3.1. Soil N_2O emissions rate

It is worth mentioning that residue mix was not directly stored on the experimental plots due to experimental design constraints to minimize damages to other treatments within the experiment. The effect of residue mix on soil GHG emissions were simulated as indicated in the materials and method by applying CRM to each individual plot. This may have some limitation to a certain degree on the level of changes in soil environment and soil GHG emissions as compared to actual piles storage as practiced by the industry. However, the objective of the study was to examine effects of the levels of CRM left on the soil surface after CRM piles removal on soil GHG emissions, which was achieved by leaving CRM on the plots for the same duration as practiced in actual storage process.

Seasonal soil N_2O emissions during the 2011 and the 2012 growing seasons were affected by CRM treatments and N rates. There were no differences between tillage systems effects on soil N_2O emissions for both years ($P = 0.54$ and 0.81 for 2011 and 2012, respectively). However, other studies have shown that having high amounts of residue left on the soil surface can increase C and N mineralization, thus promoting soil CO_2 and N_2O emissions (Cochran et al., 1997; Paustian et al., 2000; Mosier et al., 2002). Moreover, under CT the soil is looser and CRM was mixed into the tillage zone resulting in warmer soil environment than in NT (Licht and Al-Kaisi, 2005). The highest soil N_2O emissions occurred approximately two weeks after N rates application, which also coincided with the first rain event of the season and the increase in soil water content (Figs. 2 and 3). It was observed that soil water content of plots covered with 2.5 and 7.5 cm CRM under NT through the growing season in 2011 and 2012 was 0.43 $cm^3\,cm^{-3}$ and 0.31 $cm^3\,cm^{-3}$, respectively (Table 5). The soil water content across CRM treatments showed no significant differences within each tillage system, with the exception of NT in 2012, where 7.5 cm CRM had the highest soil water content (Table 5). Tillage systems affected soil water content during the growing season, where NT showed higher soil water content across CRM treatments

