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RESEARCH ARTICLE

Carbon Dioxide and Nitrous Oxide Emissions from a Typical Sugarcane Soil in the Cauca River Valley, Colombia

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Abstract

Sugarcane is an important crop for tropical countries and to accurately inventory its greenhouse gas (GHG) emissions baseline measurements are needed. In Colombia, sugarcane is one of the most important crops in terms of cultivated area and, paradoxically, scientific information reporting GHG emissions based on field measurements is almost nonexistent. The objective of this work was to quantify the direct emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O) in the sugarcane-soil system of the Cauca river valley, Colombia. For this purpose, a field experiment was established in a typic haplustert soil cropped with sugarcane. The effects of nitrogen (N) fertilization and sampling site on its GHG emissions were tested using the closed static chamber method over a period of 211 days. The main cumulative emissions were 765.14 ± 34.1 g CO_2–C m^{-2} and 125.4 ± 22.6 mg N_2O–N m^{-2}. Overall, GHG emissions were modified by N fertilization, the sampling site, and their interaction. Nitrogen fertilization with urea increased mean and cumulative CO_2 and N_2O emissions, especially at the row sampling site. This paper highlights the importance of considering these factors when the quantification of GHGs or a reduction of their associated uncertainties are required. This work reportss the first GHG emissions data for a typical sugarcane agroecosystem in Colombia.

Keywords Greenhouse gas · Urea · Soil · *Saccharum officinarum*

Introduction

Sugarcane (*Saccharum spp.*) is one the most cultivated plant species in the world, with approximately 26 million hectares harvested in 2019 (FAO, 2021). This crop is responsible for 25% of the world's production of bioethanol and its production is expected to increase (Thorburn et al. 2011; OECD-FAO 2021). The average yield of this crop ranges between 70 and 90 Mg ha^{-1}, and high doses of nitrogen (N) fertilizer (between 150 and 200 kg N ha^{-1}) are needed to achieve these yields (Thorburn et al. 2011). However, N fertilizers are a major source of N_2O emissions, especially when the N dose exceeds crop demand (Chalco Vera et al. 2022). For these reasons, concerns about the environmental impacts associated with sugarcane production make the study of greenhouse gas (GHG) emissions necessary, especially for sugarcane-producing countries with expansion potential.

In Colombia, the agriculture sector accounted for 26% of the total GHG emissions in 2012, contributing 12, 48 and 88% of the total emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), respectively (Pulido et al.

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2016). In this country, sugarcane plays an important role in the economy, occupying approximately 500,000 hectares, with about 50% of the cultivated area concentrated in the Cauca River valley region (MinAgricultura 2021). This likely makes sugarcane a major source of anthropogenic GHG emissions in Colombia. Paradoxically, scientific information reporting GHG emissions based on infield measurements is almost non-existent for Colombia. In fact, most of the national GHG emissions estimaties are based on Intergovernmental Panel on Climate Change (IPCC) default emission factors. Thus, field-scale studies to quantify GHG emissions from agroecosystems are still required. Indeed, obtaining specific information on GHG emissions for sugarcane in Colombia (as in other countries) will be useful for reducing uncertainties, identifying regional hotspots, and developing enhanced strategies to mitigate those emissions. In addition, because sugarcane is an important feedstock for bioenergy production in Colombia, field measurements of GHG emissions from this crop are essential for assessing the cost of carbon and GHG emissions from biofuel production and the fossil fuel replacement (Lisboa et al. 2011).

In general, it is well known that GHG emissions (mainly N_2O) are characterized by high spatio-temporal fluctuations (Hénault et al. 2012; Butterbach-Bahl et al. 2013) and, in sugarcane, it was found that some soil conditions could generate trade-offs among the GHGs (Chalco Vera et al. 2020). In addition, agricultural management practices associated with N or carbon (C) inputs are important factors influencing GHG emissions (Panosso et al. 2009; Vargas et al. 2014; Chalco et al. 2017; Pitombo et al. 2017; Dattamudi et al. 2019). Thus, efforts to quantify GHG emissions need to address the challenge of having to capture this spatial variability. Accordingly, in-field GHG measurements are needed to determine the effect of representative management practices in variable soil conditions for the sugarcane cropping system of Colombia. The objectives of this study was to quantify the direct emissions of CO_2 and N_2O from a typical vertisol grown with fertilized and unfertilized sugarcane under two soil sampling conditions in the Cauca River valley in Colombia.

