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The effects of agronomic practices on soil greenhouse gas emissions in maize production systems in Buea, Cameroon

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With a specific focus on zero tillage and organic fertilization, this study examines the effects of agronomic practices on soil greenhouse gas (GHGs—CO_2, N_2O, and CH_4) emissions, global warming potential (GWP), maize productivity and greenhouse gas intensity (GHGI) over two growing seasons (2020 minor and 2021 main season) in Buea, Cameroon. Two tillage practices–i.e., zero-tillage and conventional tillage with ridge formation and three fertilizer treatments—i.e., no fertilizer, synthetic fertilizer (urea), and organic fertilizer (composted municipal solid waste), were factorially combined in a split-plot design with three replications. Fertilizer was applied at a rate of 100 kg N ha^{-1}. The hybrid maize cultivar CMS 8704 was used. GHG emissions were measured using the static flux chamber method, and flux rates were calculated with the HMR package in R software. Results showed that tillage and fertilizer types significantly ($p<0.05$) influenced seasonal cumulative CO_2, N_2O, and CH_4 emissions. Synthetic fertilizer treatments produced the highest cumulative N_2O emissions, particularly under zero-tillage in 2020 and conventional tillage in 2021. Conventional tillage paired with organic fertilizer yielded the highest CO_2 emissions across both seasons, while methane fluxes were low and largely negative across treatments, indicating that the volcanic upland soils acted as CH_4 sinks. Application of synthetic fertilizer increased GWP by 20% and 322% under zero tillage in the 2020 and 2021 seasons, respectively. Under conventional tillage, GWP decreased by 15% in 2020 but sharply increased by 295% in 2021, highlighting season-specific effects. Although treatment effects were not significant ($P>0.05$) on maize yields in 2020, the highest yield (3.06 t/ha) occurred under conventional tillage without fertilization. Fertilizer type and its interaction with tillage significantly ($P<0.05$) influenced yields in 2021, with the highest yield under conventional tillage with synthetic fertilization (6.15 tons/ha). However, conventional tillage treatment without fertilization produced the highest yield (3.06 t/ha) in 2020 and the lowest GHGI (12.04 kg CO_2-eq t^{-1}). In 2021, zero tillage treatment without fertilization resulted in a high yield (5.56 t/ha) with the lowest GHGI (2.15 kg CO_2-eq t^{-1}). The results suggest that in Buea's minor growing season, conventional tillage with or without organic fertilization reduced GHG emissions without compromising yields, while in main seasons, zero tillage without fertilization offered the most favorable yield-emission balance. This study highlights the importance of context-specific soil and nutrient management strategies for sustainable agriculture and climate change mitigation. Findings provide valuable data for national GHG inventory reporting and inform agronomic practices in tropical upland agricultural systems.

KEYWORDS

greenhouse gas emissions, global warming potential, agronomic practices, zero tillage practices, organic fertilizer, maize production systems, greenhouse gas intensity (GHGI)

1 Introduction

Balancing agricultural productivity with environmental sustainability is crucial for global food security and climate-change mitigation (1). Agricultural production together with agriculture-induced land-use change and land degradation contribute significantly to greenhouse gas (GHG) emissions, accounting for up to 24% of total global anthropogenic emissions (2). Specifically, agricultural soils are major sources of GHGs, responsible for about 60% of nitrous oxide (N_2O) and 50% of methane (CH_4) emissions from human activities (3). In cropland systems, tillage and fertilizer management directly influence soil GHG emissions (4). As demand for agricultural land increases with population growth, these emissions are expected to rise (5). However, significant knowledge gaps still persist on the GHG mitigation potential of agronomic practices and their effects on crop yields in sub-Saharan African countries, including Cameroon.

Tillage, a fundamental agricultural practice, involves mechanically manipulating soil to prepare it for planting. Tillage can overcome soil-related constraints. However, if not well managed tillage may lead to adverse effects such as soil-structure degradation, loss of organic matter, and increased GHG emissions (6). In cropland ecosystems, tillage practices can influence soil CO_2 emissions by accelerating the decomposition of organic matter, increasing microbial activity, and altering soil temperature (7). For N_2O emissions, tillage enhances aeration and nitrogen availability and disrupts soil microbial communities, directly or indirectly impacting N_2O emissions (8). Additionally, tillage can affect CH_4 emissions by increasing aeration and oxygen availability, thereby disrupting anaerobic conditions and altering microbial communities (9).

Nitrogen (N) fertilizers are commonly applied in large quantities to boost crop production worldwide. From 2015 to 2020, global N fertilizer use increased by 1.5% annually, from 175 Tg N yr^{-1} to 188 Tg N yr^{-1} (10). Excessive application beyond crop requirements leads to significant environmental problems, including soil and water degradation, as well as increased GHG emissions (11). Synthetic nitrogen fertilizers are a major contributor to N_2O emissions from agricultural soils through the enhancement of microbial activity, which accelerates nitrification and denitrification processes (12). Their use also causes watershed pollution, and nitrate leaching, leading to eutrophication. Additionally, overuse of these fertilizers can elevate soil CO_2 emissions by disturbing soil structure, degrading organic matter, and altering microbial communities. The impact of N fertilizer on CH_4 emissions is complex and depends on factors like fertilizer type and soil management practices (13). Furthermore, conventional fertilizer recommendations, primarily calibrated for tillage-based systems, may not be suitable for conservation agriculture and different fertilizer management practices may perform differently under different tillage regimes.

According to Cameroon's 2021 updated Nationally Determined Contribution (NDC) report, agriculture employs nearly 60% of the population and is a key sector of the economy, contributing 23% to its gross domestic product (GDP). However, agriculture is also the largest source of GHG emissions, accounting for 69% of the total, with 24,074.61 Gt CO_2 Eq (14). Given the country's commitment to reducing its carbon footprint by 35% by 2030, agriculture presents a significant opportunity for GHG emission reduction. The NDC emphasizes promoting agricultural practices that enhance production while reducing emissions as a crucial strategy to achieve this goal.

The United Nations Framework Convention on Climate Change (UNFCCC) has established guidelines for reporting GHG emissions to the Intergovernmental Panel on Climate Change (IPCC). However, many sub-Saharan African countries, including Cameroon, lack the country-specific data needed for accurate national GHG accounting in agriculture (15). This data scarcity poses a significant challenge, especially with the upcoming shift from Biennial Updated Reports to Biennial Transparency Reports under the Enhanced Transparency Framework starting in 2025. As a result, Cameroon struggles to effectively measure, monitor, and report GHG emissions from agricultural systems, as required under the Paris Climate Agreement, which the government ratified in 2016.

Previous research on agriculture and climate change in Cameroon has primarily focused on adaptation strategies and assessing the impacts of climate change on agricultural systems

(16–18). The knowledge of how agronomic practices such as zero tillage and organic fertilizer impact GHG emissions and crop productivity in Cameroon remains limited. This study aims to address this knowledge gap by investigating the specific case of Buea, Cameroon, and exploring the complex interactions between tillage and fertilizer management and their consequences on soil GHG emissions, global warming potential (GWP), maize yield and greenhouse gas intensity (GHGI). These farm management practices are common across most agroecological zones in Cameroon. We hypothesize that agronomic practices such as reduced tillage and organic fertilizer significantly influences soil greenhouse gas (GHG) emissions, GWP, maize yields and GHGI. This research is highly relevant not only to the local context of Buea but also to sustainable agriculture in tropical regions. By examining tillage, fertilizer application, and their interaction and influence on soil GHG emissions, the study's findings can inform policy, guide agricultural practices, and enhance Cameroon's GHG reporting to the UN, using locally aggregated data. This contributes to global climate-change mitigation efforts. The following sections of the paper will detail the methodology, results, and discussions, providing an in-depth analysis of the impacts of tillage and fertilizer types on soil GHG emissions, GWP, crop productivity and GHGI in Buea, Cameroon.

2 Materials and methods

2.1 Study area

The field experiment was conducted at the teaching and research farm of the Department of Environmental Science, University of Buea, situated between latitudes 4° 03'N and 4° 12'N of the equator and longitudes 9° 12'E and 9° 20'E of the Greenwich Meridian (19). The University of Buea, located in the capital of Cameroon's Southwest region, lies along the eastern slopes of Mount Cameroon (Figure 1).