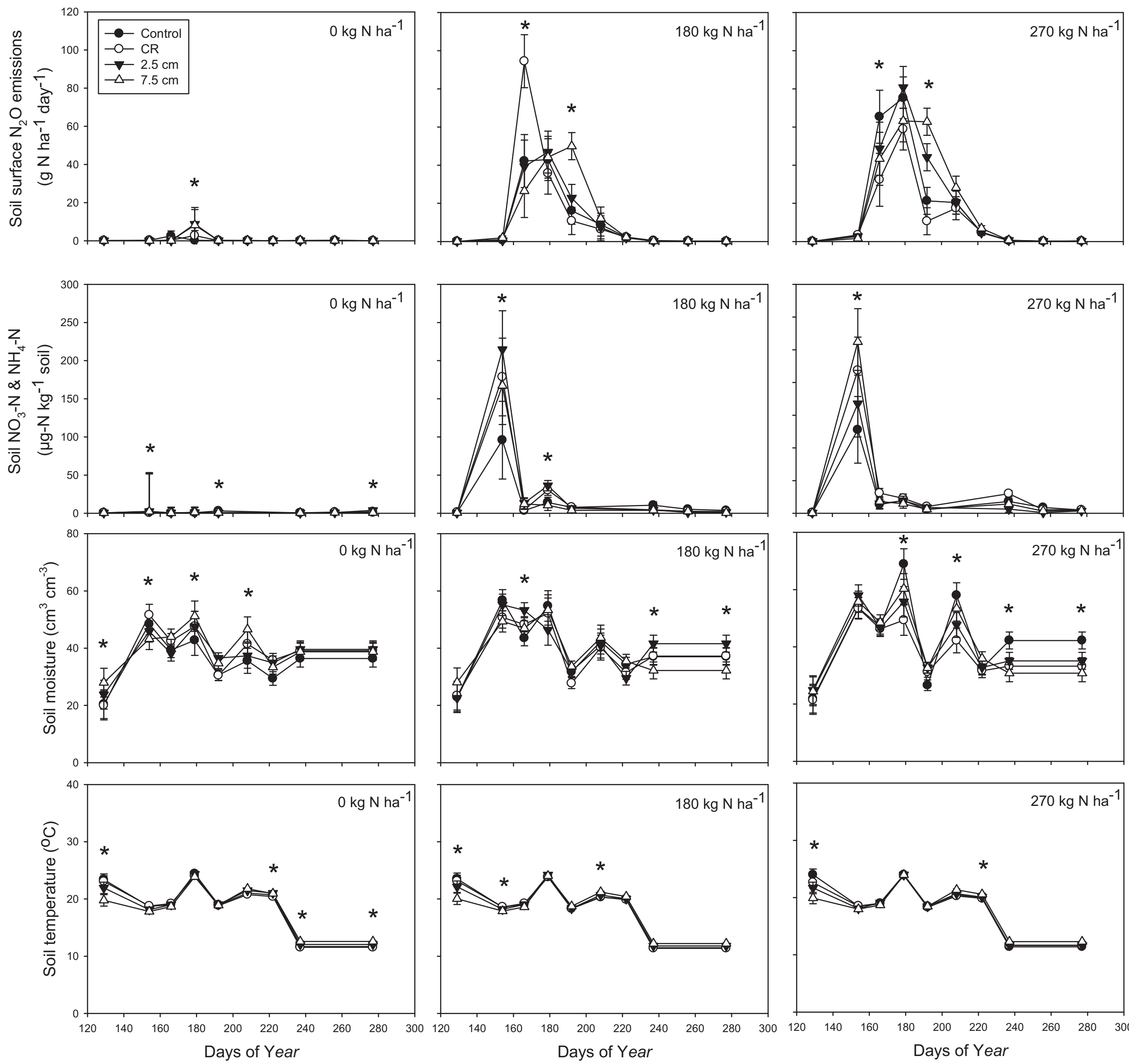

Fig. 2. Nitrogen rate and CRM effects on average soil N_2O emissions rates across two tillage systems as influenced by soil water content, soil temperature, N rate, and mineral nitrogen concentration in 2011. Error bar represents a standard deviation. A significant difference between treatments within a day is noted with an asterisk (*) at $P < 0.05$.

