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Greenhouse Gas Emissions Response to Fertilizer Application and Soil Moisture in Dry Agricultural Uplands of Central Kenya

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Abstract: In sub-Saharan Africa, agriculture can account for up to 66% of anthropogenic greenhouse gas (GHG) emissions. Unfortunately, due to the low number of studies in the region there is still much uncertainty on how management activities can affect these emissions. To help reduce this uncertainty, we measured GHG emissions from three maize (*Zea mays*) growing seasons in central Kenya. Treatments included: (1) a no N application control (C); (2) split (30% at planting and 70% 1 month after planting) mineral nitrogen (N) applications (Min—100 kg N ha^{-1}); (3) split mineral N + irrigation (equivalent to 10 mm precipitation every three days—MI); (4) split mineral N + 40 kg N ha^{-1} added as manure (MM—total N = 140 kg ha^{-1}); and (5) split mineral + intercropping with faba beans (*Phaseolus vulgaris*—MB). Soil CO_2 fluxes were lower in season 1 compared to seasons 2 and 3 with fluxes highest in Min ($p = 0.02$) in season 2 and lowest in C ($p = 0.02$) in season 3. There was uptake of CH_4 in these soils that decreased from season 1 to 3 as the mean soil moisture content increased. Cumulative N_2O fluxes ranged from 0.25 to 2.45 kg N_2O-N ha^{-1}, with the highest fluxes from MI during season 3 ($p = 0.01$) and the lowest from C during season 1 ($p = 0.03$). The average fertilizer induced emission factor (0.36 ± 0.03%) was roughly one-third the default value of 1%. Soil moisture was a critical factor controlling GHG emissions in these central Kenya highlands. Under low soil moisture, the soils were CH_4 sinks and minimal N_2O sources.

Keywords: nitrogen fertilization; greenhouse gases; sub-Saharan Africa; small scale farmers

1. Introduction

Increased atmospheric greenhouse gas (GHG) concentrations have been linked with increased mean global temperatures over the past century, with a third of the anthropogenic emissions coming from agriculture [1]. In Africa, agriculture accounts for up to 66% of anthropogenic GHG emissions, and although much of these emissions come from livestock, croplands are still responsible for approximately 15% of agricultural GHG emissions [2].

Sub-Saharan Africa (SSA), with a current population of 1.136 billion of whom 30% face acute food shortages annually [3], is home to one of the fastest growing populations in the world. According to the Food and Agricultural Organization (FAO) (2017), there are 4 million Kenyans facing acute food shortages. In response to these shortages, the Kenyan government, hoping to emulate successful projects in Malawi and the Millennium Villages, has increased incentives for smallholder farmers to purchase and apply synthetic fertilizers through the National Accelerated Agricultural Input Access Program (NAAIAP) [4] to staple crops (e.g., maize (*Zea mays*)), with the aim of improving yields [3]. As a result, Kenya experienced a 4.7% annual increase in fertilizer use between 2015 and 2018 [5].

However, increased nitrogen (N) fertilization increases anthropogenic nitrous oxide (N_2O) emissions [5,6] as N addition tends to induce nitrification and denitrification [6]. Nitrification occurs under aerobic soil conditions when ammonium (NH_4^+) is oxidized to nitrite (NO_2^-) then nitrate (NO_3^-), with N_2O sometimes released as a by-product [7]. Denitrification (i.e., the reduction of NO_3^- to N_2O and then to N_2) on the other hand occurs under anaerobic conditions with about 10% of the N being lost as N_2O [8]. These processes are regulated by soil substrate availability and soil physical properties (e.g., temperature, pH, moisture content, oxygen availability) [9]. Soil water content influences N_2O emission by affecting soil oxygen concentrations and by altering gas diffusivity rates [6,10]. Irrigation, which increases the soil water content, therefore has a direct influence on N_2O emissions. However, by affecting plant growth, irrigation may also indirectly reduce N_2O emissions as it may increase plant N requirements [11,12]. Different fertilizer sources may also affect N_2O fluxes, with manure sometimes producing less N_2O than synthetic inorganic fertilizers because of the higher proportion of organic N [13], although the addition of the labile C together with the N often increases N_2O fluxes from organic fertilizers particularly if initial soil C concentrations are low [14,15].

Methane (CH_4) and carbon dioxide, CO_2, are major GHGs emitted from agricultural croplands. Although, CH_4 is mainly from animal production systems such as manure and animal waste handling, a significant amount is emitted from croplands [16]. Methanogenic bacteria anaerobically produce CH_4 in deep layers of soils with limited oxygen which later diffuses to upper layers and is consequently released to the environment. In other circumstances, CH_4 produced is oxidized to CO_2 by methanotrophic bacteria and the balance between production and consumption leads to negative or positive CH_4 flux. CO_2 from soil and plant respiration has been of global concern especially after it was shown that the ability of terrestrial sinks is greatly reduced under increasing emissions [17]. Fossil fuels and other human activities have increasingly contributed to CO_2 emissions accounting for 75% of total CO_2 emissions. Agricultural activities and land use change together account for the rest [18] where deforestation is the major factor [19].