Buea is subject to a humid climate with two main seasons: the rainy season from mid-March to mid-October and the dry season from mid-October to mid-March. The average temperature in March is 28.7 °C, while July sees the lowest average temperature at 17.3 °C (20). Precipitation varies significantly; December is the driest month, receiving only 29 mm of rain, while August is the wettest, with an average of 488 mm (21). Buea has two growing seasons each year: the main season, from March to July, and the minor season, from September to December. The main growing season receives significantly more precipitation that the minor season. Buea soil is primarily of recent origin, formed mostly on young volcanic rocks. They are black, well-drained due to the hilly

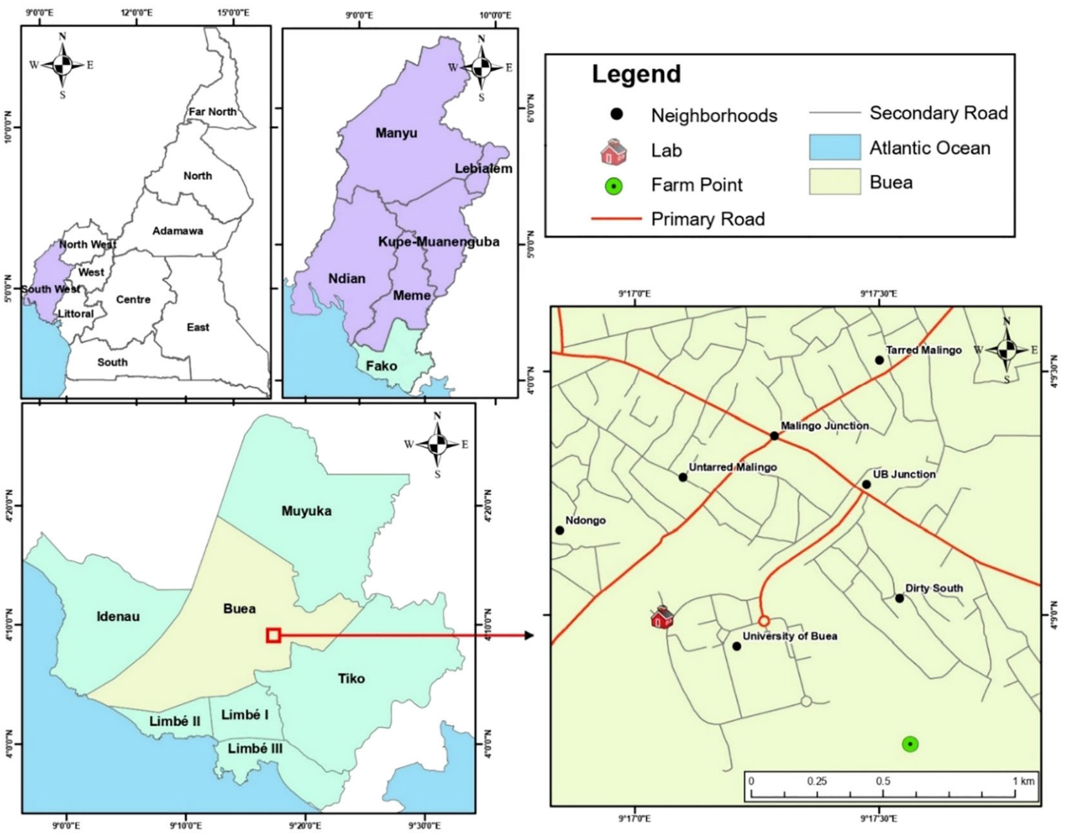

FIGURE 1
Study area map– illustrating the location of the Southwest Region within Cameroon, the position of Buea within the Southwest Region, and the location of the University of Buea campus.

terrain, and rich in nutrients (22, 23). The region's humid tropical climate and nutrient-rich volcanic soils provide ideal conditions for cultivating crops like maize, beans, groundnuts, tomatoes, and cabbage (19). The study site soil properties are presented in Table 1 (presented in section **3.1**).

2.2 Experimental design and treatments

The field experiment was conducted during the 2020 minor growing season (September to December 2020) and the 2021 major growing season (March to early July 2021). Two tillage systems and three fertilizer management practices were factorially combined in a split-plot design with three replications, giving a total of 18 sub-plot of 5 m length and 5 m width each (Figure 2). The main plot factor was the tillage system (zero-tillage (NoTill) and conventional tillage (Till)), and the subplot factor was soil amendment types (organic (ORG), inorganic (SYN), and control/no amendment (CON)). This resulted in six treatment (Figure 2) combinations as follows; NoTill + SYN, NoTill + ORG, NoTill + CON, Till + SYN, Till + ORG, and Till + CON, defined as follows;

i. NoTill + CON: Plots under zero-tillage with no fertilization.

TABLE 1 Physico-chemical properties of the soil of the study site.

Parameter	Unit of measurement	Value
Sand	%	18.0
Silt	%	33.0
Clay	%	49.0
Electrical conductivity	mS/cm	0.04
Bulk density	g/cm^3	1.15
pH-H_2O (1:2.5)		5.8
pH-KCl (1:2.5)		4.7
Total Carbon	(%)	13.3
Soil organic carbon	(%)	3.0
Calcium	(cmol(+) kg^{-1})	1.22
Magnesium	(cmol(+) kg^{-1})	0.86
Potassium	(cmol(+)kg^{-1})	1.15
Sodium	(cmol(+) $kg^{-1}g$)	0.01
Cation exchange capacity	(cmol(+) kg^{-1})	8.48
Available phosphorus	($mgkg^{-1}$)	4.10
Total nitrogen	(%)	0.01

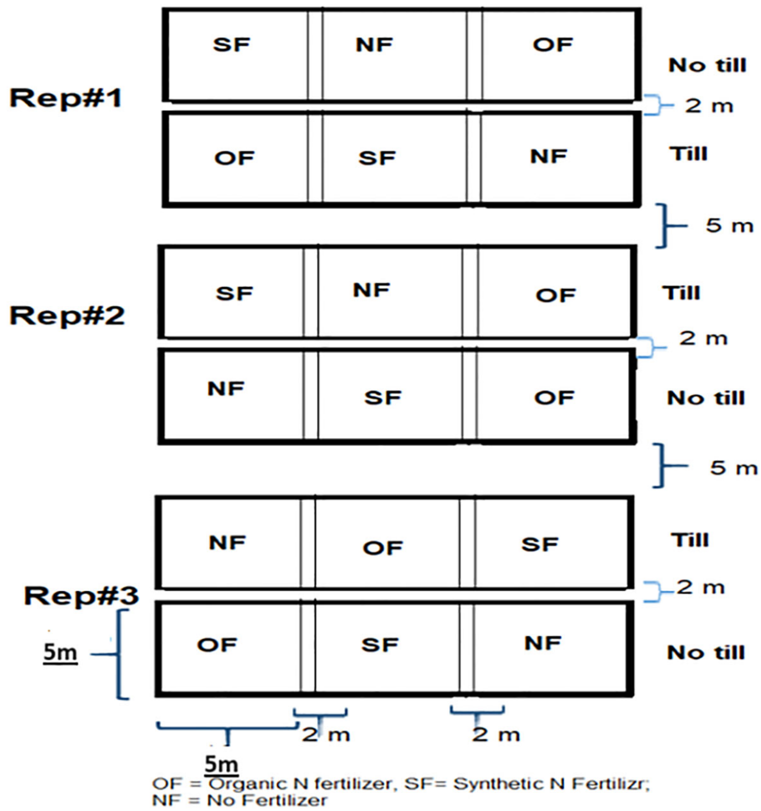

FIGURE 2
Experimental layout in a split plot design.

ii. NoTill + ORG: Plots under zero-tillage with organic fertilization.
iii. NoTill + SYN: Plots under zero-tillage with synthetic fertilization.
iv. Till + CON: Plots under conventional tillage with no fertilization.
v. Till + ORG: Plots under conventional tillage systems with organic fertilization.
vi. Till + SYN: Plots under conventional tillage systems with synthetic fertilization.

Prior to the experiment, the physicochemical properties of the soils in the study area were analyzed using standardized methodologies. Nitrogen fertilizer was applied at a rate of 100 kg/ha, as recommended by (19)for volcanic soils in Buea, Cameroon. Composted municipal solid waste was used as organic fertilizer. The nitrogen concentration of the compost was verified to match that of urea. Based on the compost N content (11%), we applied compost at the rate of 2.275 kg per 25m^2 plot to provide 100 kg N $h^{-1,}$ as recommended by (19). For Urea, which contains 46% of N, the application rate was 0.55kg per plot to achieve the same N rate equivalence. The same fertilization rate and timing were used in both seasons with application made one month after planting through broadcasting. The test crop was the hybrid maize CMS 8704, obtained from the Regional Delegation of Agriculture in the Southwest Region of Cameroon. A seeding rate of 45.55 kg/ha was used, with 114 g of maize seeds planted per 25 m^2 subplot. The experiment was conducted in a field that had been under mixed-cropping, primarily maize and cassava during the previous three years. Before establishing the experimental treatments, all remaining plant residues were cleared from the plots.

2.3 Measurement of soil GHG emissions

The static gas chamber method, adapted from (24), was employed for measuring GHG emissions. *In-situ* closed cover chambers were used to measure N_2O, CH_4, and CO_2 fluxes, using a chamber design adapted from Neville and Kevin of the W.K. Kellogg Biological Station (KBS) in S.W. Michigan, USA.

The chambers used were Letica 3.5-gallon pails (359OSTWHOO), chosen for their white color to reflect sunlight and minimize heat buildup. Equipment included an O-Ring Seal - Letica tear band lid (5LTBWHOO) as the chamber lid; Labco Extainer tubes (5.9 ml) as sample vials, a Becton Dickinson Vacutainer serum vial (10 ml) (366430) as septa, and a Becton Dickinson Luer Lok Tip (20 ml) (309604) as a syringe. Needles for the syringe were Becton Dickinson (22G 1") (305155).

The chambers were inserted into the soil using a guide hole to ensure proper placement. A board was placed on top and gently tapped around the edges to insert the chamber, minimizing soil disturbance. This was done at least one day before sampling to allow the soil to settle. If gaps formed between the chamber and soil, they were gently closed to ensure a good seal. Once positioned, the chamber height above ground was measured from four directions, and the average height and internal diameter were used to calculate the chamber volume (headspace). A standard stopwatch was used for timing and a data recording sheet was used to document basic field parameters related to the study such as sampling time and weather conditions during sampling.