Materials and Methods

Description of the Study Area

The experiment was carried out in a commercial sugarcane field located in the central region of the Cauca River valley (Fig. 1), Colombia (− 76.283825 N; 3.67235 W). Traditionally, this area has been cropped with a monoculture of sugarcane for more than 90 years. The measurements were made in a field planted with the CC01-1940 variety, the dominant variety in the region. The productive cycle normally consists of an annual harvest for a period of five years, with mean yield of 110 Mg ha^{-1}. Nitrogen fertilization is generally performed with urea at rates of 100 to 200 kg N ha^{-1} and irrigation is applied through surface canals when required. Finally, the harvest is completely mechanized without burning.

The climate is characterized by a daily mean temperature of 24.6 °C and daily mean minimum and maximum temperatures of 19.0 and 30.2 °C, respectively. The mean annual rainfall is about 1000 mm concentrated from March to May (IDEAM, 2020). The soil was classified as a Typic Haplustert, the predominant soil in the Cauca river valley (Carbonell and Osorio 2010). It was characterized by having a pH of 8.4; 2.6% of organic matter; 46.3 ppm of available phosphorus; and 0.4, 54.8, 8.6 and 0.2 cmol (+) Kg^{-1} of potassium, calcium, magnesium, and sodium, respectively. Also, this soil has an isohyperthermal regime (mean annual soil temperature $^{>}$ 22 °C), a silty clay texture dominated by the mineral montmorillonite and a high cation exchange capacity (64 cmol (+) Kg^{-1}) (*Geoportal IGAC*, 2020).

During the experimental period (211 days), the air temperature averaged 23.9 ± 1.0 °C, and the mean minimum and maximum temperatures were 19.2 ± 1.3 and 31.0 ± 1.1 °C, respectively. The total rainfall was 645.0 mm and the relative humidity averaged 78.4 ± 5.6% (Fig. 2). Evapotranspiration averaged 5.1 ± 1.3 mm d^{-1}, solar radiation averaged 460.4 ± 94.3 Cal cm^{-2}, and atmospheric pressure averaged 904.5 ± 1.4 hPa (IDEAM, 2020).

Field Experiment

To capture the natural heterogeneity of soil conditions and determine representative GHG emissions, soil apparent electrical conductivity (ECa) data were used to guide the placement of chambers in the plots (Johnson et al. 2005). A profiler EMP-400 (Geophysical Survey Systems Inc.) soil profiler equipped with an electromagnetic induction sensor and a global positioning system (GPS) was used to measure and georeference ECa data. This profiler sensed soil ECa for the first 50 cm of soil depth. Soil was sensed every 3.5 m apart in an area of 4.8 ha. To map this information, soil ECa data were interpolated using Kriging and a Gaussian model (Nugget = 32 Ms m^{-1}, Sill = 747.9 mS m^{-1}, Range = 188 m and $r^2 = 0.974$) using Qgis ® software (ver. 3.10.5; QGIS.org 2020). After this, the experiment was lay out over an area that included soil ECa values between 25 and 108 mS m^{-1} (Fig. 1) and was arranged in split-plot factorial design from a cross-combination of N fertilization (control and urea) and sampling sites (row and inter-row) as factors of treatment. Thus, sampling chambers with a maximum distance of 20 m were considered experimental units (Table 1).

Nitrogen fertilization was carried out twice, incorporating solid urea (92 kg N ha^{-1}) in the band row at a depth of 5–10 cm. Additionally, phosphorus (P), potassium (K),

