Greenhouse Gas Emissions as Influenced by Nitrogen Fertilization and Harvest Residue Management in Sugarcane Production

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Core Ideas

- Application of urea led to higher N$_2$O emissions than urea–ammonium nitrate in sugarcane.
- Residue retention led to higher N$_2$O and CH$_4$ emissions irrespective of N source.
- Both N source and residue management did not affect CO$_2$ emissions.

ABSTRACT

Sugarcane (Saccharum spp.) is a major row-crop in the southern United States with high rates of N-fertilizer application and unique harvest-residue management. A 2-yr field experiment was conducted to investigate different N-fertilizer effects (urea and urea ammonium nitrate, UAN) and harvest-residue managements (residue-retain, RR, and residue-burn, RB) on greenhouse gas (GHG) emissions from soils under sugarcane production. In 2012, a split-plot design experiment was conducted with residue managements as main-plots and N-sources as sub-plots. In 2013, two experiments were conducted to investigate UAN effect under RR and RB, and N-source effect under RB on GHG emissions. Nitrogen was applied at 135 and 157 kg ha$^{-1}$ in 2012 and 2013, respectively. Soil GHG emissions were monitored using a closed chamber method. Results showed the majority of N$_2$O emissions occurred within 4 wk after N-application. Average N$_2$O emissions from urea-treated plots were 1.43 to 1.67 times higher compared with UAN for 2 yr. Urea had a N$_2$O emission factor of 3.52 and 4.45% under RB and RR, respectively, whereas UAN had 1.67 and 2.46% under the same residue management. Higher N$_2$O emission under RR treatment was supported by 15 to 20% more water-filled pore space (WFPS) in soil than RB plots, which also increased CH$_4$ emissions. Higher correlation was found between N$_2$O emission and WFPS in 2012 compared with 2013 ($r^2 = 0.52$ vs. 0.36) because a majority of the rainfall in 2012 was received within 3 wk following N application. Nitrogen sources had no effect on CH$_4$ and CO$_2$ emissions.

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Sugarcane \((Saccharum\ spp.)\) is an important row crop grown in major parts of the world and produced commercially in Louisiana, Florida, and Texas in the United States. It is a high biomass-producing crop and requires an intensive supply of different nutrients, especially \(N\), during the growth season. Although urea has been widely used in the past, urea–ammonium nitrate (UAN) solution has gained popularity as a primary \(N\) source for sugarcane production in recent years. Because of the perennial nature of sugarcane production, proper management of residues from sugarcane harvest has been a critical factor for subsequent crop growth (Viator et al., 2008). In general, sugarcane residues can be left (residue retained, RR) or burned (residue burned, RB) in the field depending on the agro-climatic conditions of that region (Wood, 1991; Fageria et al., 1997; França et al., 2012). After harvest, sugarcane residue is generally retained in the field in Australia, because it conserves soil moisture and helps with ratoon crop production (Wood, 1991; Fageria et al., 1997). In Brazil, pre-harvest fires to burn the leaves and tops are common to facilitate harvest and minimize transportation costs (Cerri et al., 2011). Both of these residue management practices have been practiced in the United States. It is reported that approximately 38% of the sugarcane crop area was burned in 2010 (USEPA, 2015). One main reason for burning harvest residue in the field is because of significant yield reduction of ratoon crop if the harvest residue is retained. This is especially true in subtropical sugarcane production areas such as the southern United States, because higher moisture and lower temperature of the soil under crop residue hinders early plant growth due to the release of toxic compounds from the degradation of residue (Richard, 2001; Kennedy and Arceneaux, 2006; Viator et al., 2008).

Since sugarcane is a major receiver of \(N\) fertilizers, it is important to understand how its application affects GHG emissions. Research on the influence of residue management on GHG emissions, specifically \(\text{N}_2\text{O}\) fluxes, from agricultural cultivation is insufficient. This is crucial because emission potentials of various GHG can vary appreciably from region to region, due to climate and field management practices such as residue management and \(N\) fertilizer application. For instance, although the application of wheat \((Triticum\ aestivum\ L.)\) straw mulch significantly reduced \(\text{N}_2\text{O}\) emission compared with soil without straw in Northern Ireland (Cai et al., 2001), removal of straw from an irrigated wheat and canola \((Brassica\ napus\ L.)\) field significantly increased \(\text{N}_2\text{O}\) loss from the soil with \(N\) fertilization in southern Alberta, Canada (Hao et al., 2001). There are no studies on the effect of different harvest residue management schemes coupled with \(N\) fertilization on GHG emissions, specifically \(\text{N}_2\text{O}\) emissions, from sugarcane production in subtropical US climate. Therefore, the objective of this study was to quantify GHG emissions under the influence of different \(N\) sources and residue management schemes in the subtropical sugarcane production.