Currently, Kenya has 8 million smallholder farms that account for approximately 78% of agricultural production [16]. However, there are few empirical studies that have measured GHG fluxes in SSA in general and on smallholder farms in particular [14,20]. This leaves the impact of SSA smallholder agriculture on climate highly uncertain [21], resulting in large uncertainties for emission rates and a lack of clarity of what constitutes appropriate mitigation measures.

To address this lack of information on how irrigation, increased use of organic and inorganic fertilizer on smallholder Kenyan farms may impact GHG fluxes, we measured GHG fluxes for three growing seasons from maize plots receiving different amounts and types of N on an experimental farm set up to represent a typical smallholder farm in the uplands of central Kenya. We hypothesized that fertilized treatments would have higher emissions than the 0-N control, that combining manure with mineral fertilizer would decrease emissions compared with mineral fertilizer alone, and that irrigation in combination with mineral fertilizer would increase the emissions compared with mineral fertilizer alone.

2. Materials and Methods

2.1. Site Description

The study site was located on the campus of the Jomo Kenyatta University of Agriculture and Technology at 1°05′ S and 37°0′ E in Kiambu County, Central Kenya Figure 1. The area has a subtropical highland climate (cwb under the Koppen classification) with two rainy seasons per year. The first rainy season runs from March to May (Long rains) and the second from August to October (Short rains). The presence of two rainy seasons means that there are also two cropping seasons per year; the first cropping season runs from March to September and the other from November through February. Average annual rainfall and air temperature (from 2016 to 2018) at the Kenya Agriculture and Livestock Research Organization Thika weather station (18 km southwest of the experimental site) were 825 mm and 20.4 °C, respectively. Rainfall and air temperature were measured using an automated weather station (Campbell Scientific Inc., ET107, Logan, UT, USA) installed at the site in November 2016. The field had been pasture with natural vegetation and scattered bushes similar to that of a savannah ecosystem prior to 2014, after which it was converted into a long-term trial examining the effects of different fertilizers types and rates on maize yields. Since 2014, the field has been continually cropped with maize, with two seasons annually. Prior to greenhouse gas experiment, initial soil conditions were measured (Table 1).

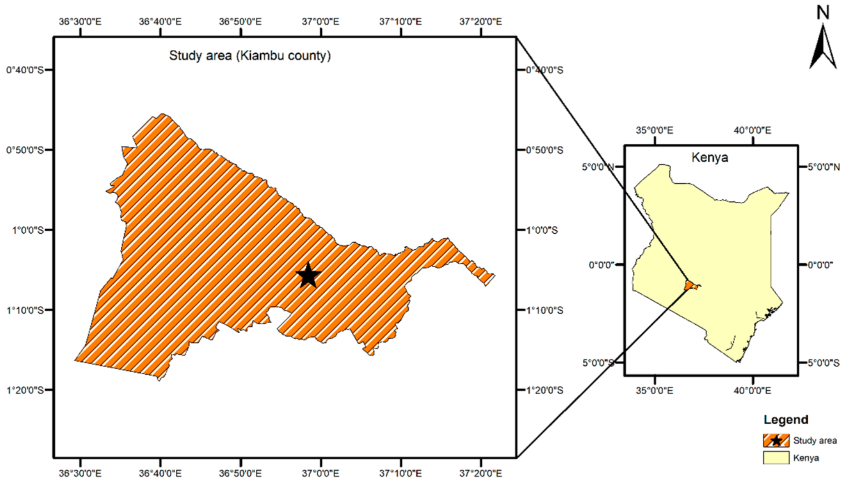

Figure 1. Map showing the study area.

Table 1. Initial soil conditions measured prior to the start of greenhouse gas measurements.

Soil Type	Chromic Vertisol
Silt content	26%
Clay content	62%
Available nitrogen (N)	374 mg/kg
SOM	2.98%
Total nitrogen	0.55%

We measured fluxes from five treatments, replicated in three blocks. The treatments used were as follows: 1. Control plot with no added N fertilizer (C); 2. Plots fertilized with diammonium phosphate (DAP) during planting with an additional topdress of urea 1 month after planting (30% of the fertilizer was applied at planting while 70% was applied as topdress), for a total of 100 kg N ha^{-1} (Min); 3. The same as Min, but with irrigation equivalent to 10 mm precipitation every three days (MI); 4. Min + 40 kg N ha^{-1} added as manure (MM)—total applied N = 140 kg); and 5. The same as Min but intercropped (MB) with faba beans (*Phaseolus vulgaris*). The plots were arranged as a randomized complete block design with the plots measuring 8 × 10 m and a buffer zone of 1 m between the plots and between the blocks.