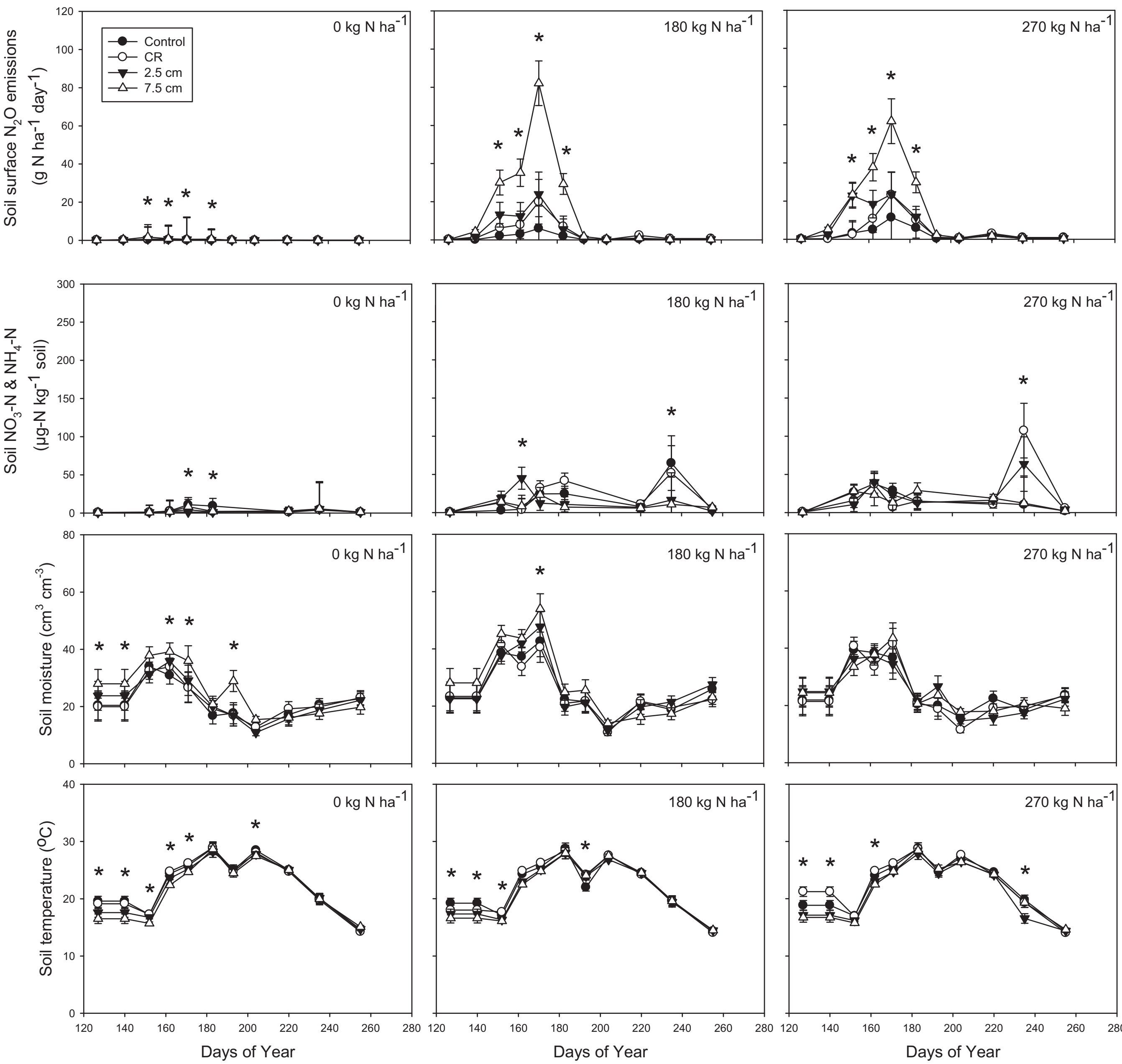

Fig. 3. Nitrogen rate and CRM effect on average soil N_2O emissions rates across two tillage systems as influenced by soil water content, soil temperature, N rate, and mineral nitrogen concentration in 2012. Error bar represents a standard deviation. A significant difference between treatments within a day is noted with an asterisk (*) at $P < 0.05$.

compared to CT in both years, with the exception of control under CT when compared to control and CR treatments for 2011 (Table 5). The combination of tillage, N rates, and CRM treatments have influenced soil N_2O emissions, where significant differences were observed on different DOYs as N_2O emissions coincide with high peaks of soil water content and temperature (Figs. 2 and 3 and Tables 4 and 5). Changes in soil water content and temperature can alter N concentration, oxygen content, and available C content (Granli and Bøckman, 1994; Tiedje, 1988). These changes in soil environment can create optimal conditions for denitrification, leading to an increase in soil N_2O emissions (Burger et al., 2005; Mosier et al., 2002; Lesschen et al., 2011). In general, changes in soil N_2O emissions due to tillage systems were not significant, but increase in N rates and soil water content during rain events as observed on several DOYs in both seasons (Figs. 2 and 3 and Table 4) caused an increase in soil N_2O emissions. During rain events in 2011, high soil N_2O emissions peaks were observed with 2.5 cm and 7.5 cm CRM on 179 and 192 DOY under 0 and 270 kg N ha^{-1}, respectively. Also, CR and 7.5 cm CRM treatments have greater soil N_2O peaks on 166 and 192 DOY, respectively under 180 kg N ha^{-1}, while control showed greater N_2O peaks on 166 DOY under 270 kg N ha^{-1} (Fig. 2). In 2012, it was observed that 7.5 cm CRM has greater soil N_2O peaks from 152 to 183 DOY under 0, 180, and 270 kg N ha^{-1} with the exception of 2.5 cm CRM where it showed similar soil N_2O peaks on 152 under 270 kg N ha^{-1} (Fig. 3). Significant correlation between soil N_2O emissions and soil water content and temperature was observed in both years with the exception of soil water content in 2011 (Table 4). The increase in N_2O emission with the complete residue removal (CR) under N rate of 180 kg N ha^{-1} in 2011, on 166 DOY can be attributed to high N availability and less N immobilization, where residue is completely removed (Fig. 2).

High peaks of soil N_2O emissions coincided with rain events (Table 4), as water content exceeded soil field capacity (0.36 cm^3 cm^{-3}) and was coupled by a greater concentration of N as NO_3^- was by 74% over NH_4^+ concentration, where total NO_3-N and NH_4-N concentrations presented in Figs. 2 and 3. In addition to N inputs and C availability, soil water content controls N_2O emissions through its influence on both microbial activity and on gas transport as water-filled pore spaces percentage change (Burger et al., 2005). Differences in seasonal soil N_2O emission across CRM treatments were expected, with changes in soil water content, soil temperature, and N rates. These are factors that influence soil N_2O emissions through change in nitrification and denitrification process (Lesschen et al., 2011; Sainju et al., 2012; Al-Kaisi and Yin, 2005; Mosier et al., 2002).

Differences in seasonal soil mineral N concentration, soil water content, and soil temperature were observed between two years (Figs. 2 and 3). In 2012, seasonal average soil mineral N concentration was 12.44 μg N kg^{-1} soil, while in 2011 seasonal average of mineral N was 20.03 μg N kg^{-1} soil across all treatments. Also, air temperatures from April to September for 2011 and 2012 were lower by 1.6 °C and higher by 0.8 °C when compared to the 30-years' average, respectively. Cumulative rainfall in both years was lower than the 30-year average, but the annual precipitation at the site in 2011 was 807 mm. However, in 2012 the average annual precipitation was 512 mm (Fig. 1). The high soil temperatures and low soil water content due to extended drought during the growing season in 2012 from June till harvest might be a contributing factor in reducing soil N_2O emissions for control, CR, and 2.5 cm CRM under all N rates, except during rain events on 152–183 DOY in 2012, where 7.5 cm CRM showed greater soil N_2O emissions than the other CRM treatments (Fig. 3). The CRM 7.5 cm created wetter condition that coupled with high temperature and high N concentration resulting in higher N_2O emission peaks with 0, 180, and 270 kg N ha^{-1} (Fig. 3). However, lack of automation in measuring N_2O emission in this study may influence the accuracy of N_2O emissions, where N_2O gas samples were collected at interval (every 7–10 days), which may lead to the potential of missing some peak periods during the growing season. Parkin and Kaspar (2004) found as the sampling period increased there is only 60–70% probability of estimating cumulative soil CO_2. However, during this study an effort was made to monitor soil N_2O emissions during and after rain events to capture the effects of soil water content under different CRM treatments on soil N_2O emission. Despite of the limitation, the results reflected CRM and N rates treatments effects on the general trend of soil N_2O and CO_2 emissions.