**MATERIALS AND METHODS**

**Site Location and Characteristics**

Sugarcane field experiments were conducted at Louisiana State University Agricultural Center Sugar Research Station in St Gabriel, LA (30°15′13″N 91°6′5″W) in a first and second year ratoon crop (variety: HoCP 96-540) in 2012 and 2013, respectively. The soil type at the site was Commerce silt loam (silt 62%, sand 22%, and clay 16%; fine-silty, mixed, super active, nonacid, thermic Fluvic Hapludalf). Surface soil samples were collected with a core sampler (15-cm depth) 1 wk before fertilizer was applied and were analyzed for \(pH\), texture, cation exchange capacity (CEC), electrical conductivity (EC), total \(N\), total C, and Mehlich-3 extractable nutrients (P, K, Ca, Mg, and S). The soil was slightly acidic (pH, 6.10) with moderate CEC (15.1 cmol, kg\(^{-1}\)). Other physiochemical properties of the background soil are presented in Table 1. During the experiment, more soil samples were periodically collected for measuring the soil bulk density (BD), which was used to calculate water-filled pore space (WFPS, %) according to the formula \(\Psi = \left(\Phi_v/T_P\right) \times 100\), where \(\Psi\) is the WFPS (%), \(\Phi_v\) is the volumetric water content (%), and \(T_P\) is the total porosity (%) of the soil.

**Nitrogen and Harvest Residue Management**

The experimental treatments included no \(N\) and two \(N\) sources (urea and UAN) and two crop harvest residue management schemes (RB and RR). Sugarcane residues from the previous year’s harvest were retained for half of the experimental field (RR treatment), and the residue on the other half of the field was burned after harvesting (RB treatment). For the first-year experiment in 2012, both \(N\) fertilizer sources and residue management scheme treatments were cross-integrated to compare main effects as well as their interactions. The experiment layout was a split-plot with randomized complete block design (RCBD) where residue managements were the main plot treatments and \(N\) sources were the sub-plot treatments with a total of eight replications. Granular urea (45.9% \(N\)) and UAN (31.9% \(N\)) were applied at 135 kg ha\(^{-1}\) on 22 May 2012. Urea was surface-broadcasted by hand on both sides of the crop row and covered with soil using a garden hoe, and UAN was injected into the soil through a liquid fertilizer applicator. For the second-year experiment in 2013, two separate field trials were performed to examine the independent effect of \(N\) fertilizers and residue management on different GHG emissions. In this case, the first trial field received only liquid UAN in RB and RR plots, whereas the second trial comparing different \(N\) sources was conducted in a more commonly used RB residue management field with \(N\) at 157 kg ha\(^{-1}\) applied on 20 May 2013. For both experiments a simple RCBD with six replications was used. Each plot was 8 m (4 rows) wide by 30.5 m long.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Avg. values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pH) (1:1)</td>
<td>6.10 ± 0.5</td>
</tr>
<tr>
<td>CEC, cmol, kg(^{-1})†</td>
<td>15.1 ± 2.9</td>
</tr>
<tr>
<td>Sand, %‡</td>
<td>22</td>
</tr>
<tr>
<td>Silt, %‡</td>
<td>62</td>
</tr>
<tr>
<td>Clay, %‡</td>
<td>16</td>
</tr>
<tr>
<td>C, %§</td>
<td>0.913 ± 0.087</td>
</tr>
<tr>
<td>N, %§</td>
<td>0.088 ± 0.923</td>
</tr>
<tr>
<td>(P), mg kg(^{-1})¶</td>
<td>28.7 ± 4.80</td>
</tr>
<tr>
<td>(K), mg kg(^{-1})¶</td>
<td>105 ± 15.5</td>
</tr>
<tr>
<td>(Ca), mg kg(^{-1})¶</td>
<td>2006 ± 252</td>
</tr>
<tr>
<td>(Mg), mg kg(^{-1})¶</td>
<td>415 ± 41.8</td>
</tr>
<tr>
<td>(S), mg kg(^{-1})¶</td>
<td>44.9 ± 6.80</td>
</tr>
</tbody>
</table>