Farm management activities were kept as similar as possible between growing seasons although there were minor differences due to weather and other technical factors. Planting was completed by hand along rows demarcated by sisal rope with an alternating inter-row spacing of 40 and 70 cm. Two seeds were placed in planting holes (approximately 2.5 cm deep) that were made in the ground 30 cm apart using a sharp stick. Intercropped plots had similar spacing but with two alternating rows of maize and beans after each "wide" spacing. The plots were thinned (i.e., the smaller maize plant removed) prior to topdressing, and then weeded using handheld hoes. In cases where germination of both seeds failed, both plants in the adjacent holes were retained so that a constant plant density per plot was achieved. During the first season, DAP fertilizer and dry solid cattle manure (total N = 3.06%, P = 0.339%, K = 2.31%, and TC = 22.52%) were applied on 4 November 2016 with the maize planted the following day. Urea was applied on 22 December and the maize was harvested on 28 February 2017. Due to intense rains that caused waterlogging in some plots, planting for the second cropping season was delayed. The plots were seeded on 22 April 2017 with fertilizer and manure applied on 3 and 11 May 2017, respectively. Urea was applied on 17 June 2017 and the plots harvested on 12 September 2017. For the third growing season, plots were planted on 5 April 2018, with fertilizer applied the following day (basal application), topdressed on 28 May 2018, and harvested between 7 and 10 August 2018. Overhead irrigation was completed periodically (4 times in season 1 and 3 times for seasons 2 and 3) for all plots when the maize showed signs of extreme water stress (i.e., to avert crop failure) while the treatment with supplemented irrigation (MI) was watered by a watering can routinely without plants having to show water stress at an interval of 3–4 days with each equal to 10 mm of rainfall.

2.2. Chamber Design

Greenhouse gas fluxes were estimated using manually sampled non-flow through, non-steady state chamber methodology [22]. Briefly, six opaque plastic bases were installed 7.5 cm into the ground in each treatment immediately after tillage and left in the field for the entire growing season. The height of the chamber was measured from the outside to ensure slight changes caused by soil compaction were captured. During deployment, vented and ventilated opaque plastic lids (25 × 35 × 12.5 cm) were fastened to the bases with clamps to ensure an airtight seal as shown in Figure 2. All openings were lined with a rubber septum to ensure the chamber was airtight.

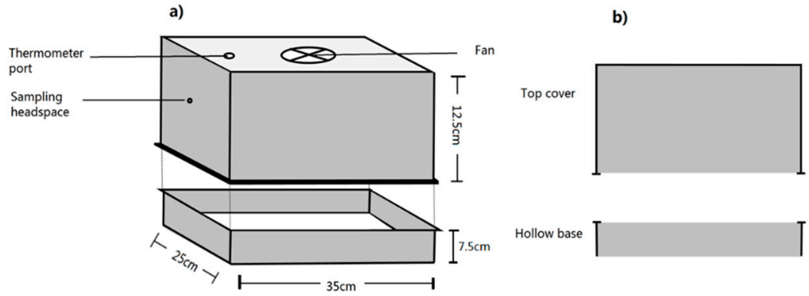

Figure 2. Schematic diagram showing the chamber design. Illustration (**a**) shows a three-dimensional hollow base and a top with a top while illustration (**b**) shows a transverse section of the base and the top cover.

2.3. Gas Sample Collection

Gas samples were collected between 9:00 am and 11:00 am to minimize temperature changes during chamber deployment and because fluxes measured during this time better represent daily mean fluxes [23]. The top of the chamber was also lined with a reflective duct tape to reduce temperature changes. Gas samples were drawn at 10 min intervals beginning at T_0 (immediately after closing the gas chamber) and ending at T_4 (30 min after closing the gas chamber). During each sampling, 20 mL of gas was drawn with a propylene syringe fitted with leuer-lock from each of the two replicates per plot and all 40 mL was injected into a 20 mL pre-evacuated glass vial for storage [24]. Air temperature was measured directly using a thermometer inserted into an air-tight port on top of the chamber. Sampling occurred twice a week during the rainy season and for the two weeks following fertilization and weekly during the rest of the growing seasons [25]. Sampling was conducted from 8 November 2016 to 28 February 2017 for growing season 1, 5 May to 15 September 2017 for growing season 2, and 13 April to 24 July 2018 for growing season 3.

2.4. Greenhouse Gas Measurements

Gas concentrations of the three greenhouse gases, N_2O, CO_2 and CH_4, were determined using SRI gas chromatographs (8610C; SRI) at the Mazingira Centre at the International Livestock Research Institute (ILRI) in Kabete, Nairobi Kenya. Flame ionization detector (FID) was used in the case of CH_4 and CO_2 (after the sample passed through a methanizer) while an electron capture detector (ECD) was used for N_2O. Hayesep-D packed columns were used in operating the chromatograph and N_2 (flow rate of 30 mL min^{-1}) used as a carrier gas for both detector lines. Oven temperature was at 65 °C while that of the methanizer and ECD was set at 350 °C [21]. The peak areas from the GC were converted to concentrations by comparing peak areas of the samples to areas of standard gases with known CO_2, CH_4, and N_2O concentrations.

2.5. Flux Calculations

Gas fluxes were calculated using Equation (1) after estimating a linear rate of change in the mixing ratios.

$$Fr = \Delta\ (C{:}Rt) \times M/22.41 \times h\ 273/(273 + T) \times 1013 \times 60/100 \tag{1}$$

where Fr is the flux rate (mg m^{-2} h^{-1}), C = calculated concentration (CH_4/CO_2—ppmv; N_2O—ppbv), Rt is the relative time, M is the molecular mass of each of the gases (g), h is chamber height (cm), T is temperature in chamber during sampling (°C), 22.41 is ideal gas volume at room temperature, P is air pressure (mb), 60 is time conversion factor from minutes to hours, 100 is chamber length conversion factor, 1013 is air pressure at standard conditions (atm).