2.3.1 Gas sampling

Gas samples were collected in the early morning, between 8:30 AM and 10:00 AM, during the transitional period between the cooler nighttime temperatures and the warming daytime temperatures. Gas samples were collected four times at 15-minute intervals following chamber closure to track changes in gas concentration over time. Sampling involved inserting a 20 mL syringe through the septa to withdraw gas, which was then transferred to a pre-evacuated glass vial sealed with a butyl rubber septum for storage. Samples were kept at room temperature, placed in zippered bags, and shipped to the USDA Northern Plains Laboratory in Sidney, Montana, USA, for gas chromatography analysis. Samples were analyzed approximately two to three weeks after their collection. Sampling was done weekly, with frequency reduced to biweekly and triweekly towards the end of the growing season. Gas sampling was also adjusted to capture short-term fluxes triggered by farm management activities like fertilizer application and manual weeding. In the first growing season, daily GHG samples were collected on nine different dates, while in the second season, GHG samples were collected on 12 different dates.

Auxiliary data were collected to understand their impact on gas fluxes (24). Soil temperature and moisture content were recorded during the flux measurement period. Soil temperature was measured with a thermometer inserted 2.5 to 7 cm into the soil, with readings taken after two minutes for stabilization. Soil moisture was assessed by oven-drying soil samples at 105 °C for 24 hours or until a constant mass was achieved.

2.3.2 Laboratory analysis and flux rate calculation

Gas samples were analyzed at the USDA Northern Plains Agricultural Research Laboratory in Sidney, Montana, using a gas chromatograph, following strict quality control and calibration procedures. Samples were inspected upon arrival, and those with broken vials were rejected. Sample details were registered in an MS Excel spreadsheet. After analysis, flux rates were calculated by measuring the increase in gas concentration within the chamber over the closure time, relative to the chamber's cross-sectional soil area. This calculation was performed using the HMR package in R Studio, with results expressed in µg ha^{-1} d^{-1} for N_2O and CH_4, and mg ha^{-1} d^{-1} for CO_2.

The flux rate at each sampling time was calculated by integrating the following parameters:

2.3.2.1 Volume of the bucket chamber headspace in liters

The volume was calculated by using the following Equation 1:

$$V = 0.5902 * Ht - 0.1991 \tag{1}$$

Where V = headspace volume in L and Ht. = the height in centimeters.

a. Exact sampling time in hours: The initial sampling time represents 0, from which subsequent time intervals (15, 30, and 45 minutes) were computed. This represents 0, 0.25, 0.50, and 0.75hrs.
b. Concentration of gas in the headspace sample units were in ppm volume or microliters of gas per L.
c. Air temperature at time of sampling in degrees was measured using an air thermometer. The temperatures were converted to degrees Kelvin using the following formula (Equation 2 (8)).

$$degrees\ Kelvin = degrees\ C + 273.15 \quad (2)$$

Kelvin is ideal for scientific calculations, where absolute temperature values are needed for consistency, especially in gas-related equations.

The HMR package in R was used to calculate the flux rates for all plots. Data visualization, depicting the impacts of tillage and fertilizer types on soil GHG emissions, was accomplished using the ggplot2 package. Additionally, the linear interpolation function in R was employed to calculate cumulative GHG emissions throughout the growing season. An analysis of variance (ANOVA) test was performed to assess significant differences in GHG emissions among the experimental treatments, and the least-significant difference (LSD) test was used to compare mean GHG fluxes. Correlation analysis was also conducted in R to examine the relationship between soil moisture and temperature and the GHG emissions.

2.4 Maize yields under different tillage systems and fertilizer types

The study employed the methodology of (25) to assess the effects of conservation agricultural practices on maize *(Zea mays)* grain yield. Maize yield was measured in tons per hectare (T/ha) at constant dry weight. Harvestable plants were counted per plot, and five representative cobs were sampled, threshed and oven-dried at 79°C to constant mass. Yield per plot was calculated by multiplying the average grain weight per cob by the number of harvestable cobs, then converting to ton per hectare. Descriptive statistics and ANOVA were conducted in R to evaluate the impact of different tillage systems and fertilizer types on maize yield.

2.5 Calculation of global warming potential and greenhouse gas intensity

According to the (26), the global warming potentials (GWPs) of CH_4 and N_2O over a 100-year time horizon are 25 and 298, respectively, relative to CO_2, which is assigned a value of 1. Based on this, the GWP in this study was estimated by multiplying the cumulative seasonal GHG emissions of CH_4 and N_2O by their respective GWP factors, following the method of (27). The results are reported as kilograms of CO_2-equivalents per hectare (kg CO_2-eq ha^{-1}). Additionally, the greenhouse gas intensity (GHGI) was determined as the ratio of GWP to maize grain yield, following the method described by (28).

3 Results

3.1 Physico-chemical properties of the study site

The study site soil is clay-rich (49% clay, 33% silt, 18% sand), with very low salinity (EC 0.04 mS cm^{-1}) and low bulk density (1.15 g cm^{-3}), indicating good structure. It is moderately acidic (pH-H_2O 5.8; pH-KCl 4.7), suggesting appreciable exchangeable acidity. Organic status is moderate (total C 13.3%; soil organic C 3.0%), yet total nitrogen is extremely low (0.01%), implying N limitation. Available phosphorus is also low (4.10 mg kg^{-1}). The cation pool shows modest Ca (1.22), Mg (0.86), and relatively high K (1.15) with negligible Na (0.01) and a low-to-moderate CEC (8.48 cmolc kg^{-1}), consistent with nutrient-responsive conditions (Table 1).

3.2 The interaction effects of tillage and fertilizer types on daily GHG emissions (N_2O, CO_2 and CH_4)

On October 13th, 2020, N_2O emissions were similar across all tillage and treatment types. However, significant spikes were observed in NoTill + CON and NoTill + SYN five days later (October 18th). These spikes were temporary, as the plots experienced a subsequent drop in N_2O emissions by October 25th. By October 30th, one month after tillage and two days after fertilizer application, N_2O emissions were relatively higher in plots under synthetic fertilization amendment in both tillage systems (10850 µg ha^{-1} d^{-1} and 7940 µg $ha^{-1}d^{-1}$ for Till + SYN and NoTill + SYN, respectively). One week after, NoTill + SYN recorded a slight drop in N_2O emissions but Till + SYN had high spikes. A little over two months after tillage and planting, N_2O emissions fluctuated in all plots regardless of tillage and fertilizer types until the end of the growing season in December 2020 (Figure 3). The highest mean N_2O emission rate (9032.27 µg $ha^{-1}d^{-1}$) across treatments was observed in the NoTill + SYN plot, while the lowest (4746.038 µg $ha^{-1}d^{-1}$) was observed in the NoTill + ORG plot (Table 2). Tillage practices and fertilizer types had no significant effects ($p>0.05$) on daily N_2O emission rates.

Prior to fertilizer application (first month of the cropping season) in the 2021 season, N_2O emissions fluctuated in all plots, regardless of tillage systems. Two days after fertilizer application on May 4th, emissions were highest under NoTill + SYN (18000 µg $ha^{-1}d^{-1}$). Conversely, plots under NoTill + CON on this date generated the lowest emissions. Between early May and June, emissions fluctuated in all plots, although higher spikes were recorded in plots under synthetic fertilization. From June until the end of the growing season,

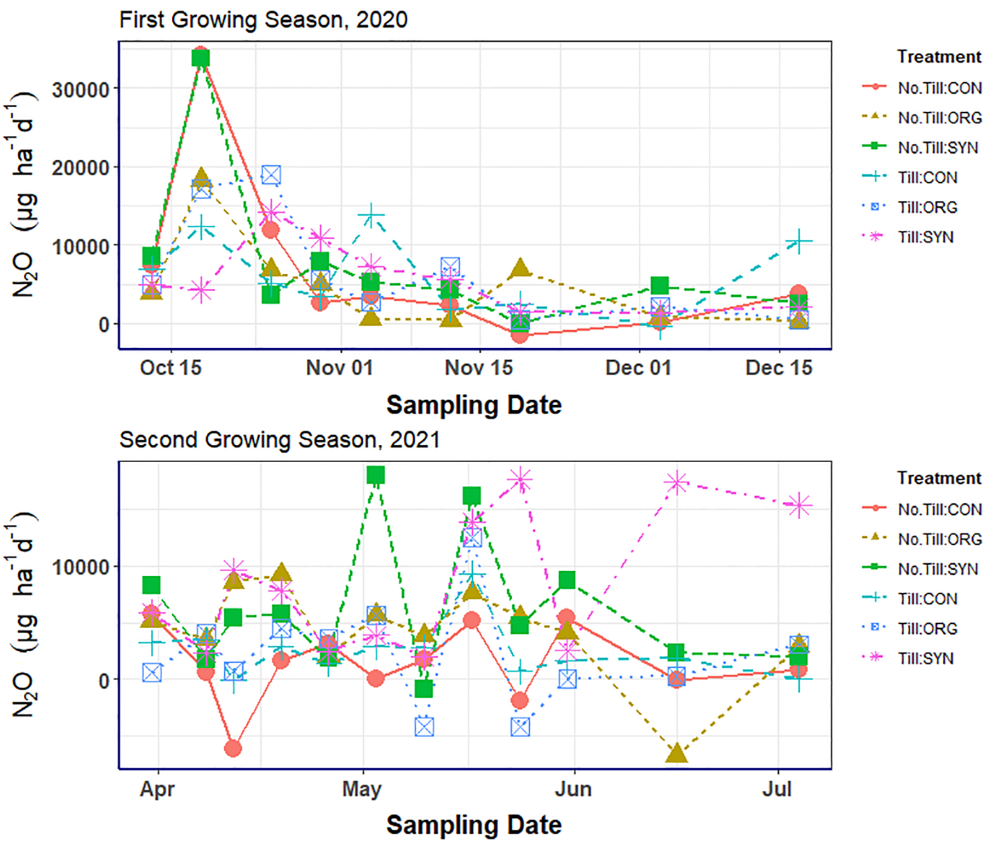

FIGURE 3
Effects of tillage and fertilizer types on soil N_2O emissions in the 2020 and 2021 growing seasons across sample dates.