† Cation exchange capacity (CEC) was analyzed using ammonium acetate replacement method.
‡ Particle size distribution (sand, silt and clay) was done using pipette method.
§ Carbon and N was analyzed based on dry combustion method.
¶ Elemental analysis was done using Mehlich-3 extraction followed by ICP analysis.
Greenhouse gas samples were collected, as explained below, beginning 2 h after N application and are presented as 0 d after N application (DAN) for the results. Greenhouse gases were collected using a closed chamber system installed in the experimental field. Stainless steel top (0.3 × 0.3 × 0.4 m³) and bottom chambers (0.3 × 0.3 × 0.2 m³) were used to collect greenhouse gas emissions from the soil. The bottom chambers were placed 10 cm deep in the soil of the fertilized rows and were kept undisturbed within the sampling period. During each sample collection, the top chambers (lid), which were fitted with rubber sampling port on top, were used to connect with the bottom chambers using metal clamps. Ethylene propylene diene monomer (EPDM) rubber weather strips were placed on top of a 2.5 cm wide flange on both chambers for air-tight sealing when clamped during sampling. In addition, each chamber system in the field was covered with a reflective aluminum insulation sheet to prevent heating the headspace inside the metal chamber from direct sun light. The first GHG samples were taken 2 h after fertilizer application followed by sampling every alternate day for the first 3 wk and then once a week for 2.5 mo in 2012 and for about 4 mo in 2013. In 2012, collection of gas samples was shortened due to hurricane Isaac in August, which caused lodging of the sugarcane crops. For each gas sampling event, gas samples were collected from the head space of the chamber system using a 15-ml syringe at 0-, 30-, and 60-min intervals, and the collected gas samples were stored in pre-vacuumed vials fitted with butyl rubber septa. Collection of the gas samples was completed during the same time of the day (between 0900 and 1100 h) to minimize the diurnal variations between samples was completed during the same time of the day (between 0900 and 1100 h) to minimize the diurnal variations between sampling days. Collected gas samples were then analyzed using a Varian CP-3800 gas chromatograph (GC) (Varian Inc., Palo Alto, CA) equipped with a flame ionization detector (FID for CO₂ and CH₄) and electron capture detector (ECD for N₂O). Soil and air temperatures were recorded using a portable soil temperature probe at every gas sampling event. At each gas sampling event, additional soil samples were collected to determine gravimetric moisture content and WFPS of the field plots. Rainfall data for the experimental sites was obtained from the Louisiana State University (LSU) AgCenter weather station website for the Sugar Research Station.

Emission Factor Analysis

The emission factor (EF) of N₂O–N for the sugarcane-growing season was calculated using the following formula:

\[
EF (%) = \frac{\Sigma [(N_2O−N)_\text{fertilizer} − (N_2O−N)_\text{control}]}{\text{Applied fertilizer − N}} \times 100
\]

where N₂O–N_{fertilizer} and N₂O–N_{control} are the total N₂O–N emissions from the fertilized field and the control plot, respectively. Applied fertilizer N is the amount of N applied of respective source in the field (kg ha⁻¹).

Statistical Analysis

Statistical analyses were completed using SAS 9.3 (SAS Institute, 2012) for analysis of variance (ANOVA) with PROC MIXED and mean separation was done by Tukey-Kramer method at a P < 0.05 level. Regression procedure was used to determine the relationship between GHG emissions with soil moisture and soil/air temperature.

RESULTS AND DISCUSSION

Soil and Environmental Conditions

Air temperature throughout the sampling period was very similar in both years with an average temperature of 34.0°C and 34.3°C for 2012 and 2013, respectively. The average soil temperature in 2012 (29.2°C) was higher than in 2013 (27.1°C). Almost twice as much rainfall was received during the 2013 sample collection period compared with 2012. The majority of the rainfall (more than 50%) was received within 3 wk of sample collection in 2012, whereas in 2013 almost 75% of the rainfall was received 3 wk after N fertilizer application (Fig. 1 and 3). Bulk density was approximately 7% higher in RB plots (1.31 g cm⁻³) compared with RR plots (1.23 g cm⁻³). This could be attributed to the harvest residues in the RR treatment that added more organic matter to the soil leading to the lower BD (Kornecki and Fouss, 2011; Blanco-Canqui et al., 2009). Increased organic matter led to a decrease in soil bulk density due to its lower density as well as increased water content and decreased soil compactibility (Barzegar et al., 2000). Average WFPS of RR plots (41.8%) was relatively higher than the RB plots (36.7%) in 2012 and 2013. This could be attributed to the harvest residues remaining in the field in RR plots that acts as a blanket on the soil surface leading to reduced soil moisture losses.