To calculate daily flux rate, the equation below was used.

$$DFr = Fr \times 100 \times 24\ (\text{kg ha}^{-1}\ \text{day}^{-1}) \tag{2}$$

where DFr is the daily flux rate, Fr is the hourly flux rate and the 100 is to convert from mg m^{-2} to kg ha^{-1}.

2.6. Soil Analysis

Soil samples from each plot were collected (once every 4 weeks for seasons 1 and 3, bi-weekly for season 2) using a regular 5 cm wide soil auger to a depth of 10 cm. Plastic zip-lock bags were used to store the samples, which were then transported in a cooler box to a laboratory for nitrate (NO_3^-) and ammonium (NH_4^+) extraction within 24 h. For the extraction, 20 g of fresh soil was mixed with 100 mL of 2 M KCl by shaking for 30 min at 175 rpm on an orbital shaker. The mixture was then allowed to settle for one hour, after which it was centrifuged at 3000 rpm for 10 min. The supernatant was then filtered into a vial and refrigerated (4 °C) until it could be analyzed. NO_3^- and NH_4^+ concentrations were determined by first reducing the NO_3^- in the extract to nitrite by use of cadmium granules coated by copper. Sulphanilic acid and 5-amino-2-naphthalene sulphonic acid were used in diazotization to produce a colored dye which was quantitatively measured using a photometric analyzer (Aquakem 200: Thermo Scientific, Waltham, MA, USA). Standards of known concentrations analyzed alongside the samples were used to calculate the concentration of NO_3^--N and NH_4^+-N in the soil. Soil NO_3^- and NH_4^+ intensities were then calculated using the time-weighted sum of soil NO_3^--N and NH_4^+-N concentrations [25].

Soil moisture content was estimated by drying approximately 30 g of the soil at 105 °C for 24 h with the weight change from the fresh soil weight expressed as a percentage of the final dry soil's weight [21]. Soil carbon (%) was calculated from measured soil organic matter using van Bemmelen factor (0.58)

2.7. Statistical Analysis

Cumulative flux data (model residuals) were checked for normality using SPSS (Shapiro–Wilk) and was normal at 95% confidence interval without transformation. This normality test was used since our sample size was <50 hence it had high accuracy of detecting non-normality of data and guided the choice of further methods of analysis. A general linear model was used where treatments were fixed factors, seasons were set as random factors and cumulative flux as the dependent variable. Least Significant Difference (LSD) was used as a post hoc test as all variances were equal. Regression models and Pearson's correlation were used to check the significance of measured variables (soil moisture content, NO_3^- and NH_4^+ concentrations and intensities, and plant biomass) to emissions. All analyses were completed using Windows SPSS version 20.0 at significance level of <0.05 unless stated otherwise.

3. Results

3.1. Environmental Factors

The first cropping season (November 2016–March 2017) received a total of 75 mm of precipitation and was the driest of the three seasons. Season 2 (April–August 2017) received a total of 303 mm of rainfall while the third season (April–August 2018) received 599 mm, the highest amount of precipitation for all the three seasons (Figure 3). The large amount of precipitation during season 3 caused flooding of some of the plots and delayed planting. Much of the precipitation in seasons 2 and 3 was during the first 2 months. Air temperatures were similar across the three seasons, with average daily maximums of 24 °C and average daily minimums of 13 °C. February was the hottest month while July–August was the coolest (Figure 3).

Soil moisture content showed no difference between treatments during the three growing seasons although it did correlate with rainfall events as higher moisture content was observed soon after rainfall episodes. The range was from 19 to 42% for season 1, 26–42% for season 2, and 23–61% for season 3 for all the treatments. The average soil moisture content was lowest in season 1 < season 2 < season 3 (Figure 3) ($p = 0.05$). During heavy rainfall episodes in seasons 2 and 3, ponded water formed on MB treatment and remained on the soil surface for 2–3 days. Initial soil C concentrations were highest in the control treatment and lowest in the MB treatment (Table 2). Total N concentrations in the soil followed an inverse pattern to the soil C concentrations with the C treatment having the lowest total N concentrations and the MB (along with the Min) treatment having the highest total N concentration which is in contrast to C:N ratios in undisturbed soils [26] (Table 2).

Table 2. Soil organic carbon (%) and soil nitrogen (TN) measured using samples collected from maize plots with different fertilizer treatments at the research farm at Jomo Kenyatta University Kenya during growing season 2.

	Total Soil Nitrogen	**Soil Organic Carbon**
C	0.13 ± 0.005^{a}	1.85 ± 0.15^{a}
Min	0.16 ± 0.006^{a}	1.76 ± 0.17^{a}
MI	0.15 ± 0.005^{b}	1.71 ± 0.05^{b}
MM	0.14 ± 0.011^{b}	1.72 ± 0.04^{c}
MB	0.16 ± 0.005^{a}	1.61 ± 0.06^{d}

Note: C = control (no N fertilizer applied); Min = mineral fertilizer (100 kg N ha^{-1}) applied; MI = Min + irrigation; MM = Min + additional 40 kg N ha^{-1} added as cattle manure; MB = maize intercropped with Fava beans. Different letters indicate significance at 0.05.