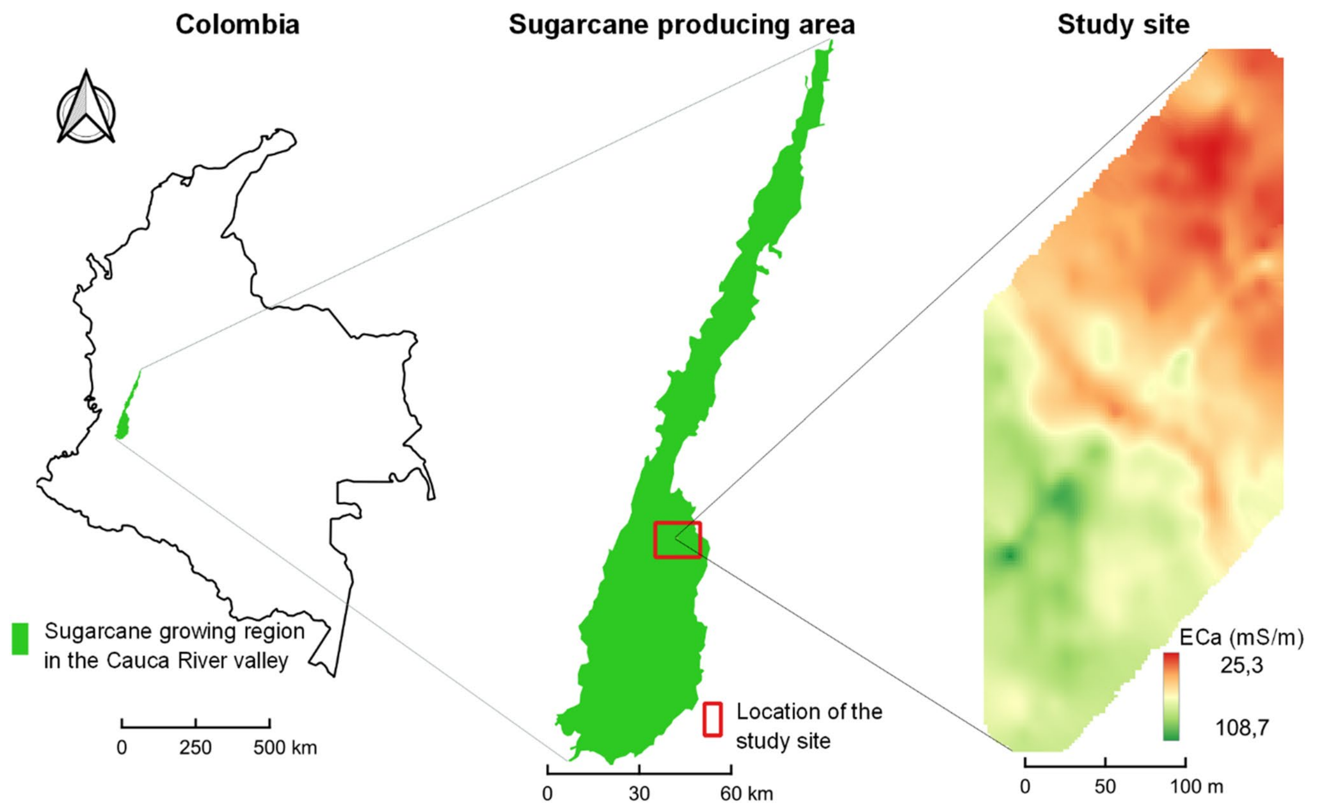

Fig. 1 Geographical location of the sugarcane production region in the Cauca River valley, Colombia (in green) and detail of the spatial distribution of Apparent Electrical Conductivity (ECa) of the soil in the study site

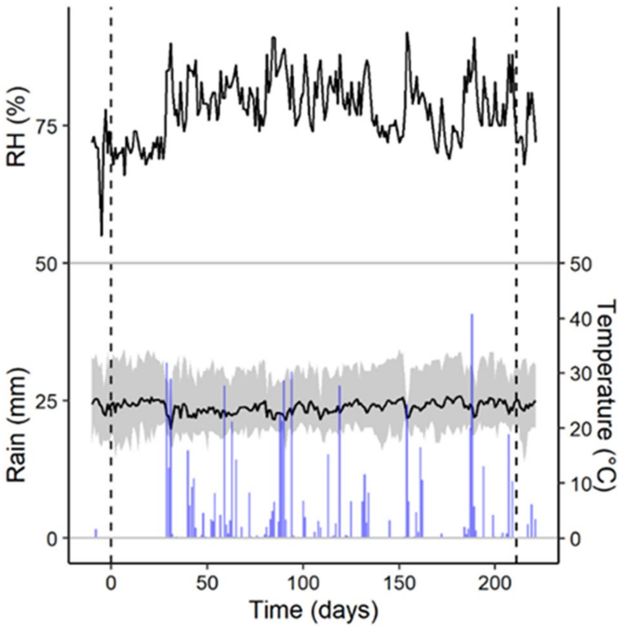

Fig. 2 Dynamic of relative humidity, air temperature, and daily precipitation in the study area during the evaluation period in the Cauca River valley, Colombia