Nitrous Oxide Emissions

The influence of different N sources and residue management on daily N₂O emissions in 2012 is presented in Fig. 1A. A significant amount of N₂O was emitted starting a day after the N fertilizer was applied and, overall, major emissions were observed within 24 DAN. Similar to this study, the majority of N₂O emissions has been reported within a few weeks of N fertilizer application to wheat and cotton (Gossypium hirsutum L.) fields (Weitz et al., 2001; Baggs et al., 2003; Zebarth et al., 2008; Halvorson et al., 2010; Sistiani et al., 2011; Liu et al., 2014; Tian et al., 2015). The highest N₂O emissions for all the treatments were recorded at 1 DAN. At 1 DAN, the Urea-RR treatment had the highest N₂O emission at 75.3 g N ha⁻¹ d⁻¹ followed by Urea-RB, UAN-RR, UAN-RB, Control-RR, and Control-RB with 51.8, 39.3, 28.0, 8.4, and 7.7 g N ha⁻¹ d⁻¹, respectively. Other higher peaks of N₂O emission occurred at 17 and 34 DAN and corresponded with relatively high soil moisture content days (Fig. 1D). Higher moisture content creates anaerobic microsites in the soil that promote denitrification leading to higher N₂O emissions (Burton et al., 2008, Oertel et al., 2016). Previous studies indicated that soil temperature plays a significant role on N₂O emissions because of the higher microbially induced nitrification and denitrification processes in the soil (Dobbie and Smith, 2003; Wang et al., 2005; Horvath et al., 2006; Zhang and Han, 2008). No particular relationship was observed between temperature and N₂O losses except for a few days (4, 17, and 34 DAN) where higher air and soil temperature may have contributed to greater gas emissions compared with adjacent sampling days. This could be due to the assertion that application of N fertilizers has been shown to increase the sensitivity of microbial activity to soil moisture while lowering the sensitivity to temperature (Oertel et al., 2016).

Application of different N sources affected N₂O emissions during 2012 (Fig. 2A). Average N₂O emissions from urea-treated plots (7.27 kg N ha⁻¹ sampling period⁻¹) was significantly higher (P < 0.05) than UAN-treated plots (5.07 kg N ha⁻¹ sampling period⁻¹), and the control (no N) plots (2.30 kg N ha⁻¹ sampling period⁻¹).
Fig. 1. Daily greenhouse gas emissions (A, B, C), rainfall, soil moisture content (D), and air and soil temperatures (E) following N applications in 2012.

Fig. 2. Total emissions during the sampling period for N₂O (A), CH₄ (B), and CO₂ (C) from a sugarcane field in 2012. The same lowercase letters on top of the bar are not statistically significant at $\alpha = 0.05$ level.
Fig. 3. Daily greenhouse gas emissions (A, B, C), rainfall, soil moisture content (D), and air and soil temperatures (E) following N applications from a fertilizer field in 2013.