Table 1
Summary of treatments effects test at $P < 0.05$ to evaluate treatments effects on cumulative soil N_2O emissions within each year.

Effect[a]	Cumulative soil N_2O emission	
	2011 *P*-value	2012
Till	0.1038	0.4536
CRM	0.4932	0.0003
Nitrogen	<0.0001	0.0002
Till × CRM	0.1268	0.2625
Till × nitrogen	0.5993	0.8310
CRM × nitrogen	0.3205	0.0561
Till × CRM × nitrogen	0.3228	0.8844

[a] Till is tillage; CRM is corn cob and residue mix; and nitrogen is N rate.

3.2. Cumulative soil N_2O emissions

Years were significantly different in affecting cumulative soil N_2O emissions ($P < 0.0001$). Furthermore, statistical analysis of cumulative soil N_2O emissions for each year separately (Table 1) showed that only N rate had significant effect on soil N_2O emission in both years ($P < 0.0001$ in 2011 and $P = 0.0002$ in 2012), but no significant effect due to tillage systems ($P = 0.10$ in 2011 and $P = 0.45$ in 2012) in both years. It was also observed that CRM treatments affected cumulative soil N_2O differently in both years. In 2011, no significant differences in cumulative soil N_2O emissions between CRM treatments ($P = 0.49$) within each N rate; however, in 2012, CRM treatments had significant effects on soil N_2O emissions ($P = 0.0003$). Soil cumulative N_2O showed significantly higher values with 7.5 cm CRM treatment compared to CR in 2011 under 270 kg N ha^{-1} N rate. Also, in 2012, 7.5 cm CRM showed higher cumulative soil N_2O when compared to the rest of CRM treatments under 180 and 270 kg N ha^{-1} N rates with the exception of 2.5 cm CRM with 270 kg N ha^{-1} (Table 2). Treatments with 0 kg N ha^{-1} had the lowest cumulative soil N_2O emissions compared to 180 and 270 kg N ha^{-1} N rates. This indicates that the role of high amount of CRM in N deficient environment can cause N immobilization due to CRM high C:N ratio of 67:1 (Ahmad et al., 1973). Also, the reduction in cumulative N_2O emissions in 2012 can be attributed to serve drought conditions during the growing season (Fig. 1). In 2011, averaged across all CRM treatments (no significant differences, Table 1), cumulative N_2O emissions with 0, 180, and 270 kg N ha^{-1} N rates through the growing season were 0.13, 2.63, and 3.72 kg N_2O ha^{-1}, respectively. However, in 2012, CRM treatments showed significant differences in affecting N_2O emissions ($P = 0.0003$) as well as N rate ($P = 0.0002$) as compared to 2011 (Table 1). The highest

Table 2
Cumulative soil N_2O emissions from April to October across tillage systems as affected by CRM treatment and nitrogen rate in 2011 and 2012.

CRM[a] treatment	Nitrogen rate (kg N ha^{-1})	Cumulative soil N_2O emission (N_2O kg ha^{-1})	
		2011	2012
Control	0	0.08e	0.02d
CR	0	0.07e	0.02d
2.5 cm	0	0.19e	0.03d
7.5 cm	0	0.18e	0.04d
Control	180	2.29d	0.16d
CR	180	2.96bcd	0.55cd
2.5 cm	180	2.41d	0.62cd
7.5 cm	180	2.86bcd	2.00a
Control	270	3.84abc	0.35cd
CR	270	2.60cd	0.42cd
2.5 cm	270	4.13ab	0.89bc
7.5 cm	270	4.30a	1.44ab

Treatments with the same letter within each year are not significantly different at $P \leq 0.05$.
CRM is corn cob and residue mix.
[a] Control is no CRM applied, CR is 7.5 cm CRM depth applied in the fall and completely removed early spring, 2.5 cm is CRM depth applied, and 7.5 cm is CRM depth applied.