TABLE 2 Summary statistics showing the interaction effect of tillage and fertilizer types on GHG (N_2O, CO_2 and CH_4) emissions in the 2020 and 2021 growing seasons.

Type practice	N_2O emissions (µm $ha^{-1}d^{-1}$)			CO_2 emissions (mg $ha^{-1}d^{-1}$)			CH_4 emissions (µm $ha^{-1}d^{-1}$)		
	Mean	Std	Group	Mean	Std	Group	Mean	Std	Groups
First growing season, 2020									
NoTill + CON	7689.72	17600.87		37439.13	23608.99	Bc	-9459.917	34215.33	
NoTill + ORG	4746.03	7726.053		31642.92	19616.43	C	-21819.6	40507.23	
NoTill + SYN	9032.27	15459.84		29266.67	11614.62	C	-11663.86	25374.65	
Till + CON	6240.12	8959.373		44620.0	22611.17	Ab	226.16	9499.95	
Till + ORG	7220.82	8260.48		55470.59	15861.03	A	-8490.90	19414.36	
Till + SYN	6165.41	8707.98		46240.91	21938.24	Ab	-12457.1	30262.5	
Second growing season, 2021									
NoTill + CON	1218.15	6179.39		31192.0	22089.66		-22939.5	42374.45	
NoTill + ORG	4137.06	8497.59		38137.77	21372.15		12490.29	69212.78	
NoTill + SYN	5772.82	8612.54		37667.29	18374.68		-5525.65	40046.34	
Till + CON	2572.34	4096.29		43371.84	22520.5		-3984.0	48735.26	
Till + ORG	2304.66	7117.55		43366.0	30402.7		-8576.4	34161.64	
Till + SYN	8851.45	11591.46		41230.29	26157.93		-17187.8	70654.48	

Std: Treatments with the same Group letter notation are not significantly different (($p \leq 0.05$), NS: Not significant.

Till + SYN had higher N_2O emissions, which continued until the end of the growing season (Figure 3). The highest average N_2O emission (8851.45 µg $ha^{-1}d^{-1}$) occurred in Till + SYN plots, while the lowest (1218.14 µg $ha^{-1}d^{-1}$) was recorded in the NoTill + CON plot. Tillage and fertilizer types had no significant (p>0.05) effect on N_2O emissions recorded under different treatments (Table 2).

A few weeks after the start of the first growing season when the plots were differentiated just by tillage systems, CO_2 emissions exhibited fluctuations in all plots. By October 30th, 2020, two days after fertilization, CO_2 emissions peaked at 71600 mg $ha^{-1}d^{-1}$ in the Till + ORG plots. In early November, CO_2 emissions were notably higher in plots under conventional tillage. This pattern persisted throughout the growing season, with plots under conventional tillage (Till + ORG, Till + SYN, and Till + CON) consistently showing higher CO_2 emission rates than plots under zero-tillage (NoTill + ORG, NoTill + SYN, NoTill + CON) (Figure 4). Till + ORG plots recorded the highest daily mean CO_2 emission (55470.59 mg $ha^{-1}d^{-1}$) across treatments while the lowest (29266.67 mg $ha^{-1}d^{-1}$) was recorded in the NoTill + SYN. CO_2 emissions across treatments were significantly different (p<0.05). Tillage practice and fertilizer types showed no significant effects (p>0.05) on daily CO_2 emission rates (Table 2).

In the 2021 growing season, there were significant changes in CO_2 emissions across all plots with different tillage systems. The application of fertilizer in early May resulted in comparatively higher CO_2 emissions in tilled plots. By the end of the growing season, CO_2 emissions remained notably higher in all tilled plots (Till + ORG, Till + SYN, and Till + CON) compared to untilled plots (NoTill + ORG, NoTill + SYN, NoTill + CON) (Figure 4). Till + ORG and Till + CON emitted the highest average daily CO_2 levels (43–366 mg $ha^{-1}d^{-1}$ and 43371.84 mg $ha^{-1}d^{-1}$ respectively), while NoTill + SYN had the lowest (31192 mg $ha^{-1}d^{-1}$) (Table 2). Tillage systems and fertilizer types used in this study did not significantly affect CO_2 emissions in this season.

At the onset of the 2020 growing season, when the plots were distinguished solely by their tillage systems, CH_4 emissions were either negative or slightly above zero in all plots, irrespective of their tillage types. After fertilizer application, only the NoTill + CON plot exhibited slightly positive values on October 30th. By November 4th, CH_4 emissions remained negative in all plots except for Till + CON, which recorded a slightly positive value. From that point onward, CH_4 emission rates were negative in all plots throughout the growing season, except on November 12th, when Till + ORG recorded a positive value (Figure 5). The highest mean daily CH_4 emission (226.16µg $ha^{-1}d^{-1}$) in the sampling period in 2020 occurred under Till + CON while NoTill + ORG had the lowest (-11663.86 µg $ha^{-1}d^{-1}$) (Table 2). Results showed that the main effects of tillage practice and fertilizer types were not significant (p>0.05).

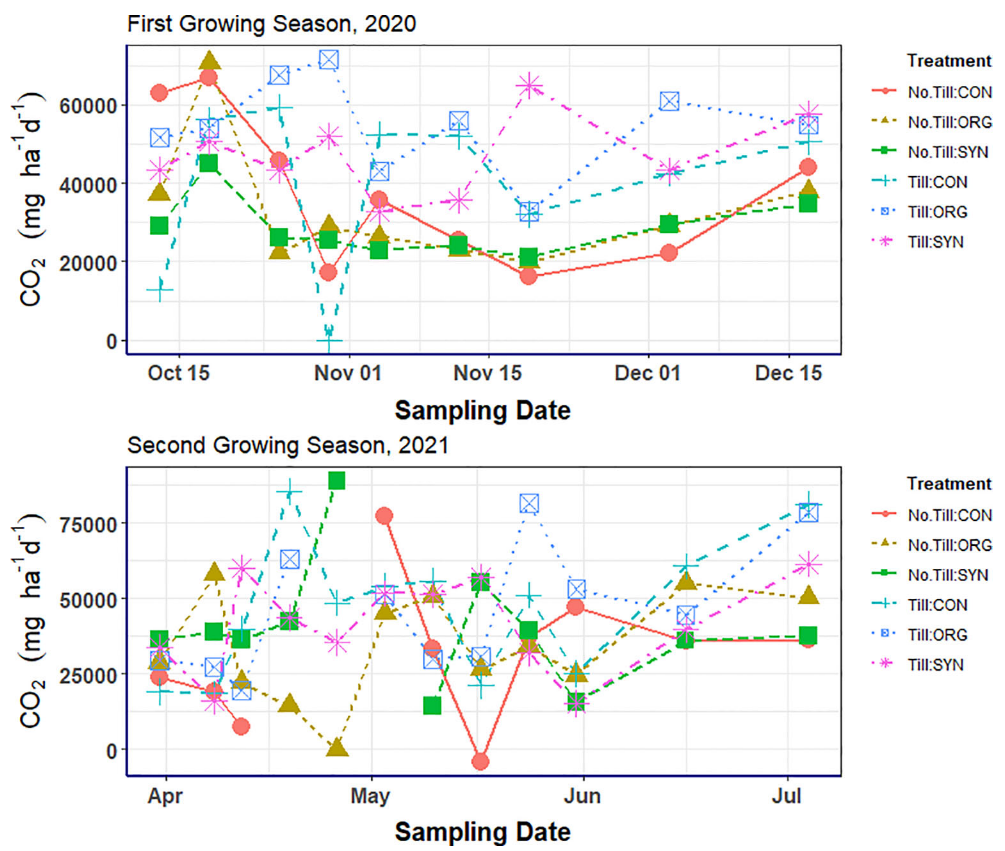

FIGURE 4
The combined effects of tillage and fertilizer types on daily soil CO_2 emissions in the first and second growing season across sample dates.

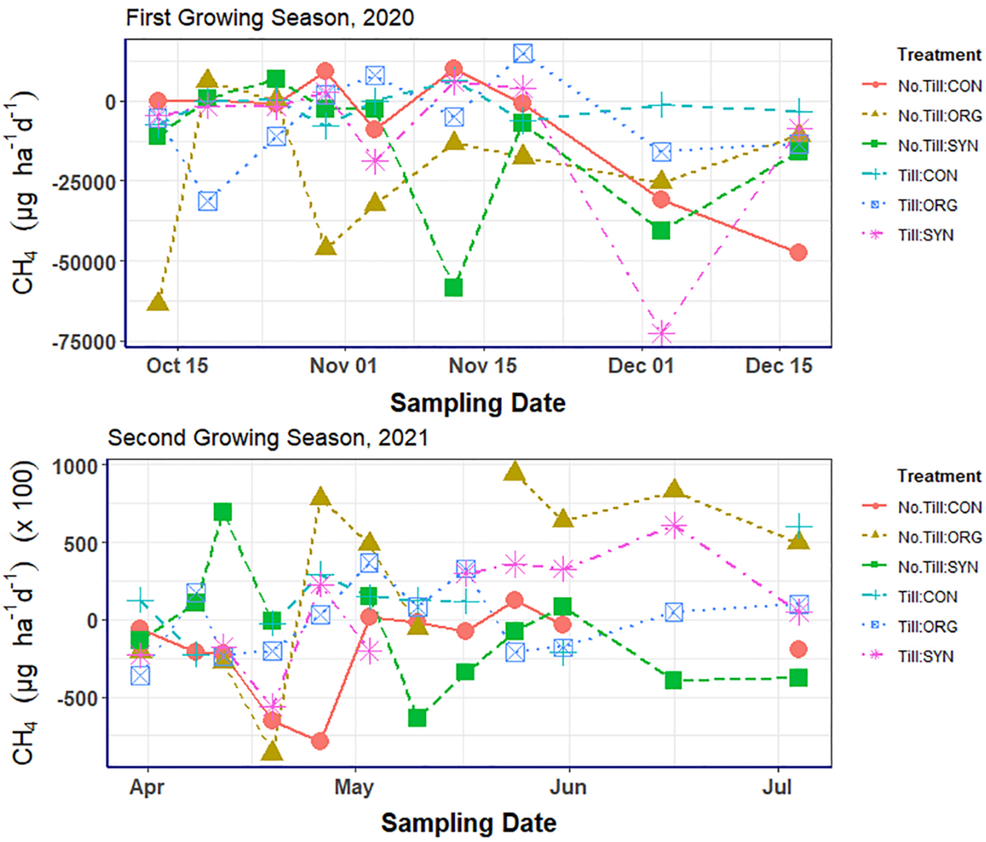

FIGURE 5
The effects of tillage and fertilizer types on daily soil CH_4 emissions in the 2020 and 2021 growing seasons.