Fig. 4. Daily greenhouse gas emissions (A, B, C), rainfall, soil moisture content (D), and air and soil temperatures (E) following N applications from a residue field in 2013.
Higher N₂O emissions from the urea treatments under both the residue management systems were consistently observed throughout the monitoring period. Overall, N₂O emissions from urea treatments were 1.43 and 3.16 times higher compared with UAN and control, respectively. The lower total N₂O emissions from UAN treatment could be from the deeper placement and reduced N₂O emissions from nitrification, because 25% of N in UAN is in NO₃⁻ form. Also, deeper placement of UAN (15–20 cm) could lead to a slower oxidation of NH₄⁺, leading to lower N₂O emissions from the nitrification process compared with broadcasted urea at shallow soil depths. This suggests that urea-treated plots probably had higher amounts of NH₄⁺ and NO₃⁻ available for N₂O emission (nitrification and denitrification processes) from soil than UAN-treated plots. Few studies that compared the treatment differences of urea and UAN also reported about 27 to 35% lower N₂O emissions from UAN application compared to urea (Halvorson et al., 2010; Hatfield and Ventera, 2014). However, Halvorson et al. (2010) observed a significant difference between urea and UAN in 1 of 2 yr. Conversely, Sistani et al. (2011) reported no significant differences between the two N sources. Although N fertilizer application is known to generally increase soil N₂O emission through microbially mediated pathways of nitrification and denitrification (Maljanen et al., 2003; Zhang and Han, 2008), other factors, especially regional climate and cropping systems, likely have significant influence on these processes (Tian et al., 2015; Liu et al., 2017). This study suggests that in subtropical sugarcane production, the application of UAN significantly lowers the N₂O emission compared with urea. Additionally, because there was no significant difference between UAN and control plots for the RR treatment, this suggests that using UAN as the primary N source in sugarcane production will likely minimize N₂O emission than urea from soils in which residue is retained in the field.

In 2012, the average N₂O emission from RR plots (5.72 kg N ha⁻¹ sampling period⁻¹) was significantly higher (P < 0.05) than RB (4.04 kg N ha⁻¹ sampling period⁻¹) plots. Although RR had higher emissions compared with RB with both N sources, the difference was significant only for urea treatment (Fig. 2A). This is possibly because retained residue holds more soil moisture (Dattamudi et al., 2016), which favors urease activity in the soil (Jacinthe and Lal, 2003) to release more readily available NH₄⁺ for nitrification and creates anaerobic or semi-anerobic soil conditions. The latter would increase denitrification and subsequently more N₂O emission. This assumption was supported by the higher measured WFPS in RR treatment compared with RB (Fig. 1D). In addition, higher residue in RR treatment provides an ample supply of organic C (Sousa Junior et al., 2018) that could stimulate the activity of denitrifying microorganisms as well as provide additional N from residue mineralization (Baggs et al., 2003; Jacinthe and Lal, 2003; Sistani et al., 2011). Lower N₂O emissions in RB treatment could also be caused by the adsorption of NH₄⁺ and NO₃⁻ by biochar formed from an incomplete burn of sugarcane residue in RB plots. Biochar has been shown to increase soil adsorption of both NH₄⁺ and NO₃⁻ ions (Yao et al., 2012; Bohara et al., 2019), and therefore could minimize N availability for nitrification and denitrification activities. Also, Liu et al. (2018) reported that biochar could have inhibitory effect on urease enzyme activity that slows down urease hydrolysis of urea and formation of NH₄⁺. Comparison of unfertilized residue treatments with fertilized treatments showed that urea significantly increased total N₂O emissions under both residue managements (RB and RR), whereas UAN had a significant increase only under RB (Fig. 2A). This result was consistent with the findings of Jacinthe and Lal (2003), who reported that addition of wheat straw in urea-applied field increased total N₂O emissions. Interaction of residue management and N source did not show a significant effect on cumulative N₂O emissions.

Nitrous oxide emissions from fertilizers and residue management practices were separately examined in 2013 to elucidate the clear impact of individual treatments (residues and fertilizers) on N₂O emission from sugarcane fields. Samples from both experimental fields were collected until 115 DAN (Fig. 3A and 4A). Similar to 2012, a significant amount of N₂O loss from N-treated plots started 1 DAN to the soil and overall about 70% of the emissions occurred within 3 wk after N application (Fig. 3A). In comparing N-fertilization practices, N₂O emissions from urea and UAN plots leveled off after 24 DAN and were similar to control except on 31, 43, and 58 DAN, where the presence of higher soil moisture (Fig. 3D) could have contributed to more N₂O–N emissions. In comparing residue management, large amounts of N₂O were emitted 1 DAN, and about 74 to 77% of the total N₂O emission happened within 25 DAN (Fig. 4A). Higher N₂O peaks at 14, 21, and 31 DAN were correlated to higher soil moisture recorded on those sampling days. Nonetheless, similar to 2012, no relation was observed between N₂O emissions and soil/air temperatures for both residue managements and N sources.