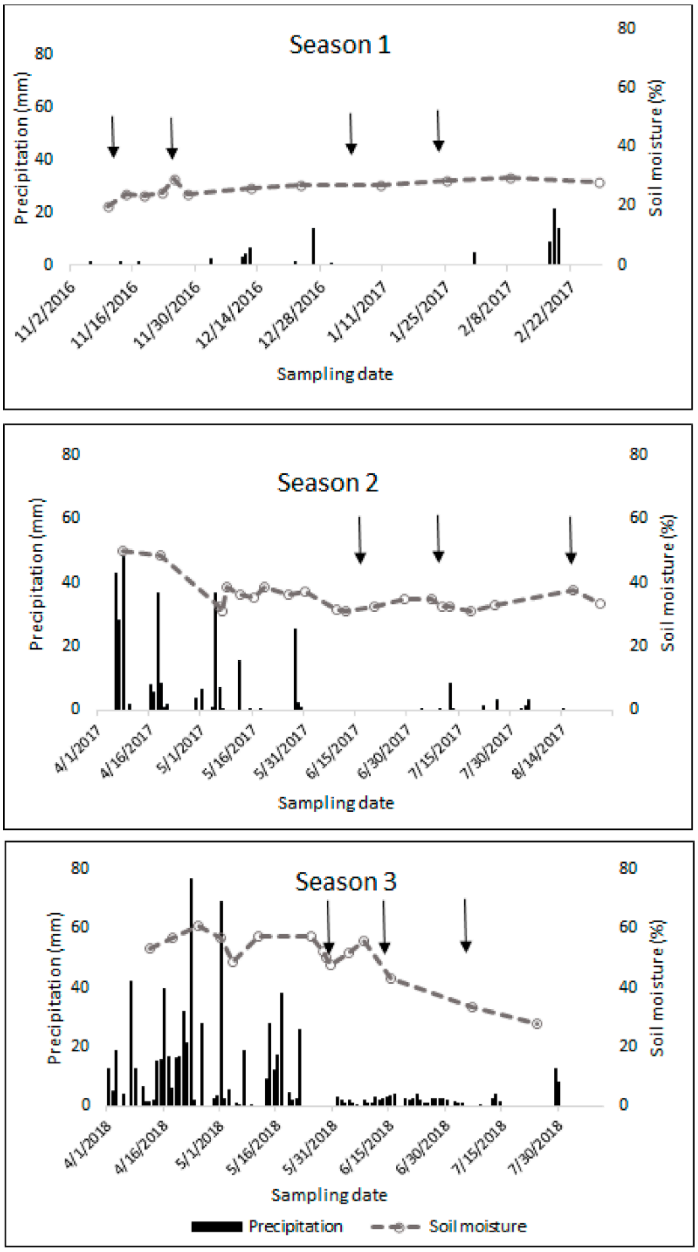

Figure 3. Average daily rainfall and gravimetric soil water content measured during gas sampling to a depth of 20 cm during three maize growing seasons: Season 1 (November 2016–February 2017), season 2 (April–September 2017), and season 3 (April 2018). Vertical arrows indicate supplemented overhead irrigation.

For the fertilized plots, the soil NO_3^- concentrations increased following fertilization (mean of 17.5 mg N kg^{-1} soil) and decreased gradually through the growing season to a mean concentration of approximately 10 mg N kg^{-1} soil at the end of the growing season. Soil NH_4^+ concentrations averaged 1.7 mg N kg^{-1} soil at the start of the season and 1 mg N kg^{-1} soil at the end of the season with no discernible pattern (Figure 4). For both the NO_3^- and the NH_4^+ concentrations, the increases after fertilization were greater during season 2 than in either season 1 or 3.

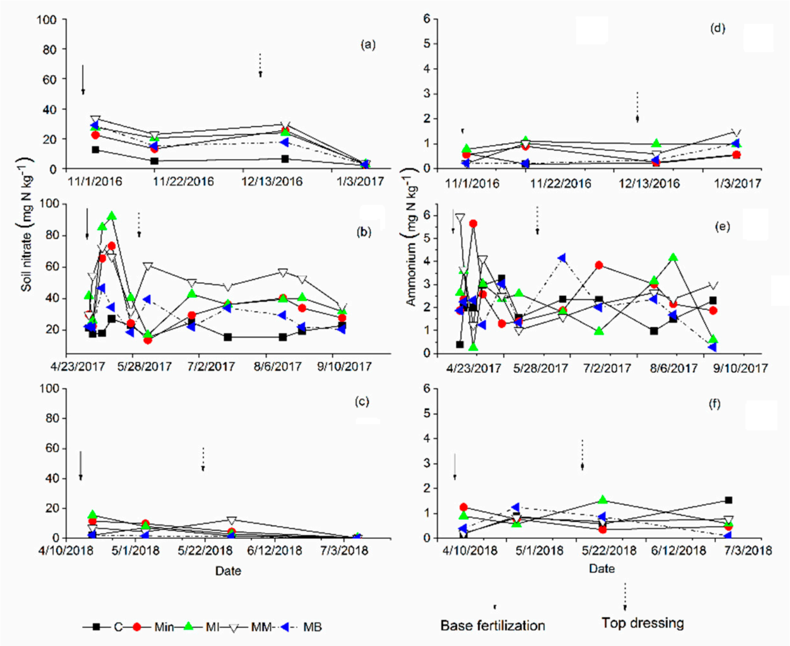

Figure 4. Soil nitrate (mg kg^{-1} soil), (**a**–**c**) for seasons 1, 2, and 3, respectively, and soil ammonium (mg kg^{-1} soil) (**d**–**f**) for seasons 1, 2, and 3, respectively, measured during gas sampling to a depth of 20 cm.