At the start of second growing season in April 2021, tillage had little or no effect on soil CH_4 emission, as almost all plots recorded negative CH_4, except for NoTill + SYN, which exhibited positive values around mid-April. Following fertilizer application in early May, CH_4 emissions were 36480 µg ha^{-1}d^{-}1 in Till + ORG. From this period, fluctuations in CH_4 emission rates occurred throughout the growing season (Figure 5). In 2021, NoTill + ORG recorded the highest average (12490.29 µg ha-1d-1) CH_4 emission rates while NoTill + CON recorded the lowest (-22939.5 µg ha^{-1}d^{-1}). The main effects of Tillage and Fertilizer types on CH_4 emission rates were not significant (p>0.05).

3.3 Effects of tillage and fertilizer types on the cumulative GHG (N_2O, CO_2 and CH_4) emissions

Study findings reveal that in 2020 tillage practice and fertilizer types significantly affected total N_2O in the cropping year (p<0.05). NoTill + SYN exhibited the highest cumulative N_2O emissions (0.128 kg CO_2-eq ha^{-1}), while NoTill + ORG had the lowest cumulative emission (0.078 kg CO_2-eq ha^{-1}) (Figure 6).

There was a significant difference (p<0.05) in cumulative CO_2 emission rates among the different tillage systems and fertilizer types. The highest cumulative CO_2 emission of 3.6 kg ha^{-1} in the first year was observed under Till + ORG, while NoTill + SYN exhibited the lowest cumulative emissions (1.8 kg ha^{-1}) (Figure 6).

For CH_4, our result reveal that tillage and fertilizer types significantly (p<0.05) affected cumulative CH_4 emission. The highest cumulative CH_4 emission were recorded under Till + CON, with a value of -0.004 kg CO_2-eq ha^{-1}. NoTill + ORG exhibited the lowest cumulative CH_4 emissions at -0.051 kg CO_2-eq ha^{-1} (Figure 6).

In the 2021 study period, the main effects of tillage and fertilizer type were significant (p<0.05) on cumulative N_2O emissions. Till + SYN exhibited the highest cumulative N_2O emissions (0.267 kg CO_2-eq ha^{-1}), while NoTill + CON had the lowest cumulative N_2O emissions (0.033 kg CO_2-eq ha^{-1}) (Figure 7).

Tillage practice and fertilizer types also significantly affected cumulative CO_2 emissions (p<0.05).

The highest cumulative CO_2 emission rate of 6.8 kg ha^{-1} was observed in Till + ORG, while NoTill + CON had the lowest value of 3.110 kg ha^{-1} (Figure 7).

The main effects of tillage and fertilizer type were also significant (p<0.05) on cumulative growing season CH_4 emissions. For CH_4, the highest cumulative growing season emission of 0.0625 kg CO_2-eq ha^{-1} was observed in NoTill + ORG, while NoTill + CON emitted the lowest cumulative CH_4 emissions (-0.04 kg CO_2-eq ha^{-1}) (Figure 7).

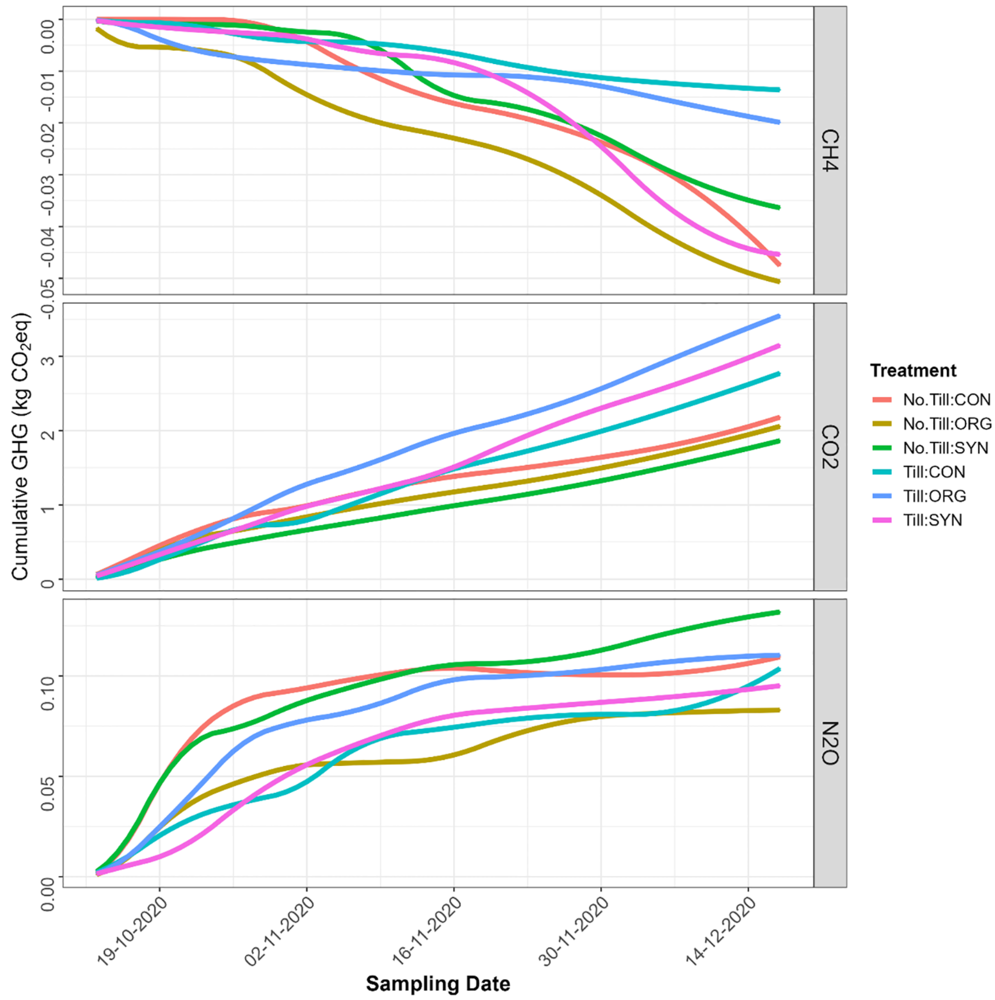

FIGURE 6
Effects of tillage and fertilizer types on the cumulative growing-season GHG emissions in 2020.

3.4 Correlation analysis of GHG emissions and environmental variables

Our results revealed weak relationships between GHG emissions and measured environmental variables (Figure 8). N_2O emissions exhibited a weak positive correlation with soil temperature (0.07) and almost no correlation with soil moisture (-0.01). CO_2 emissions had a very weak positive correlation with soil temperature (0.02) and no correlation with soil moisture (0). Methane emissions also had a weak positive correlation with soil temperature (0.07) and a weak negative correlation with soil moisture (-0.03) (Figure 8).

3.5 Effects of tillage and fertilizer types on maize yields

In the 2020 growing season, there were no statistically (P >0.05) significant effects of the interaction between tillage and fertilizer types on maize yields, although differences in mean yield were observed among treatments. The highest mean maize yield that year was recorded in the conventional tillage without fertilizer treatment (Till+CON), at 3.06 T ha^{-1}, while the lowest yield (1.44 T ha^{-1}) was observed in the no-tillage with organic fertilizer treatment (No Till +ORG) (Table 3).

In contrast, during the growing season of 2021, fertilizer type and their interaction between tillage and fertilization significantly (P< 0.05) influenced maize yields, while tillage alone had no significant effect. Yield differences among the treatment combinations were statistically significant. The highest mean maize yield (6.15 T ha^{-1}) was recorded under conventional tillage with synthetic fertilizer (Till + SYN), while the lowest yield (1.44 T ha^{-1}) occurred under conventional tillage without any N application (Till + CON) (Table 3).

Maize yields differed significantly (P< 0.05) between the 2020 and 2021 growing seasons, with mean yields per plot generally higher in the minor growing season than in the main growing season, indicating improved performance across treatments in the second growing season.