Comparison of N source showed average N₂O–N emissions were the highest from urea (9.43 kg N ha⁻¹ sampling period⁻¹) followed by UAN (5.65 kg N ha⁻¹ sampling period⁻¹) and control (3.03 kg N ha⁻¹ sampling period⁻¹) in 2013 (Fig. 5A). Statistical analysis showed that N₂O emissions from control, UAN, and urea treatments were significantly different from each other (P < 0.05). Among the N sources, urea produced significantly higher N₂O emissions than UAN under RB in 2013, unlike 2012, where there was no significant difference. The 2-yr data from this study indicate that urea has higher potential to lose N as N₂O compared with UAN under both RR and RB residue management. On the other hand, average N₂O–N emission from RR plots (11.9 kg N ha⁻¹ sampling period⁻¹) was significantly higher (P < 0.05) than RB plots (8.34 kg N ha⁻¹ sampling period⁻¹) in 2013 (Fig. 5B). This was equivalent to 43.4% higher emissions of N₂O from RR than from RB. This was different from the 2012 result, where there was no statistically significant difference in N₂O emissions between the RR and RB treatments that received UAN, despite the RR having 45.5% higher N₂O emissions than the RB plots. As discussed previously, studies in the past have shown that retained residues can have considerable influence on N₂O emissions compared with the bare land or cultivated soil without any crop residue. Similar to this study, in previous studies the addition of straw residue as a mulch at 16 Mg ha⁻¹ produced two times higher N₂O–N emission than bare soil (Jacinthe and Lal, 2003), whereas retained residue plots emitted 1.52 to 1.96 times more N₂O from a wheat field compared to a residue burned field (Ma et al., 2010). A recent meta-analysis of various published data on GHG emissions from agricultural soils by Shan and Yan (2013) also showed that burned residue practices decreased N₂O emissions by about 26.7%, similar to our findings in both of the study years.

Emission factors estimated for each N source under different residue management were significantly different (Table 2). Average EFs for UAN and urea under RB were 1.67 and 3.52, respectively, and they were 2.46 and 4.45 under RR. This indicates that the use of urea as N source has 1.81 and 2.10 times higher EF than UAN.
Fig. 5. Total emissions during sampling period for N$_2$O (A, B), CH$_4$ (C, D), and CO$_2$ (E, F) from a sugarcane field in 2013. The same lowercase letter on top of the bar are not statistically significant at $\alpha = 0.05$.

Fig. 6. Relation between daily N$_2$O emissions and water-filled pore space (%) in 2012 and 2013.

In 2012:
- $y = 1.74x - 42.21$
- $R^2 = 0.52
(P < 0.01)$

In 2013:
- $y = 1.72x - 42.71$
- $R^2 = 0.36
(P < 0.05)$
under RB and RR, respectively. On the other hand, average EFs for RB and RR residue management of 2.60 and 3.45, respectively, were significantly different. These EFs were in line with EFs reported for various other crops and grasslands under different climates (Dobbie and Smith, 2003; Novoa and Tejeda, 2006; Liu et al., 2011). Novoa and Tejeda (2006) reported N$_2$O EF in the range from 0.48 to 2.90% for agricultural crop production systems with 60 to 190 kg N applied as crop residue. Similarly, average N$_2$O EFs for a wheat straw–incorporated field that received urea-N in Northern China was 2.32% (Liu et al., 2011). These results along with ours indicate that EFs vary significantly from region to region and depending on specific cropping systems and management. Although sugarcane is one of the major crops grown worldwide and has different residue management and N fertilizer applications, the EFs estimated in this study could help in better predicting the regional and global N$_2$O emission inventory from subtropical sugarcane fields.