3.2. CH_4 Fluxes

Growing season 1 began with all treatments having an average emission rate of 0.3 mg h^{-1} except for the Min treatment which had −1.2 mg h^{-1} uptake. Average flux rates across all treatments were low (about 0.01 mg CH_4-C m^{-2} h^{-1}) with 69% of the fluxes being negative (i.e., uptake) (Figure 5). Growing season 2 also had primarily negative fluxes with 59% of measurements being uptake, and fluxes averaging −0.01 mg CH_4-C m^{-2} h^{-1}. Season 3 had the lowest number of negative fluxes (52%) with emission rates as high as 0.12 mg CH_4-C m^{-2} h^{-1} whereas uptake rates were quite low peaking at 0.03 mg CH_4-C m^{-2} h^{-1}. Generally, high emission rates were recorded between the first week of May and the first week of June when many of the plots were flooded while the rest of the season had average emissions of −0.02–0.02 mg CH_4-C m^{-2} h^{-1}.

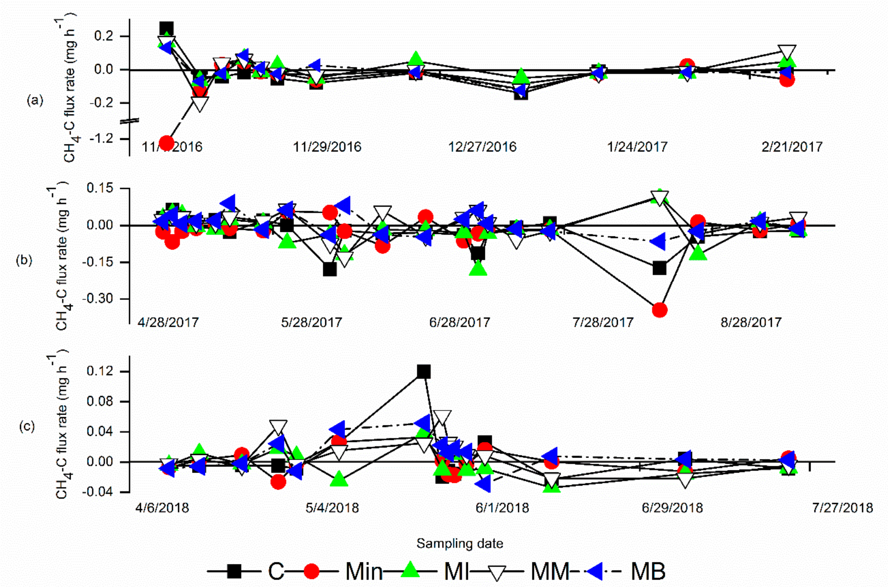

Figure 5. CH_4 (CH_4−C mg ha^{-1} h^{-1}) flux rate measured from spontaneous gas measurements for three different seasons: season 1 (**a**), season 2 (**b**), and season 3 (**c**).

Cumulative CH_4 fluxes ranged from −1.83 to −0.04 kg CH_4-C ha^{-1} for season 1, −1.6 to 0.33 kg CH_4-C ha^{-1} for growing season 2, and −0.19 to 0.24 for growing season 3 with the Min treatment having the highest uptake in two of the three seasons (Figure 6). Soils were CH_4 sinks and the rate of uptake changed from season 1 to season 3 with the highest uptake recorded in season 1. During the second season, four out of five treatments had negative flux rates measured over a period of 4.5 months (Figure 5). The order of cumulative fluxes for the three combined seasons was MM > MB > MI > C > Min. There was a significant correlation between mean seasonal soil moisture content and cumulative seasonal fluxes (p = 0.038). However, there were no correlations between soil moisture content and instantaneous CH_4 fluxes for any of the three seasons.

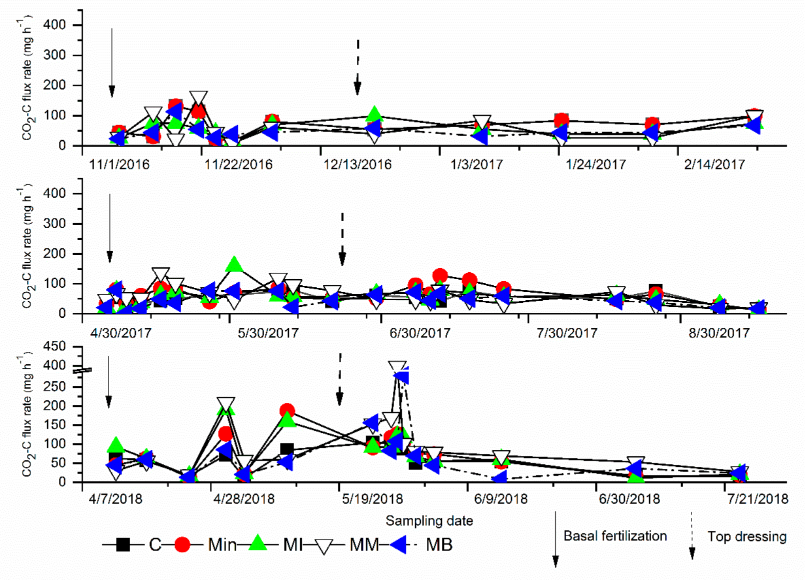

Figure 6. CO_2 (CO_2−C mg ha^{-1} h^{-1}) flux rates from maize plots with different nitrogen (N) fertilizer treatments and a no N control (C) over three crop growing seasons. Continuous line arrows indicate basal fertilizer application while dashed line arrows indicate top dressing.