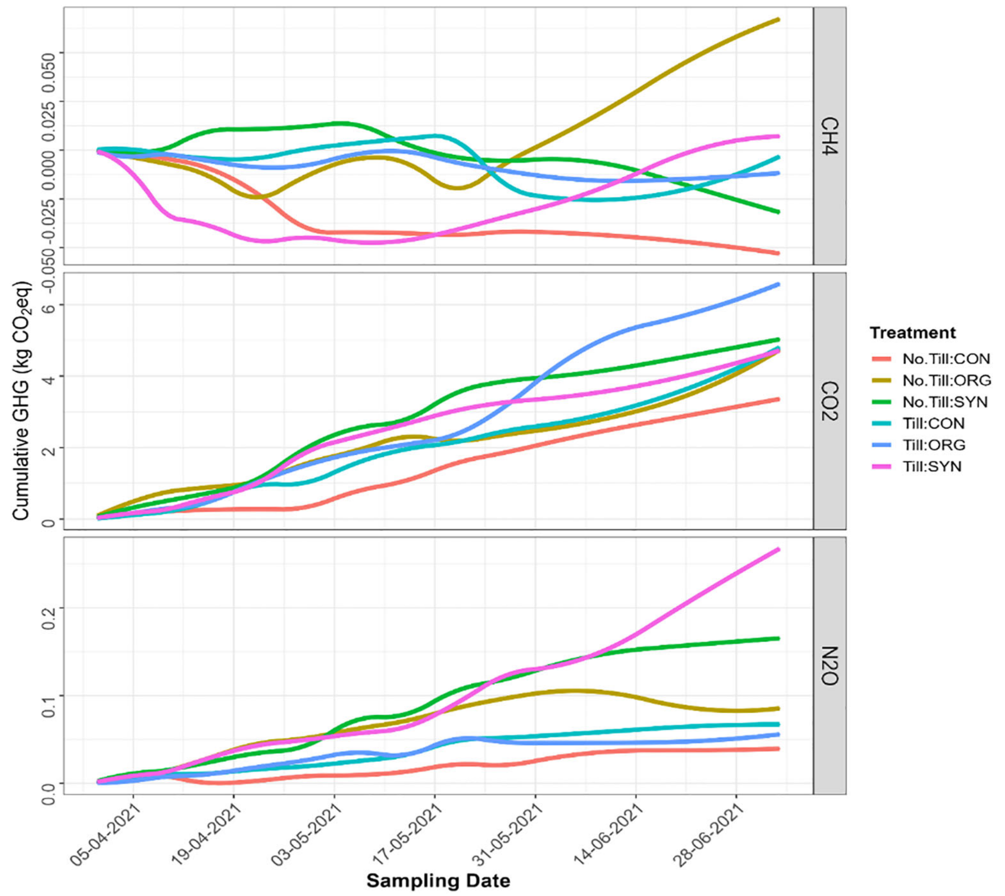

FIGURE 7
Impacts of tillage and fertilizer types on the cumulative growing-season GHG emissions in the 2021 study season.

3.6 Global warming potential and greenhouse gas intensity

In the 2020 growing season, the highest GWP was recorded under No.Till + SYN (39.044 kg CO_2-eq ha^{-1} season^{-1}), followed by Till + ORG (37.668 kg CO_2-eq ha^{-1} season^{-1}) and Till + CON (36.87 kg CO_2-eq ha^{-1} season^{-1}). The lowest GWP was observed in NoTill + ORG (24.02). Greenhouse gas intensity (GHGI) was lowest under Till + CON (12.049 kg CO_2-eq t^{-1} ha^{-1} season^{-1}) and highest under No.Till + ORG (16.679 CO_2-eq t^{-1} ha^{-1} season^{-1}), indicating that synthetic fertilizer under tilled conditions had the most emissions per ton of maize produced.

In 2021, GWP increased sharply under Till + SYN (84.41 kg CO_2-eq ha^{-1} season^{-1}), more than doubling its 2020 value, while NoTill + SYN also exhibited a high GWP (50.45 84.41 kg CO_2-eq ha^{-1} season^{-1}). The lowest GWP was recorded in NoTill + CON (11.94 kg CO_2-eq ha^{-1} season^{-1}). GHGI followed a similar pattern, with the lowest value under NoTill + CON (2.15 kg CO_2-eq t^{-1} ha^{-1} season^{-1}) and the highest under Till + SYN (13.72).

4 Discussion

4.1 Impacts of tillage and fertilizer application on soil GHG emissions

Soil tillage results in changes in soil aeration, soil temperature, and moisture (29, 30) thus tillage type and timing can directly or indirectly influence N_2O, CO_2 and CH_4 emissions (4). Similarly, the type of N fertilizer applied to agricultural soils to increase productivity directly or indirectly affects soil GHG fluxes (31).

4.1.1 Soil N_2O emissions

The observed interaction between tillage and N fertilizer type had a clear and seasonally distinct effect on soil N_2O emissions. In 2020, NoTill + SYN treatment significantly increased cumulative N_2O emissions, while in 2021, Till + SYN treatment significantly increased cumulative N_2O emissions (Table 2). This pattern underscores the critical role of soil moisture and aeration status in regulating soil microbial processes of N transformation, both of

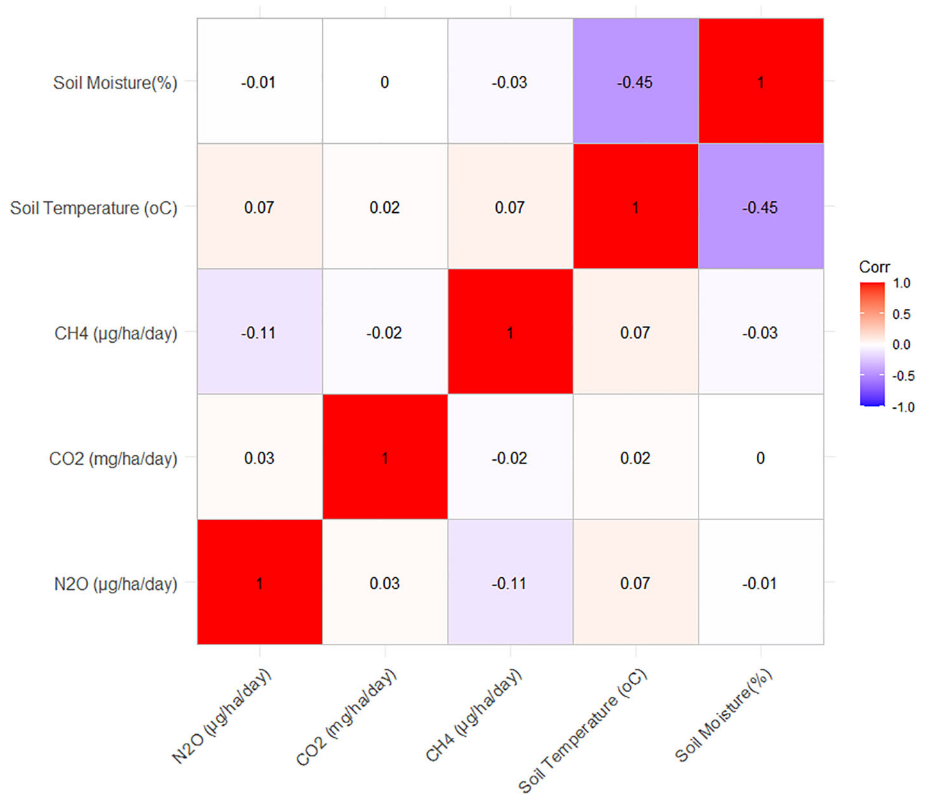

FIGURE 8
Correlation of GHG emissions and environmental variables.

which are strongly influenced by tillage regime and environmental conditions such as rainfall and temperature.

In the 2020 dryer growing season (late September to December), the zero tillage practice likely enhanced water retention relative to tillage practice by reducing soil moisture loss through evaporation. This enhanced moisture retention may have maintained optimal water-filled pore space (WFPS) for aerobic microbial processes, particularly nitrification, which is known to peak around 60% WFPS (32). Under these conditions, the application of synthetic fertilizer provided an immediate and mineralized nitrogen source (ammonium and nitrate), promoting nitrifier activity and associated elevating N_2O emissions. The higher cumulative N_2O fluxes observed in NoTill + SYN (Table 2) plots during this season are consistent with this mechanism.

Conversely, during the 2021 main growing season (March to July), rainfall was markedly higher, especially between mid-May and July. Under these wetter conditions, NoTill plots experienced elevated WFPS, often exceeding 80%, which would limit gas diffusion and oxygen availability. This anaerobic environment favors denitrification, the gradual reduction of nitrate to dinitrogen (N_2) with N_2O acting as an obligate intermediate. However, under highly saturated conditions, N_2O is often further

TABLE 3 The effects of tillage and fertilizer types on global warming potential, maize yields and greenhouse gas intensity.

	N_2O emissions (kg ha^{-1} season^{-1})		CO_2 emissions (kg ha^{-1} season^{-1})		CH_4 emissions (kg ha^{-1} season^{-1})		GWP (kg CO_2-eq ha^{-1} season^{-1})		Yield (t/ha)		GHGI (kg CO_2-eq t^{-1} ha^{-1} season^{-1})	
Treatment	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
NoTill + CON	0.106	0.033	2.15	3.11	-0.048	-0.04	32.538	11.944	2.33	5.56	13.964807	2.148201
NoTill + ORG	0.078	0.078	2.05	4.67	-0.051	0.0625	24.019	29.4765	1.44	4.2	16.679861	7.018214
NoTill + SYN	0.128	0.156	1.8	4.89	-0.036	-0.037	39.044	50.453	2.68	4.84	14.568657	10.42417
Till + CON	0.115	0.056	2.7	4.68	-0.004	-0.001	36.87	21.343	3.06	3.43	12.04902	6.222449
Till + ORG	0.116	0.044	3.6	6.8	-0.02	-0.013	37.668	19.587	2.93	4.9	12.855973	3.997347
Till + SYN	0.098	0.267	3.2	4.69	-0.045	0.006	31.279	84.406	2.42	6.15	12.92521	13.72455

reduced to N_2 before escaping the soil matrix. Therefore, the decline in N_2O emissions recorded in NoTill plots during this wet season is consistent with a likely reduction of N_2O to N_2.