Table 1 Number of chambers by factors evaluated

Fertilization	Sampling site	Chamber
Control (0 kg N ha^{-1})	Row (at 0 m from the row)	4
	Inter-row (at 0.8 m from the row)	4
Urea (184 kg N ha^{-1})	Row (at 0 m from the row)	20
	Inter-row (at 0.8 m from the row)	10

sulfur (S) and zinc (Zn) were applied to supply the crop requirements according to Viveros Valens (2018). To reproduce possible application effects in the control treatment, the fertilization machinery was used without fertilizer. Management practices summarized in (Table 2).

Gas Sampling

Greenhouse gases were sampled using the closed static chamber method (Norman et al. 1997; de Klein et al., 2012). Each chamber consisted of two attachable PVC-cylinders (base and lid) 0.1 m in height with an inside diameter of 0.25 m. The base was buried 0.05 m into the ground. The lid had two rubber stoppers: one to insert a digital thermometer and record air temperature, and

Table 2 Crop management practices conducted in the sugarcane field during the period 2019–2020

Activity	Date	Description
Fertilization	20 August 2019	(92 kg N + 8.6 kg P + 2.5 kg S + 0.5 kg Zn + 2 g B) ha^{-1}
	14 October 2019	(92 kg N + 120 kg K + 2.5 g Zn) ha^{-1}
Irrigation	August 30th, 2019	Open channel gravity irrigation system
	September 4th, 2019	
	September 15th, 2019	
	December 10th, 2019	
	January 22nd, 2020	

the other to draw the air sample using 20 mL polypropylene syringes. Immediately after coupling cylinders, four samples were extracted (0, 20, 40 and 60 min) from each chamber and they were stored individually in 5.9 ml evacuated vials (Exetainer, Labco ®).

Field gas sampling was performed between 8 and 11 AM to reduce environmental variations. Sampling began after the second harvest of the crop and continued a weekly for the first four months and, thereafter, every 30 days for the remainder of the growing season (211 day in total). In addition, when N fertilization was scheduled, gas sampling was performed one day before and the three days following application of the N fertilizer, totaling 20 sampling dates. The same sampling frequency was used in the unfertilized plots. Mobility restrictions established by the Colombian government to mitigate the spread of the SARS-Covid 2 virus impeded sampling from day 97 to day 168 of the evaluation. The concentration (ppm) of each GHG was determined by mean of gas chromatography using a Shimadzu ® GC-201 (Shimadzu Corp., Japan) equipped with a flame ionization detector for CO_2 and an electron capture detector for N_2O (*GC-2014*, 2020).

Calculation of GHG Emissions

The GHG emissions were calculated using a restricted quadratic regression as explained by Venterea et al. (2020). To screen data the minimum detectable flux (MDF) was calculated for CO_2 and N_2O following Parkin et al. (2012). The daily mean emissions were estimated based on the method and constants proposed by Parkin and Kaspar (2003) for CO_2 and Parkin and Kaspar (2006) for N_2O. To calculate the cumulative emission of each of the GHG, the daily mean emissions were projected according to the day of evolution (daily emission fluxes), then the projected points were linearly interpolated and the area under the curve was calculated. This method was applied including the interrupted sampling period.

Statistical Analysis

In order to test differences among treatment effects over time, a linear mixed model was adjusted following akaike criteria (Chalco Vera et al. 2017) considering factors of treatments (fertilizer and sampling site) as fixed effects and time as a random effect. The type III hypothesis test was used to control for possible directional, non-directional, and combined errors during hypothesis testing (Shaffer 2002), and the LSD Fisher test with at 0.05 level was used to compare adjusted means (Westermann et al. 2021). In addtion, ANOVAs at 0.05 level were used to determine significant treatment effectson cumulative GHG emissions.