N_2O emissions were as a result of increase in N rate and soil water content as main drivers for soil N_2O emissions (Parkin and Kaspar, 2006; Bouwman, 1996; Pelster et al., 2011). In 2011 and 2012, differences in cumulative soil N_2O emissions correlated with soil water content and temperature with the exception of soil water content in 2011 (Table 5). The lack of correlation of N_2O emission and soil water content in 2011 may be as a result of high variability among CRM and N rates treatments (Table 5). Soil water content variability and the role of CRM in reducing water loss, especially during dry condition as we experienced in 2012, may contribute to N_2O emissions variability. In general, greater cumulative soil N_2O emissions with increase of N rate and soil water content, yielded greater soil NO_3^- and NH_4^+ concentrations, which are major factors in controlling nitrification and denitrification, thus, altering soil N_2O emissions (Chen et al., 2013).

3.3. Soil CO_2 emissions rate

Soil CO_2 emissions rates were significantly affected by CRM treatments and tillage systems. There were no differences between soil CO_2 emissions as a result of different N rates in both years (P = 0.07 and 0.99 for 2011 and 2012, respectively) (Figs. 4 and 5).

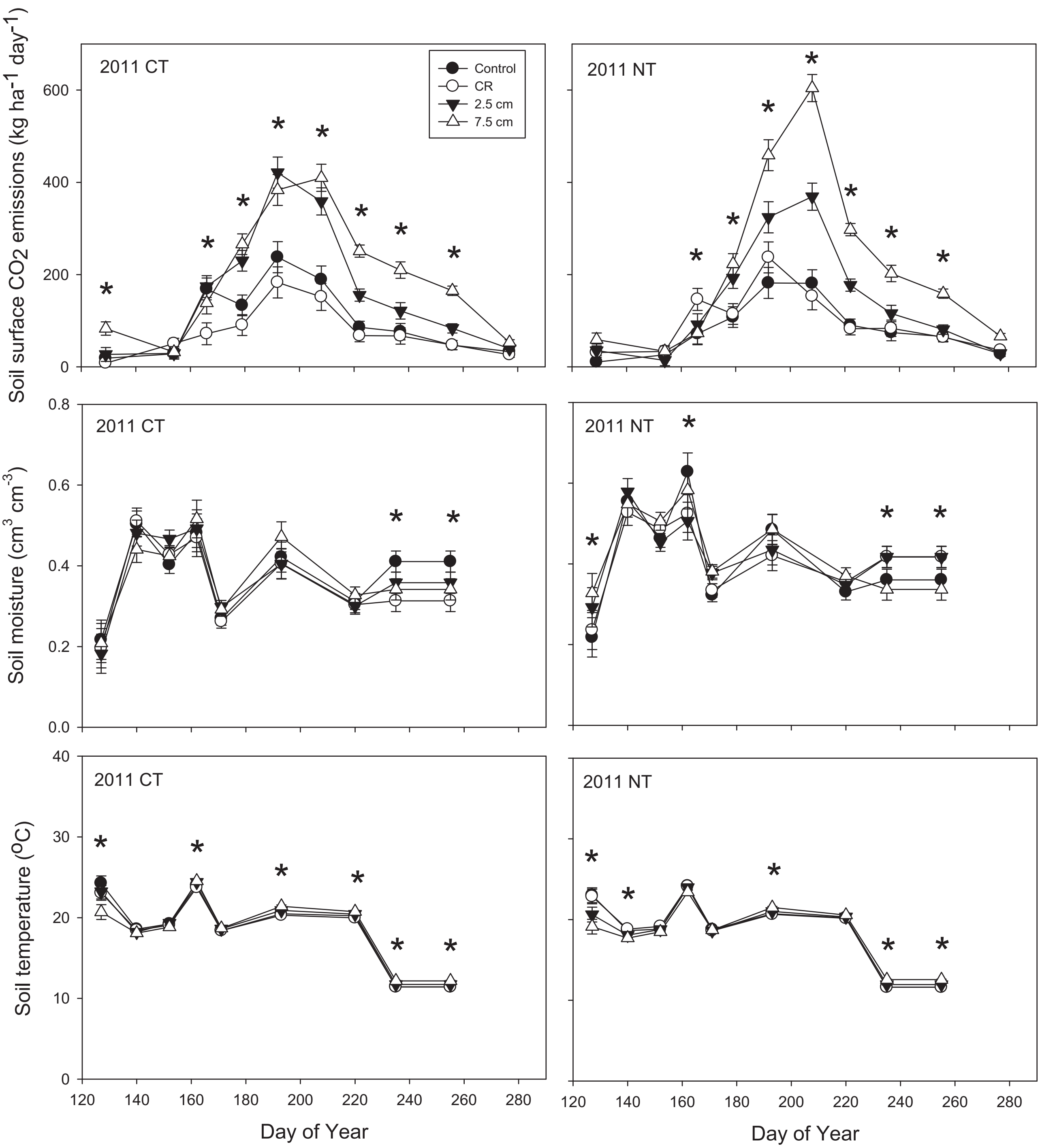

Fig. 4. Tillage and CRM effects on average soil CO_2 emissions rates across N rates as influenced by tillage, soil water content, and soil temperature in 2011. Error bar represents a standard deviation. A significant difference between treatments within a day is noted with an asterisk (*) at P < 0.05.