The shift in peak emissions to the Till + SYN plots during 2021 (Table) is likely a result of improved soil aeration in these plots, even under high rainfall. Tillage disrupts soil aggregates and increases porosity, thereby enhancing oxygen diffusion and favoring nitrification pathways where N_2O is release. These results are consistent with previous studies (32)which found that tillage effects on N_2O emissions are modulated by soil moisture, with NoTill systems emitting more under dry conditions and tilled systems emitting more under wet conditions. Zero tillage systems typically have more surface residue cover and less soil disturbance. This leads to Better soil structure and more continuous pores, which can improve moisture retention even during drier periods. Under dry conditions, these small pockets of retained moisture can create localized anaerobic microsites that allow nitrification to occur and thus generate more N_2O, even when the overall soil appears dry. Tilled systems on the other hand disrupt soil structure and usually increase evaporation and aeration. In these wet conditions, aerated soils maintain oxygen in pore spaces, enabling nitrifying bacteria to convert ammonium to nitrate effectively. Good aeration prevents the soil from becoming fully anaerobic, thus supporting continuous and efficient nitrification (32).

This seasonal difference is also supported by a growing body of literature indicating that tillage effects on N_2O fluxes are highly context dependent. Some studies report elevated emissions from NoTill systems in dry climates due to moisture conservation (27), while others find higher emissions under conventional tillage during wetter seasons (33). Moreover, several meta-analyses report cases where no significant difference is observed between tillage treatment, particularly under moderate moisture conditions (28).

These findings are consistent with our mechanistic understanding of N cycling in soils. Nitrification-driven N_2O emissions dominate when WFPS is between 40–70%, while denitrification contributes more substantially above 60% WFPS. At WFPS >80%, oxygen diffusion becomes severely limited, favoring the complete reduction of N_2O to N_2 (34).The pronounced drop in emissions in NoTill plots during July 2021 corresponding with the peak rainfall strongly suggests that this threshold was likely exceeded in the NoTill plots, thus suppressing N_2O release.

The fertilizer effect observed across both seasons is equally notable. Synthetic N treatments consistently produced the highest average daily and cumulative N_2O emissions, highlighting the importance of N form and availability in affecting emissions. Urea, being highly soluble and rapidly hydrolyzed to ammonium, provides an immediate substrate for both nitrifiers and denitrifiers. The sharp N_2O spikes following fertilizer application in both years (October 30, 2020, and May 4, 2021) further supports the phenomenon of fertilizer-induced emissions, as reported in prior studies (35).

In contrast, plots amended with composted municipal solid waste exhibited substantially lower N_2O emissions. This is likely due to the slower mineralization rates of organic N compounds, which result in more gradual available N release. This reduced availability of readily mineralized N limits substrate supply for denitrification and slows nitrification turnover, thereby reducing N_2O fluxes. The discrepancy between our findings and those of studies using poultry manure (34) reinforces the importance of organic amendment type: poultry manure typically contains higher proportions of labile nitrogen compounds compared to compost.

These results align with broader observations in tropical agroecosystems, where the combination of high rainfall, reactive soils, and rapid microbial turnover makes N_2O emissions particularly sensitive to both management and weather variability. The interplay between tillage, moisture, and fertilizer type clearly governs not just the magnitude but also the timing of emissions. These findings emphasize the importance of tailoring nutrient and tillage management to seasonal rainfall patterns in order to minimize emissions while maintaining productivity. (30, 31, 35–44)

4.1.2 Soil CO_2 emissions

It is important to note, that this study did not differentiate between microbial and root-derived CO_2 emissions. As such, the observed fluxes represent total soil respiration, which includes both heterotrophic (microbial decomposition of organic matter) and autotrophic (root metabolic) components. While the contribution of microbial respiration is expected to dominate following fertilizer application and tillage-induced decomposition, particularly in treatments receiving organic inputs, root respiration may also have contributed variably depending on plant growth stage and treatment effects on root biomass which was not measured in this study.

Overall, our findings indicate that tillage practices had a consistent and statistically significant influence on daily CO_2 fluxes and cumulative seasonal emissions across both growing seasons. CO_2 emissions were markedly higher under conventional tillage, particularly when organic fertilizer was applied. The highest seasonal emissions were observed under the Till + ORG treatment in both years (Table 2), highlighting the synergistic effects of soil disturbance and the addition of labile organic carbon through compost on soil respiration.

Tillage breaks down aggregates and enhances soil aeration, thereby accelerating organic matter decomposition and microbial activity. These effects increase CO_2 emissions by stimulating the mineralization of soil organic carbon and the decomposition of crop residues and amendments. When combined with compost, which supplies an additional source of readily decomposable carbon, the result is a pronounced rise in microbial respiration. This mechanism is well-documented in the literature; for example (44), reported higher CO_2 emissions from tilled compared to no-till soils due to increased microbial decomposition under improved aeration conditions (39).

Further, tillage physically exposes protected organic matter within soil aggregates which enhance substrate availability to soil microbes. This exposure leads to elevated CO_2 fluxes through increased heterotrophic respiration. Similar outcomes have been reported in other studies: for instance (34), documented a 27%

increase in CO_2 emissions following tillage, while (40) observed reduced emissions under zero-tillage in continuous maize systems. These results reinforce the role of zero-tillage as a viable strategy for mitigating CO_2 emissions by preserving soil structure and limiting microbial access to soil carbon. In addition to tillage, fertilizer type also significantly influenced CO_2 emissions. Treatments receiving organic amendments showed consistently higher average CO_2 flux rates and cumulative emissions. This is consistent with findings from other studies (41, 42), which report elevated CO_2 release following organic fertilizer application due to enhanced microbial decomposition of the added organic matter. Compost, in particular, provides a sustained source of carbon that supports microbial growth and activity throughout the growing season.

Conversely, the lowest CO_2 emissions in 2020 were recorded under the NoTill + SYN treatment (Table 2), where minimal soil disturbance was combined with the use of urea, a nitrogen source that does not supply organic carbon. This outcome highlights the role of substrate availability in driving microbial respiration. Moreover, inorganic nitrogen application can suppress microbial breakdown of soil organic matter by providing readily available N, thereby reducing the microbial demand for nitrogen via mineralization processes.

Indeed, previous research (43) has shown that urea and other synthetic N fertilizers may either suppress or have a neutral effect on soil CO_2 emissions. One possible explanation is that urea application alters soil pH, potentially creating unfavorable conditions for microbial activity. For example (44), reported a 30–40% reduction in CO_2 emissions following ammonium nitrate (NH_4NO_3) application, attributing this to reduced microbial respiration due to acidification.

Taken together, our results demonstrate that both tillage and nitrogen source play significant roles in promoting soil CO_2 emissions. The combination of conventional tillage and organic fertilizer poses the highest risk for elevated CO_2 fluxes, while conservation practices such as zero tillage paired with synthetic N can substantially reduce microbial CO_2 release. These findings contribute to the growing body of evidence supporting integrated soil and nutrient management strategies aimed at reducing carbon losses from agricultural systems. However, our inability to separate heterotrophic and autotrophic respiration underscores the need for complementary methods, such as isotopic tracing or root exclusion techniques in future studies aiming to partition the sources of soil CO_2 emissions.

It should be noted that this study did not incorporate crop residues. Without surface residues, soils receive fewer carbon inputs and lose mulch that cools and moistens the top layer. The bare surface heats and dries faster, stimulating microbes to mine organic matter, increasing CO_2 fluxes. Residues promote aggregate formation and protect organic matter; their absence leaves carbon exposed to decomposition. A similar experiment with residues may yield different results. (45, 46) Rochette & Angers, (2019) (42, 47–52)

4.1.3 Soil CH_4 emissions

Methane (CH_4) emissions were consistently small in magnitude compared to those of CO_2 and N_2O across all treatments and both growing seasons. This pattern is characteristic of well-drained upland agricultural systems, where methanogenesis is generally suppressed, and methane oxidation can dominate. In our study, CH_4 fluxes were predominantly negative, confirming the role of the volcanic upland soils as active methane sinks.

These findings align with numerous studies showing that upland, oxidized soils—particularly those with good aeration and drainage—serve as net consumers of atmospheric methane due to the activity of methanotrophic bacteria (45). Under aerobic conditions, these microbes oxidize CH_4 into CO_2, thereby contributing to negative or near-zero net emissions. The physical and chemical properties of the volcanic soils at the study site likely provided favorable conditions for CH_4 oxidation, limiting the formation of anaerobic microsites that would otherwise promote CH_4 production.

Across both growing seasons, CH_4 fluxes were predominantly negative in all treatments, confirming the role of the study site's volcanic upland soils as consistent methane sinks. These results are consistent with numerous studies that demonstrate the capacity of well-aerated, oxidized soils, particularly in upland environments to consume atmospheric methane through microbial oxidation (45). Methane oxidation in soils is mediated by methanotrophic bacteria, which utilize CH_4 as a carbon and energy source and convert it to CO_2 under aerobic conditions. The prevalence of negative fluxes suggests that oxygen availability was sufficient to support active methanotrophic communities, which suppress net CH_4 emissions by offsetting or entirely preventing methane production.

The strong sink strength observed in this study is characteristic of upland agroecosystems, particularly those situated on well-drained volcanic soils with inherently high porosity and aeration. These physical soil properties limit the development of anaerobic microsites, thereby constraining methanogenesis and favoring CH_4 oxidation. Our findings align with those of (34), who reported similar net CH_4 uptake in aerobic cropping systems.