Results

CO_2 Emissions

Although the CO_2 emissions had a gap of 71 days due to the interruption of sampling (Fig. 3A,C), the daily mean CO_2 emissions differed significantly for the fertilization factor ($p<0.01$). The interaction between fertilization and the sampling site also generated a significant effect ($p < 0.05$). The highest CO_2 emissions were observed at 45, 50, 80 and 211 days of evaluation, and the lowest CO_2 emissions were recorded during the first four days of evaluation (0–3 days) (Fig. 3A, C). The time (random effect) only explained 20,5% of the random variance of the model. Overall, urea generated a higher daily mean CO_2 emission than the control (3.55 ± 0.3 vs. 2.84 ± 0.35 g CO_2–C m^{-2} d^{-1}, respectively). The ranking of the daily mean CO_2 emissions for the interaction fertilization-sampling site (from highest to lowest) was: 3.6 ± 0.34; 3.5 ± 0.31; 3.3 ± 0.41 and 2.3 ± 0.41 g CO_2–C m^{-2} d^{-1} for Urea*Inter-row, Urea*Row, Control*Row and Control*Inter-row, respectively. The mean cumulative CO_2 emission during the evaluation period (211 days) was 765.14 ± 34.1 g CO_2–C m^{-2}. Fertilization factor had a significant effect on cumulative CO_2 emissions ($p < 0.05$)

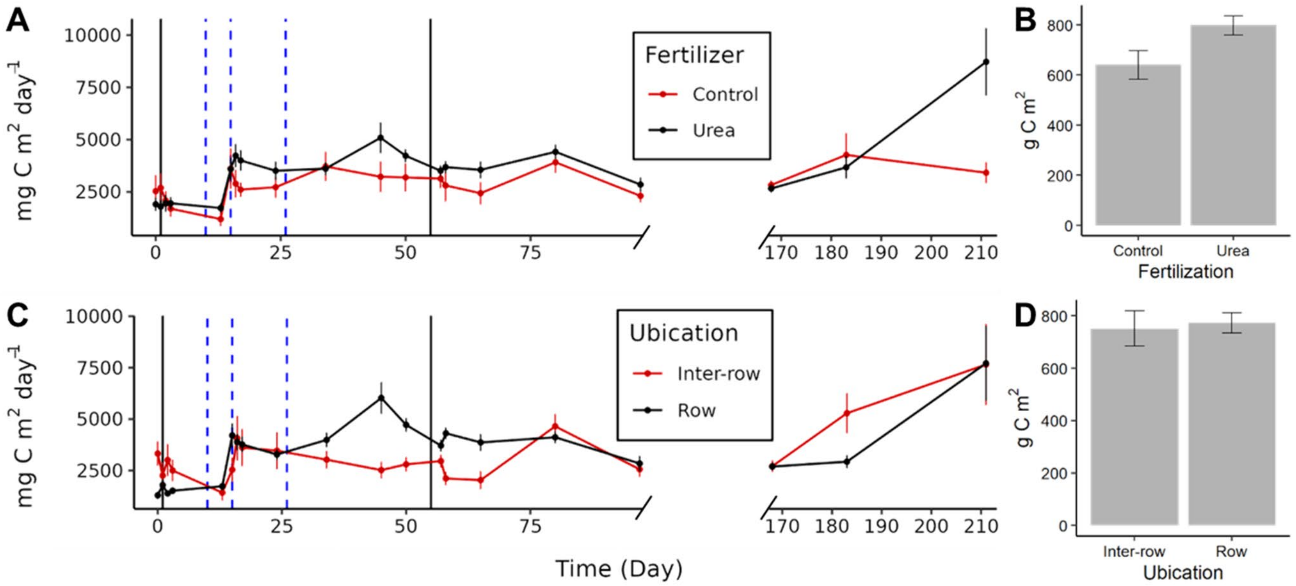

Fig. 3 Dynamics of emissions and cumulative emissions of CO_2, considering the fertilization factor (**A** and **B**, respectively) and sampling site factor (**C** and **D**, respectively) for the evaluated growing season of sugarcane in the Cauca River valley, Colombia. Black (continuous) and blue (dotted) vertical lines indicate irrigation and nitrogen fertilization applications, respectively. Bars represent standard errors

(Fig. 3B), but the sampling site of the chambers or the fertilization-by-sampling site interaction did not have a significant effect ($p > 0.05$) (Fig. 3D). The urea generated higher cumulative CO_2 emissions than the control (810.2 ± 38.1 vs. 640.4 ± 89.7 g CO_2–C m^{-2}, respectively).