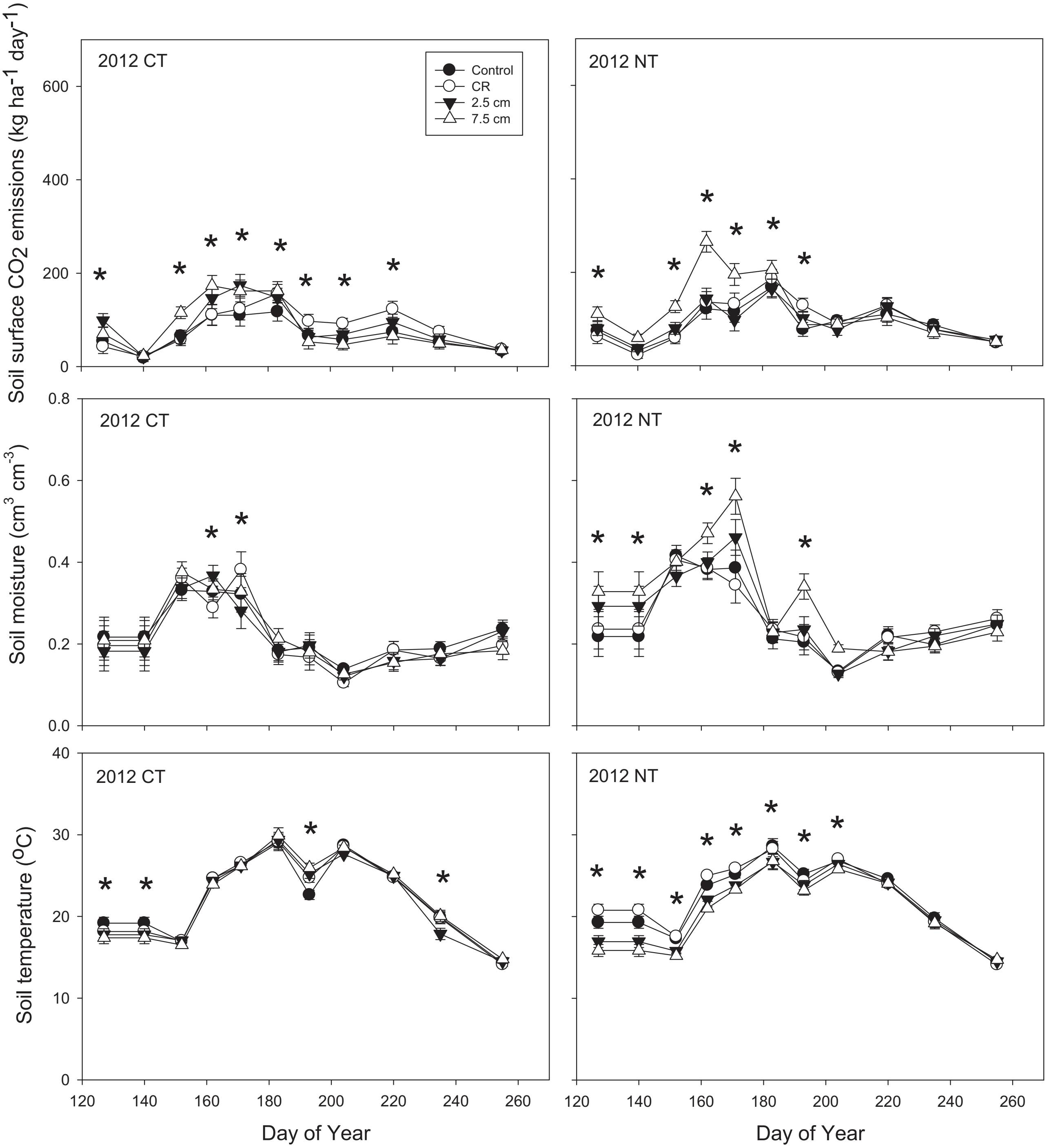

Fig. 5. Tillage and CRM effects on average soil CO_2 emissions rates across N rates as influenced by tillage, soil water content, and soil temperature in 2012. Error bar represents a standard deviation. A significant difference between treatments within a day is noted with an asterisk (*) at $P < 0.05$.