3.3. CO_2 Fluxes

Relatively low peaks in CO_2-C emission rates were observed at the beginning and end of each of the three growing seasons (Figure 6). Initial fluxes for growing season 1 ranged between 20 and 40 mg CO_2-C m^{-2} h^{-1} then rose steadily to a maximum of 160 mg CO_2-C m^{-2} h^{-1} in between 14 and 22 November 2016. The flux rates then decreased, remaining below 100 mg CO_2-C m^{-2} h^{-1} for the rest of the season. Season 2 followed a similar trend but had higher measurements initially, increasing to almost 500 mg CO_2-C m^{-2} h^{-1} in mid-May before decreasing rapidly and returning to fluxes of about 20 mg CO_2-C m^{-2} h^{-1} for most of the growing season. Growing season 3 showed a different pattern, with emissions initially ranging from about 80 to 250 mg CO_2-C m^{-2} h^{-1} before decreasing, only to increase again in late April and again in early June when they peaked at about 400 mg CO_2-C m^{-2} h^{-1} before returning to an average of 25 mg CO_2-C m^{-2} h^{-1} at the end of the season (Figure 6).

The lowest cumulative seasonal flux measured was 1246 kg ha^{-1} in the C treatment during growing season 3 while the highest was 2054 kg ha^{-1} in Min during growing season 2. Cumulative flux for the three seasons ranged from 4100 to 5543 kg CO_2-C ha^{-1}. Cumulative CO_2 fluxes tended to be lower in the MB treatment than in the other treatments with no consistent differences between the other treatments (Figure 7). There were no significant correlations between flux rates and either soil moisture (p = 0.431) content or yield (p = 0.503)

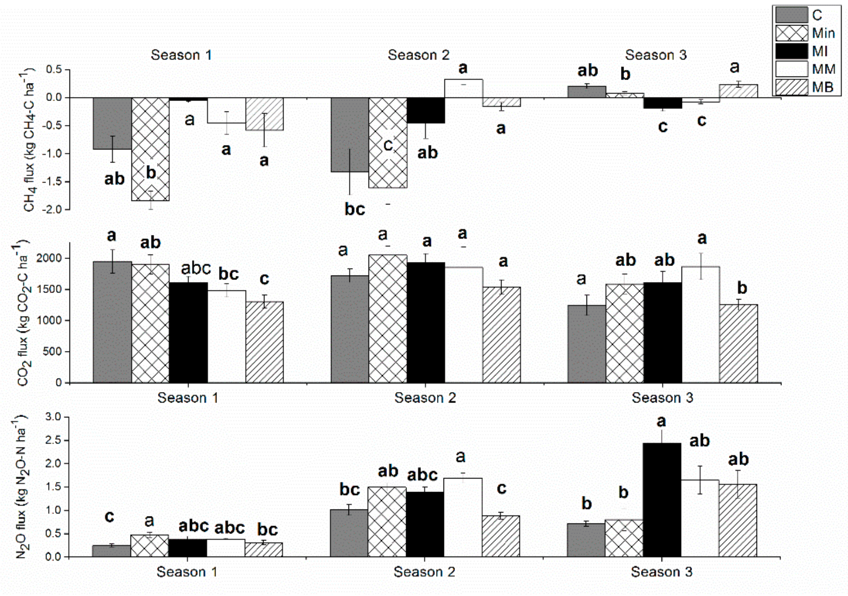

Figure 7. Cumulative CH_4 (CH_4-C kg ha^{-1}), CO_2 (CO_2-C kg ha^{-1}), and N_2O (N_2O-N kg ha^{-1}) with standard errors fluxes over the three growing seasons sampled from different plots with different fertilizer and manure/irrigation treatments. Bars with different letters indicate significant differences among the treatments (Duncan's test 0.05 significance level).