N_2O Emissions

The N_2O emissions had a gap similar to that of the CO_2 flux (Fig. 4A, C). However, the daily mean N_2O emissions had no significant differences between fertilizer treatments, sampling site, or their interaction ($p > 0.05$). In fact, there

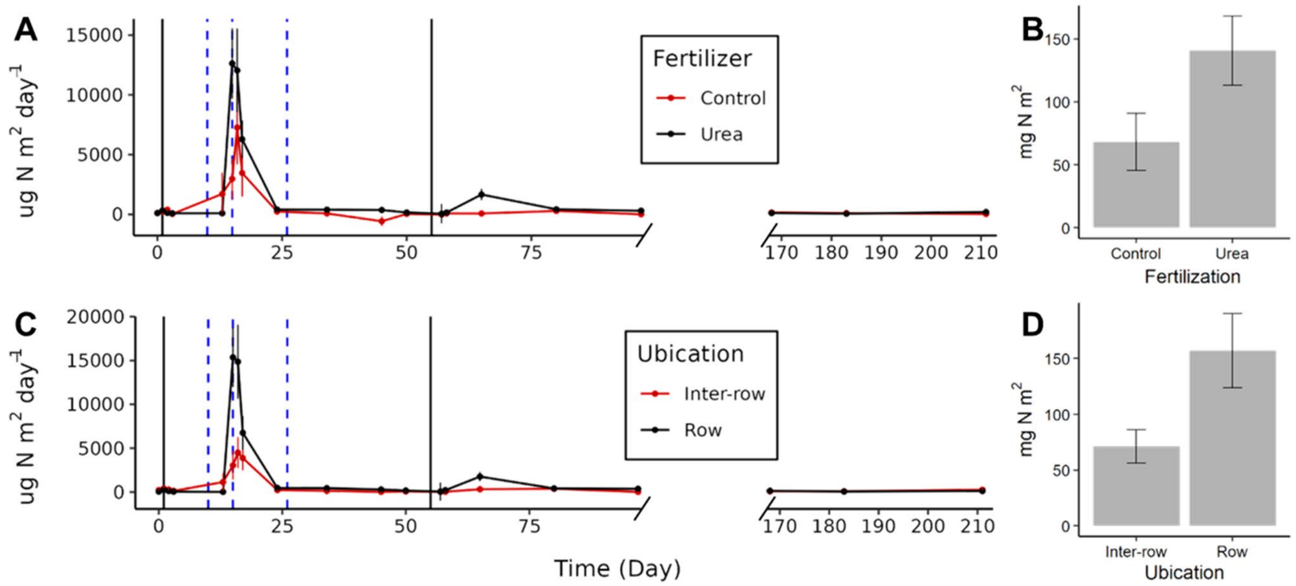

Fig. 4 Dynamics of emissions and cumulative emissions of N_2O, considering the fertilization factor (**A** and **B**, respectively) and sampling site factor (**C** and **D**, respectively) for the evaluated growing season of sugarcane in the Cauca River valley, Colombia. Black (continuous) and blue (dotted) vertical lines indicate N fertilization and irrigation applications, respectively. Bars represent standard errors

was important variability in the N_2O emissions: approximately 385 and 363% for fertilized and unfertilized treatments, respectively. The daily mean N_2O emission of urea and control was 1.52 ± 0.77 and 0.99 ± 0.05 mg N m^{-2} d^{-1}, respectively. The dinamic of N_2O emissions showed two emission peaks: at 14 days after the first fertilizer application and two days after the second fertilizer application (Day 55) (Fig. 4A, C). The time (random effect) only explains 30.1% of the random variance of the model. The mean cumulative N_2O emission during the evaluation period (211 days) was 125.4 ± 22.6 mg N_2O–N m^{-2}. The factors fertilization, sampling site, and their interaction had no significant effect ($p > 0.05$) (Fig. 4B, D). Although there was no significant effect ($p = 0.32$), urea tended to produce higher cumulative N_2O emissions than the control (140.7 ± 27.5 and 68.2 ± 22.7 mg N_2O–N m^{-2}, respectively).

Discussion

Despite there is valuable information regarding GHG emissions in sugarcane, this manuscript reports the first GHG emission data obtained in the field for a typical sugarcane agroecosystem in the Cauca River valley, Colombia. It is important to note that in this work the uncertainty associated with the interruption of measurements (see Material and Methods section) was partially addressed through linear interpolation of data. Although this method has some shortcomings (Levy et al. 2017), the overall uncertainty generated on the effects of N fertilization or chamber location could be considered negligible, since the interruption began 40 days after the last N fertilization, outside the critical period caused by N application (Smith and Dobbie 2001; Reeves and Wang 2015; Ferrari Machado et al. 2019).