### Relationship between Nitrous Oxide Emissions and Soil Water-Filled Pore Space

The emission of N$_2$O from soil is known to be influenced by soil moisture content (Baggs et al., 2003; Dobbie and Smith, 2003; Oertel et al., 2016). To evaluate the specific effect of soil moisture on N$_2$O emission from sugarcane fields, average N$_2$O emission was plotted against soil WFPS (%) for both 2012 and 2013 (Fig. 6). The regression analysis showed a relatively stronger linear relationship between average N$_2$O emissions from all plots and WFPS in 2012 than in 2013 ($r^2 = 0.52$, $P < 0.01$ vs. $r^2 = 0.36$, $P > 0.05$), even though the amount of rainfall received in 2013 resulted in almost 25% higher WFPS than that in 2012. This was likely because almost 50% of the total rainfall received in 2012 was within 21 DAP when the N$_2$O emission flux was high from N fertilizer application, whereas the majority of the rainfall in 2013 was received 3 wk after N application when the N$_2$O concentration was already very low. On the other hand, when separating the N source and residue management treatment effects, urea had a slightly higher correlation with WFPS ($r^2 = 0.45$) compared with UAN ($r^2 = 0.40$), whereas, RR plots showed slightly stronger correlation of N$_2$O emission with WFPS ($r^2 = 0.46$) than RB plots ($r^2 = 0.40$). Previous studies reported that the relationship of N application and N$_2$O emission is generally linear (Bouwman, 1996; Gregorich et al., 2005; IPCC, 2006; Jarecki et al., 2008) and sometimes shows a threshold effect (McSwiney and Robertson, 2005). Higher soil moisture increases urea hydrolysis producing NH$_4^+$ that is the primary source for N$_2$O emissions from nitrification and denitrification pathways. The presence of 20% higher WFPS in RR plots than in RB plots (Fig. 4D) could lead to a greater number of anaerobic sites that facilitates N$_2$O emission through denitrification. The results of this study showed the relationship between N$_2$O emission and WFPS was more linear in 2012 ($r^2 = 0.52$), but displayed a threshold effect in 2013 ($r^2 = 0.36$), which was likely caused by difference in precipitation pattern following the N fertilization (Fig. 6).

### Methane and Carbon Dioxide Emissions

Results of from the 2-yr field experiments showed emissions as well as consumption of CH$_4$ by soil under both residue management treatments and N sources (Fig. 1B, 3B, and 4B). It is well known that upland soils acts as sinks for CH$_4$ under aerobic conditions; however, they become a source of CH$_4$ emissions as soil moisture content/WFPS increases (Tian et al., 2015; Moore et al., 2018). Major positive (emission) peaks in 2012 (9, 14, 17, 34, 37, and 51 DAP) corresponded with higher WFPS, soil temperature, and air temperature (Fig. 1B), whereas negative (absorption) CH$_4$ peaks (7, 11, 22, and 44 DAP) corresponded with drier days with low WFPS and relatively lower soil temperature. Positive CH$_4$ peaks (14, 21, 31, 58, and 79 DAP) and negative CH$_4$ peaks (11, 16, 23, 65, and 72 DAP) were also observed in 2013, corresponding with high and low WFPS, respectively (Fig. 3B). These observations can be supported by the fact that higher WFPS indicates more anaerobic soil conditions that are essential for methanogenic bacteria (Wang et al., 1993; Liang et al., 2007; Saggar et al., 2008).

Methane fluxes were generally higher in N-fertilized fields compared with non-fertilized fields under both residue management treatments in 2012 (Fig. 2B). In 2013, cumulative CH$_4$ emissions were numerically higher in N-fertilized plots compared with control plots, but not significantly (Fig. 5C). In 2012, average CH$_4$–C emission from urea-treated plots (8.74 kg C ha$^{-1}$ sampling period$^{-1}$) was numerically higher than UAN (6.75 kg C ha$^{-1}$ sampling period$^{-1}$) and control (5.53 kg C ha$^{-1}$ sampling period$^{-1}$) plots ($P > 0.05$). In 2013, cumulative CH$_4$ emissions from UAN and urea fertilized plots and the control were 11.4, 13.5, and 9.78 kg CH$_4$–C ha$^{-1}$, respectively. Though not significant, higher CH$_4$ emissions from N-fertilized plots was similar to the results observed in cotton and rice (Oryza sativa L.) paddy fields (Tian et al., 2015; Jacinthe and Lal, 2003; Cai et al., 2007; Ma et al., 2007; Liu and Greaver, 2009; Wang et al., 2013). In a review on N fertilization effects on CH$_4$ emissions, Cai et al. (2007) stated that N-fertilization could cause positive, negative, or no effects on CH$_4$ emissions, depending on specific agroecosystems and N forms. Although the application of N fertilizers could generally stimulate higher microbial activity leading to higher CH$_4$ emissions, urea could cause higher CH$_4$ emissions compared with UAN because of a drop in redox potential during its hydrolysis process (Wang et al., 1992). Further, the NH$_4^+$ released from N fertilizers could compete with CH$_4$ for methane monooxygenase enzymes and cause an inhibition of CH$_4$ oxidation (Liu and Greaver, 2009). The relatively lower CH$_4$ emissions in the UAN treatment could be attributed to the NO$_3$– portion of UAN that serves as an electron acceptor and raises redox potential leading to the inhibitory effect on methanogenic process (Cai et al., 2007).