High soil CO_2 emissions rates were observed during the 2011 growing season. The high CO_2 emissions in both tillage systems were associated with high CRM treatments and peaks of CO_2 coincided with increase in soil water content and temperature (Table 4), where significant correlations between CRM treatments were observed (Figs. 4 and 5). The changes in soil water content and temperature can influence microbial activities and residue decomposition as a source of CO_2, where high supply of mineralizable C was available (Mosier et al., 2002; Burger et al., 2005; Hernandez-Ramirez et al., 2009). The effects of CRM treatments on soil CO_2 emissions rates varied according to weather conditions, where the average annual temperature and annual precipitation at the site in 2011 was 8.7 °C and 807 mm, respectively (Fig. 1 and Table 4). Soil CO_2 emissions with 2.5 cm and 7.5 cm CRM showed greater peaks on 179–237 DOY for both tillage systems in 2011 (Fig. 4). However, there are some exceptions as on 166 DOY 2.5 cm CRM and CR treatments showed higher peaks for CT and NT, respectively. Also, 7.5 cm CRM has greater peak on 256 DOY for both tillage systems in 2011 (Fig. 4). In 2012, the differences between CRM treatments diminished due to weather changes, where the average annual temperature was 11.4 °C and annual precipitation was 512 mm (Fig. 1 and Table 4). The soil CO_2

emissions for 2012 with 7.5 cm CRM showed higher peaks on 152–171 DOY for both tillage systems, while on 183–220 DOY CR treatment has higher soil CO_2 peaks than the rest of CRM treatments under CT and on 183–193 under NT system (Fig. 4)

Nevertheless, high soil CO_2 emissions rates occurred in the subsequent days after rain events, where soil water content was at or just above field capacity (0.36 $cm^3\,cm^{-3}$). It was observed that soil water content of plots covered with 2.5 and 7.5 cm CRM under NT through the growing season in 2011 and 2012 was 0.43 $cm^3\,cm^{-3}$ and 0.31 $cm^3\,cm^{-3}$, respectively (Table 5). The soil water content across CRM treatments showed no significant differences within each tillage system, with the exception of NT in 2012, where 7.5 cm CRM had the highest soil water content (Table 5). Tillage systems affected soil water content during the growing season, where NT showed higher soil water content across CRM treatments compared to CT in both years, with the exception of control under CT when compared to control and CR treatments for 2011 (Table 5). The increase in soil CO_2 emissions with 2.5 cm and 7.5 cm CRM treatments under CT and NT can be attributed to an increase in C input, microbial activity, and C mineralization (Dick, 1992).

There is a potential that storage and removal of CRM may affect seasonal soil GHG emissions by altering gas diffusivity due to an increase in soil bulk density, or soil compaction, altering soil porosity (Wilhelm et al., 2004; Graham et al., 2007). However, the results of this research showed that the correlation between bulk density and soil GHG (CO_2 and N_2O) emissions was not significant (Table 4). This may be due to the short period of this study in changing soil bulk density significantly.

3.4. Cumulative soil CO_2 emissions

The soil cumulative CO_2 emissions through the growing season were affected by the interaction of CRM treatments and tillage systems in both years, with no significant differences due to N rate ($P = 0.52$ and 0.68 for 2011 and 2012, respectively). In general, the average soil cumulative CO_2 emissions associated with both CT and NT systems across all CRM treatments in 2011 were 30.16 and 30.37 Mg CO_2 ha^{-1}, respectively. However, in 2012 the soil cumulative CO_2 emissions were different for both tillage systems, where on average soil cumulative CO_2 emission from CT across all CRM treatments was 8.83 Mg CO_2 ha^{-1} compared to 11.48 Mg CO_2 ha^{-1} under NT. The difference in cumulative CO_2 emissions between CT and NT with high CRM treatments can be attributed to the dry conditions and low soil water content in the CT system as compared to the NT system, where in the months of May June, and July of 2012, the site received on average 40 mm less rainfall and air temperature was 5 °C higher compared to the 2011 growing season (Fig. 1 and Table 4). Also, the CT soil water content across all CRM treatments averaged 0.22 $cm^3\,cm^{-3}$, where NT averaged 0.28 $cm^3\,cm^{-3}$. Previous research findings suggested a reduction in soil CO_2 production at low soil water content (Linn and Doran, 1984; Fortin et al., 1996; Chen et al., 2013). Also, differences in soil cumulative CO_2 emissions within each tillage system for different CRM treatments were observed in 2011 (Table 3). In general, the highest soil cumulative CO_2 emissions were observed from the 7.5 cm CRM treatment for CT and NT systems compared to the rest of the CRM treatments. Also, treatments covered with 2.5 cm CRM showed greater soil cumulative CO_2 emissions than the control and CR treatments in 2011 (Table 3). In 2012, there was no difference in soil cumulative CO_2 emissions across all CRM treatments under CT. However, under NT, the residue treatment with 7.5 cm CRM showed greater soil cumulative CO_2 emissions compared to the control and CR under NT and CT across all CRM treatments. These differences can be attributed to CRM decomposition as a source for CO_2 and the effect of CRM in conserving soil moisture (Chen et al., 2013), especially with NT as compared to CT. The incorporation of CRM with CT in soil reduced its effectiveness in conserving soil moisture as one of the drivers for increasing soil CO_2 emissions.