Our results showed significant CO_2 and N_2O emission rates during the crop cycle. In fact, CO_2 emissions ranged between about 1.98 ± 0.25 and 243.9 ± 15.87 g CO_2–C m^{-2} d^{-1} over the entire experimental period. These emissions are close to those informed by others studies for sugarcane under tropical climate (La Scala et al. 2006; Silva-Olaya et al. 2013; Farhate et al. 2019). However, they were higher than those reported by Vasconcelos et al. (2018) for a Typic Acrudox, this difference could be associated with the high content of organic matter in our conditions, which could promote more decomposition and CO_2 production. In the same way, N_2O emissions found in this study (between about 0.09 and 33.9 mg N_2O–N m^{-2} d^{-1}) were similar to those reported by Bolfarini et al. (2018) for an oxisol in Sorocaba, Brazil (0.6–22.8 mg N_2O–N m^{-2} d^{-1}); but lower than those found in Piracicaba, Brazil (≤ 0.7 mg N_2O–N m^{-2} d^{-1}) by Vasconcelos et al. (2018).

Concerning the effect of N fertilization on GHG emissions, we found that the peaks in emissions of N_2O and CO_2 following urea application events were expected and in agreement with the literature (Dattamudi et al. 2016; Tamale, van Straaten, et al., 2021; Vasconcelos et al. 2022). For our conditions, N fertilization increased CO_2 emissions by 24.6% with respect to unfertilized treatment. We attribute the significant difference to the reaction and extra CO_2 release of the carbonyl group of urea in soil (De Klein et al. 2006). In addition, the supply of N most likely enhanced microbial activity since it could support the required amino acid synthesis (Tian et al. 2015; R. Liu et al. 2017), which ultimately resulted in higher CO_2 emissions. Our results agree with those of Dattamudi et al. (2019) who found higher CO_2 emissions in sugarcane when it was fertilized with N; but contrast with those found for a subtropical sugarcane agroecosystem (Chalco Vera and Acreche 2018). In this last case, the soil had a much lower pH (5.9) than our condition (8.4), which probably decreased CO_2 emissions due to a reduction in urea hydrolisis (Cabrera et al. 1991).

With respect to N_2O emissions, this study quantified the influence of N fertilization for the first time for sugarcane soils in Colombia, where, until now, no previous data was available. Nitrogen fertilization tended to increase (106%) cumulative N_2O emissions in relation with unfertilized treatment. This could be attributed to an increase in soil inorganic N availability which enhanced nitrification and denitrification processes (Denmead et al. 2010; Signor et al. 2013; da Silva et al. 2014; Neto et al. 2016; W. J. Wang et al. 2016). However, our research did not address soil variables to understand the mechanisms that control GHG emissions in the soil. Therefore, this will be mandatory to better explain the effects of sugarcane management practices on GHG emissions. Moreover, we highlight the need to determine and validate the variables behind the soil ECa that explain its influence on GHG emissions.

On the other hand, our results showed that the location of the chambers had a significant effect on N_2O emissions. The importance of chamber location in the crop has also been demonstrated by Allen et al. (2010) and Westermann et al. (2021), and it is key for monitoring N_2O emission peaks generated by fertilizer application (Williams et al. 1999; Tamale et al. 2021a, b). Thus, this study suggests that the allocation of chambers in the inter-row site could not be avoided to reduce the cost of intensive gas sampling when the specific objective of testing N fertilization strategies to mitigate N_2O emissions is addressed.

Conclusions

Greenhouse gas emissions from the sugarcane soil system in the Cauca River valley were closely modified by N fertilization, the sampling site and their interaction. This work demonstrates the importance of considering these factors when representative GHG quantification is targeted. Nitrogen fertilization was an important management practice that increased N_2O and CO_2 emissions, which until now had not been quantified in Colombia. This shows the necessity to address new studies assessing mitigating management practices focused on N fertilization alternatives. This paper contributes to our understanding of the dynamics of CO_2 and N_2O emissions from sugarcane soils in Colombia. However, more experiments should be performed to analyze in more detail the effects of soil conditions on GHG emissions.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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