Of the two residue management treatments in both years, RR plots had higher CH$_4$ emissions than RB plots. In 2012, average cumulative CH$_4$ emissions were 6.52 and 7.49 kg CH$_4$–C ha$^{-1}$ sampling period$^{-1}$ for RB and RR, respectively (Fig. 2B), whereas in 2013 CH$_4$ emissions were 7.48 and 10.5 kg CH$_4$–C kg ha$^{-1}$.

### Table 2. Average emission factor of N$_2$O–N of different N treatments under different harvest residue management in sugarcane field.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Residue burned</th>
<th>Residue retained</th>
<th>Avg. N source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>UAN†</td>
<td>1.67 ± 0.27</td>
<td>2.46 ± 0.38</td>
<td>2.07</td>
</tr>
<tr>
<td>Urea</td>
<td>3.52 ± 0.32</td>
<td>4.45 ± 0.46</td>
<td>3.99</td>
</tr>
<tr>
<td>Avg. residue management</td>
<td>2.60</td>
<td>3.46</td>
<td>–</td>
</tr>
</tbody>
</table>

† UAN, urea ammonium nitrate.
sampling period\(^{-1}\), respectively (Fig. 5B). This represents 1.30 and 1.42 times higher CH\(_4\) emissions under RR compared with RB. In 2013, RR plots (10.5 kg C ha\(^{-1}\) sampling period\(^{-1}\)) produced significantly higher \((P < 0.05)\) CH\(_4\) emission (Fig. 5D) compared with RB plots (7.48 kg C ha\(^{-1}\) sampling period\(^{-1}\)). Higher CH\(_4\) emissions under RR were consistent with the greater crop residue input that provides more organic matter for soil methanogenic organisms (Liang et al., 2007) as well as 20% higher WFPS that favors more anaerobic soil conditions and CH\(_4\) production compared with RB.

The average CO\(_2\) emissions from urea (8344 kg CO\(_2\)–C ha\(^{-1}\) sampling period\(^{-1}\)) and UAN-treated plots (8172 kg CO\(_2\)–C ha\(^{-1}\) sampling period\(^{-1}\)) were very similar to control plots (7402 kg CO\(_2\)–C ha\(^{-1}\) sampling period\(^{-1}\)) in 2012 (Fig. 2C). In 2013, average CO\(_2\) emissions for the urea, UAN, and control plots were 8063, 7758, and 7265 kg CO\(_2\)–C ha\(^{-1}\) sampling period\(^{-1}\), respectively (Fig. 5E). In both years, there was no significant difference among these treatments, although N-fertilized plots had numerically higher CO\(_2\) emissions than control plots. The higher CO\(_2\) emissions were likely due to the stimulated microbial degradation of organic matter with N addition. Similar observations were also reported by others (Nikiêma et al., 2011; Tian et al., 2015; Liu et al., 2017).

**CONCLUSIONS**

This 2-yr field experiment showed that N fertilizer source and residue management significantly influenced N\(_2\)O emissions in sugarcane production. The application of urea led to N\(_2\)O emissions with average EFs of 1.81 to 2.10 times higher than that of UAN application. Most of the N\(_2\)O emissions occurred within 3 to 4 wk after N application. The RR treatment exhibited significantly higher N\(_2\)O emissions with EFs of 1.26 to 1.47-fold higher than the RB treatment, regardless of N source. The daily N\(_2\)O flux was positively related to WFPS and the RR plots had generally higher WFPS than RB plots. Average CH\(_4\) emission was significantly higher from the RR plots than from the RB plots in 2013, although both temporal emission and absorption of CH\(_4\) was observed throughout the sampling period. On the other hand, neither N source nor residue management showed significant effect on CO\(_2\) emission, although it was generally higher in N-fertilized plots. Overall, this study provides valuable N\(_2\)O EFs for urea and UAN under different residue management approaches in sugarcane production from humid, subtropical regions. These EFs can be used for more accurate prediction of N\(_2\)O inventories. The results of C-gas emissions also help in refining GHG inventory models since they vary by crop, fertilizer source, management, and climate.

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