However, a few instances of positive CH_4 emissions were recorded, notably under the Till + ORG treatment in 2021 (Table 2). This may be attributed to the combination of organic matter input and elevated soil moisture and temperature during the peak of the growing season, which could have created localized anaerobic zones favorable to methanogenesis. The decomposition of compost under warm and moist conditions can elevate labile carbon availability, enhancing microbial respiration and quickly depleting oxygen, particularly in compacted or water-saturated microsites.

Other studies have reported similar effects. For instance (12), observed a two- to ninefold increase in CH_4 emissions following compost incorporation in tropical maize systems, with emissions rising linearly up to 3% depending on the compost rate. Similarly (46), demonstrated that the magnitude of CH_4 emissions is influenced by the quality of the organic amendment, particularly its carbon concentration and C:N ratio, higher values promote methanogenesis, whereas lower ratios suppress it.

Nonetheless, the overall patterns in our data reinforce the prevailing conclusion that CH_4 oxidation dominates in well-aerated soils, particularly when organic inputs are moderate, and soil moisture is not excessive. Both tillage and well-structured no-till systems maintained sufficient oxygen levels to limit methane production and sustain oxidation activity. These findings further support the recognition of upland agricultural soils as potential CH_4 sinks, especially in systems that avoid excessive organic inputs or poorly drained conditions.

4.2 Maize yields, GWP and GHGI

Maize yields varied substantially across treatments and between the two growing seasons, reflecting the influence of both agronomic management and climatic conditions. In 2020, yields were generally lower and showed no statistically significant treatment effects, although the highest yield was recorded under conventional tillage without fertilization. In contrast, the 2021 season exhibited significantly higher yields, particularly in treatments receiving synthetic fertilizer, likely due to more favorable rainfall patterns and growing conditions (Table 4). These results emphasize the responsiveness of maize yield to nutrient availability and environmental conditions and highlight the importance of seasonal variability in interpreting agronomic outcomes.

The study revealed a significant variability in global warming potential (GWP) among treatment, primarily influenced by fertilizer type, tillage regime, and inter-annual climatic conditions. In 2020, the highest GWP was recorded under the NoTill + SYN treatment (39.04 kg CO_2-eq ha^{-1} $season^{-1}$), underscoring the contribution of synthetic fertilizer use, particularly in no-till systems to increased nitrous oxide emissions. In contrast, NoTill + ORG yielded the lowest GWP (24.02) (Table 3), suggesting that organic fertilization under no-till conditions can mitigate overall GHG emissions by avoiding highly reactive N inputs.

In 2021, GWP increased across nearly all treatments, with a dramatic rise observed under Till + SYN (84.41 kg CO_2-eq ha^{-1}) (Table 3). This increase is likely attributable to higher N_2O emissions driven by favorable microbial activity and increased soil moisture resulting from higher seasonal rainfall. These findings emphasize the sensitivity of GWP to both agronomic management and inter-annual climatic variability. Specifically, the application of synthetic fertilizer under no-tillage increased GWP by 20% and 322% in 2020 and 2021, respectively. Under conventional tillage, GWP declined slightly in 2020 (–15%) but increased sharply in 2021 (+295%), illustrating that emissions outcomes are not only treatment-dependent but also season-specific.

While GWP offers a cumulative measure of emissions, GHGI provides a more nuanced evaluation by relating emissions to crop productivity. In 2020, GHGI values varied widely due to differences in yield performance. The lowest GHGI (12.05 kg CO_2-eq t^{-1}) was observed under Till + CON, which also produced the highest yield (3.06 t/ha). This suggests that even moderate emissions can be offset by efficient production, highlighting the importance of yield as a denominator in climate-smart metrics. In contrast, the NoTill + ORG treatment, with its low yield (1.44 t/ha), exhibited a relatively high GHGI (16.68), reinforcing that low productivity can amplify emissions per unit output (Table 3).

In 2021, GHGI values declined markedly in treatments where yields improved significantly. Notably, NoTill + CON achieved both low GWP (11.94 kg CO_2-eq ha^{-1}) and a substantial maize yield (5.56 t/ha), resulting in the lowest GHGI of the study (2.15 kg CO_2-eq t^{-1}) (Table 3). This treatment demonstrates that minimal inputs under no-till can achieve a favorable balance of emissions and productivity. Similarly, Till + ORG also showed improved emission efficiency (GHGI = 3.99), despite its relatively higher GWP, due to a concurrent yield increase.

Overall, NoTill + CON in 2021 emerges as the most climate-efficient treatment, combining moderate emissions with high productivity. This outcome suggests that conservation tillage paired with low-input management may offer a viable strategy for sustainable, low-emission maize production in tropical upland systems. The results further reinforce the importance of assessing mitigation strategies not solely on absolute emission levels, but in the context of yield-scaled metrics like GHGI, which better capture the trade-offs and synergies between productivity and environmental performance. (53, 54) Fowler et al. (2009) (55)

TABLE 4 Effects of tillage and fertilizer types on maize productivity in the 2020 and 2021 growing season.

Combined tillage and fertilizer	Year	
	2020	2021
NoTill + CON	2.33	5.56
NoTill + ORG	1.44	4.2
NoTill + SYN	2.68	4.84
Till + CON	3.06	3.43
Till + ORG	2.93	4.9
Till + SYN	2.42	6.15

5 Conclusion

This study provides important insights into the effects of agronomic practices, specifically tillage systems and fertilizer types, on greenhouse gas (GHG) emissions under maize cultivation in volcanic upland soils of Buea, Cameroon. Across two growing seasons, the study concludes that that the combination of tillage and fertilization significantly influenced soil cumulative seasonal emissions of N_2O, CO_2, and CH_4, as well as global warming potential (GWP), maize yield, and greenhouse gas intensity (GHGI).

The study concludes that in the 2020 season, cumulative N_2O emissions were highest under NoTill + SYN, while CO_2 emissions peaked under Till + ORG. Although all CH_4 fluxes were negative, indicating net methane uptake, their relative magnitudes varied across treatments, with Till + CON showing the least negative values. In 2021, N_2O emissions were greatest under Till + SYN, and CO_2 emissions again peaked under Till + ORG. Although the NoTill + ORG treatment recorded slight positive CH_4 emissions, most treatments remained net methane sinks, affirming the role of well-aerated upland soils in CH_4 oxidation.

Zero tillage, particularly when combined with organic inputs or no fertilization, consistently reduced GHG emissions and GHGI while maintaining competitive yields. These results support its potential as a viable strategy for climate-smart, low-emission maize production. In contrast, synthetic fertilizers, while promoting yields, especially under conventional tillage also contributed to significantly higher N_2O emissions and overall GWP, particularly under wetter conditions.

The study further underscores that fertilizer type has differential effects on GHG dynamics: synthetic fertilizers increase N_2O emissions due to immediate nitrogen availability, whereas organic fertilizers tend to elevate CO_2 (and occasionally CH_4) through microbial decomposition of added organic matter. However, the emissions associated with organic inputs were substantially moderated under no-till systems. These findings emphasize the importance of context-specific agronomic strategies. Agronomic practices must consider not only yield outcomes but also emission profiles, especially under changing climatic conditions. The variability observed between seasons reinforces the sensitivity of soil GHG fluxes to rainfall, temperature, and soil moisture conditions.

Importantly, this study contributes valuable data for Cameroon's national GHG inventory reporting and informs climate-resilient soil management strategies for smallholder systems in similar tropical agroecosystems.

6 Limitations of the study

This study was conducted over a relatively short timeframe, two growing seasons across two consecutive years, which limits the ability to generalize the results across longer-term climatic variability and soil system responses. Given the strong inter-annual influence of rainfall and temperature on GHG dynamics, a longer study period (ideally 5–10 years) would provide a more robust understanding of the long-term impacts of conservation agriculture practices on soil GHG emissions in tropical upland systems.

Additionally, due to the absence of an on-site weather station, site-specific meteorological data (e.g., rainfall, temperature, and soil moisture) were not collected during the experiment. This limited our ability to directly correlate climatic variables with GHG fluxes, particularly during peak emission periods. The lack of high-resolution weather data constrains mechanistic interpretations and limits the potential for model calibration or extrapolation beyond the study period. Integrating continuous climatic monitoring in future work would significantly improve the explanatory power of treatment effects.

Furthermore, CO_2 flux measurements in this study represent total soil respiration, encompassing both autotrophic (root-derived) and heterotrophic (microbial) sources. The inability to separate these components may have led to overestimations of microbial CO_2 emissions, and consequently, inflated estimates of cumulative CO_2, GWP, and GHGI. Similarly, while CH_4 fluxes indicated net methane uptake, the study did not quantify methanotroph activity or assess soil microbial communities, limiting mechanistic insight into the biological drivers of methane oxidation. Future studies incorporating root exclusion techniques and microbial or isotopic analyses would provide a more refined understanding of the biogeochemical processes governing GHG dynamics in these systems.

Lastly, we acknowledge that matching compost and urea on total N does not ensure equivalence in plant-available N, because compost N requires mineralization whereas urea N is immediately available; we did not directly quantify compost mineralization rates in this study.

Data availability statement

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Author contributions

GA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. PN: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. VM: Conceptualization, Data curation, Investigation, Project administration, Supervision, Validation, Writing – review & editing. AT: Conceptualization, Data curation, Investigation, Project administration, Validation, Writing – review & editing. IO: Data curation, Formal analysis, Software, Visualization, Writing – review & editing. TS: Data curation, Investigation, Methodology, Validation, Writing – review & editing.

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