Table 4
Correlation between cumulative soil CO_2 and N_2O emissions, bulk density (ρ_b), soil temperature, and soil water content in 2011 and 2012 growing seasons at the top 15 cm soil depth across all management practices (tillage, CRM treatments, and N rates).

Parameter	2011			2012		
	ρ_b	Temp (°C)	θ	ρ_b	Temp (°C)	θ
	P-value					
CO_2	0.4264	<0.0001	<0.0001	0.3608	<0.0001	<0.0001
N_2O	0.5340	<0.0001	0.6825	0.8170	0.0174	<0.0001

Level of significance for $P = 0.05$.
ρ_b is the soil bulk density ($g\,cm^{-3}$) at 7.5 cm soil depth.
Temp (°C) is the soil temperature in degrees Celsius.
θ is the soil water content ($cm^3\,cm^{-3}$).
CRM is corn cob and residue mix.

Table 3
Cumulative soil CO_2 emissions from April to October across nitrogen fertilizer rates as affected by tillage and CRM treatment in 2011 and 2012 (no significant difference between N rates effects on CO_2 emission).

Tillage[a] system	CRM[b] treatment	Cumulative soil CO_2 emission (CO_2 Mg ha^{-1})	
		2011	2012
CT	Control	22.20c	5.74c
CT	CR	17.12c	11.13ab
CT	2.5 cm	36.24b	10.95ab
CT	7.5 cm	45.08a	7.47bc
NT	Control	18.71c	11.71ab
NT	CR	21.71c	8.29bc
NT	2.5 cm	31.89b	10.69ab
NT	7.5 cm	49.16a	15.25a

Least significant means with the same letter within each year are not significantly different at $P \leq 0.05$.
CRM is corn cob and residue mix.
[a] CT is conventional tillage and NT is no-tillage.
[b] Control is no CRM applied, CR is 7.5 cm CRM depth applied in the fall and completely removed early spring, 2.5 cm is CRM depth applied, and 7.5 cm is CRM depth applied.

Table 5
Soil water content and temperature average from April to October across nitrogen fertilizer rates as affected by tillage and CRM treatment in 2011 and 2012.

Tillage[a] system	CRM[b] treatment	2011		2012	
		Temp (°C)	θ	Temp (°C)	θ
CT	Control	18.7a	0.38bc	22.3a	0.23c
CT	CR	18.4a	0.36c	22.3a	0.22c
CT	2.5 cm	18.7a	0.37c	22.1ab	0.22c
CT	7.5 cm	18.6a	0.37c	22.3a	0.23c
NT	Control	18.6a	0.41ab	22.2ab	0.26b
NT	CR	18.6a	0.41ab	22.5a	0.26b
NT	2.5 cm	18.4a	0.42a	21.0bc	0.28b
NT	7.5 cm	18.3a	0.43a	20.5c	0.31a

Least significant means with the same letter within each year are not significantly different at $P \leq 0.05$.
ρ_b is the soil bulk density ($g\,cm^{-3}$) at 7.5 cm soil depth.
Temp (°C) is the soil temperature in degrees Celsius.
θ is soil water content ($cm^3\,cm^{-3}$).
CRM is corn cob and residue mix.
[a] CT is conventional tillage and NT is no-tillage.
[b] Control is no CRM applied, CR is 7.5 cm CRM depth applied in the fall and completely removed early spring, 2.5 cm is CRM depth applied, and 7.5 cm is CRM depth applied.

4. Conclusions

The amount of CRM left on the soil surface had an effect on soil N_2O and CO_2 emissions, where high soil cumulative and seasonal emissions, especially CO_2 were associated with high amounts of CRM left on the soil surface regardless of N rates during the growing season. The complete removal (CR) of CRM enhanced N_2O emissions in contrast to high amounts of CRM left on the soil surface. This may be attributed to N immobilization with CRM high C:N ratio (67:1), especially with high CRM treatments. The increase in soil N_2O emissions generally coincided with high N rates, soil mineral N concentration, and high moisture events, especially with low or removed CRM treatments. However, no such effect was observed on soil CO_2 emissions. Tillage system showed minimum effect on soil N_2O emissions, but under dry condition differences in soil CO_2 emissions under different tillage systems were observed, where CO_2 emissions were much greater with NT as compared to CT. Also, CO_2 emissions were highly associated with high amounts of CRM left on the soil surface. These findings suggest that the amount of CRM left on the soil surface can cause an increase in soil CO_2 emissions in particular due to availability of C source for microbial decomposition and CO_2 release. Therefore, an adequate cleanup of CRM mix after storage in the field should be less than 7.5 cm deep to reduce soil CO_2 emission.

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