3.4. *N_2O Fluxes*

The N_2O flux rates during season 1 increased shortly after the initial fertilizer application (4 November 2016), with the highest rates measured in late November (Figure 8). Rates remained elevated until early December 2016, when they decreased to less than 10 µg N_2O-N m^{-2} h^{-1} until the end of the sampling period. Season 2 N_2O flux rates followed a similar pattern, peaking shortly after fertilization before returning to baseline rates approximately 1 month later (Figure 8). However, during season 2, N_2O flux rates increased in the MM and MI treatments to almost 100 µg N_2O-N m^{-2} hr^{-1} on 17 August 2017. The first measurement of season 3, which was after basal fertilization, captured a declining peak with MB and MI maintaining relatively higher flux rates as compared to the other treatments. Emissions in season 3 had peaks other than those observed immediately after fertilization, with high emissions observed a few days after high precipitation episodes. The flux rates for all treatments except C increased after topdressing in late May, with the flux rates declining over the subsequent weeks to baseline and remaining low until the end of the season. Cumulative fluxes ranged between 0.25 and 0.48 kg ha^{-1} during season 1, 0.89–1.69 kg ha^{-1} during season 2, and 0.72–2.45 kg ha^{-1} during season 3. Cumulatively, growing season 1 had the lowest emissions while growing season 3 had the highest (Figure 7). Cumulative emissions from MI were 2.24 kg ha^{-1} greater than emissions from C treatment ($p = 0.046$) while the other treatments were similar. The emission factor was highest in MM treatment for seasons 1 and 2 whereas it was the second highest in season 3 (Figure 7).

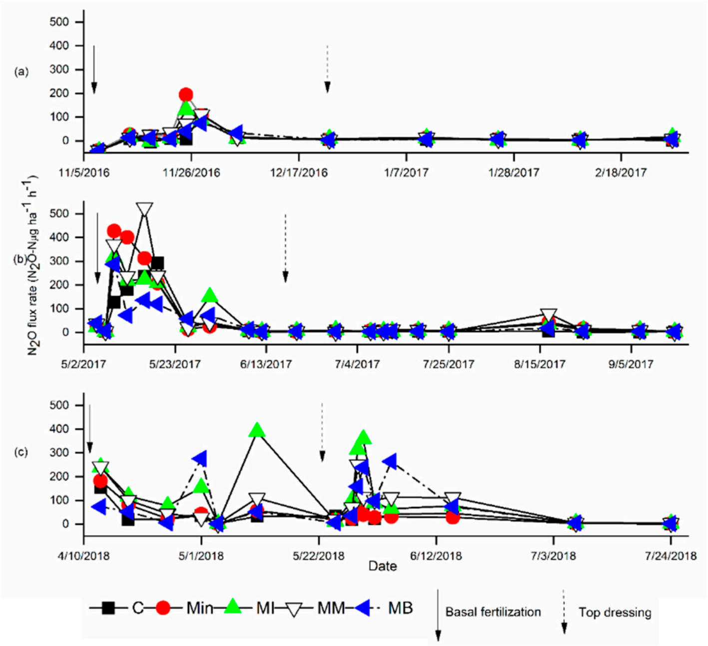

Figure 8. N_2O (N_2O-N µg ha^{-1} h^{-1}) flux rate from maize plots with different nitrogen (N) fertilizer treatments and a no N control (C) forcrop growing season 1 (**a**), season 2 (**b**) and, season 3 (**c**). Continuous line arrows indicate basal fertilizer application while dashed line arrows indicate top.

There was a correlation between soil moisture content and cumulative N_2O emission (F = 58.2, $p = 0.02$). All the treatments had Emission Factors (EF) less than 1% during all three growing seasons (Table 3). Instantaneous flux rates showed no correlation with soil nitrate concentrations, yield, nor soil moisture content for all seasons. Nitrate intensity was not significantly correlated to cumulative emissions at $R^2 = 0.216$ ($p = 0.213$), 0.120 ($p = 0.173$) for seasons 1 and 2, respectively, whereas there was a significant correlation in season 3 ($R^2 = 0.520$; $p = 0.021$).

Table 3. N_2O Emission Factor which is a percentage of fertilizer applied released as N_2O emission (IPCC, 2006) for different fertilizer treatments and management depicting small scale farming systems in Central Kenya.

	Season 1	Season 2	Season 3	Mean
Min	0.23 ± 0.02	0.49 ± 0.01	0.08 ± 0.02	0.27 ± 0.12
MI	0.13 ± 0.03	0.39 ± 0.01	0.17 ± 0.03	0.23 ± 0.08
MM	0.14 ± 0.06	0.68 ± 0.03	0.93 ± 0.15	0.58 ± 0.23
MB	0.06 ± 0.06	0.12 ± 0.31	0.84 ± 0.26	0.34 ± 0.25

4. Discussion

4.1. CH_4 Emissions

CH_4 emissions are important in estimation of total GHG emissions since CH_4 is produced anaerobically by methanogenic microbes and later it may be oxidized to CO_2 by methanotrophic bacteria under aerobic conditions. Thus, CH_4 flux is important since it influences CO_2 flux [27]. CH_4 is also an important greenhouse gas since it has a global warming potential (GWP) of 25–28 in relation to CO_2 [28]. Methane flux rates were similar to a previous study completed in the region [13] where emissions from maize fields with different fertilizer and manure treatments ranged from −2.6 to 5.8 kg ha $^{-1}$ over a 6-month period. The oxidation of CH_4 during the two drier seasons (i.e., seasons 1 and 2) was consistent with prior studies that showed how upland soils tend to be CH_4 sinks when dry, and that the sink strength is much diminished (or the soils may even become sources) when wet, as seen in season 3 [14,29,30]. Increased soil moisture content can reduce diffusion of atmospheric CH_4 into the soil, thus reducing the ability of the soil to act as a CH_4 sink. However, fertilizer addition can also inhibit CH_4 oxidation, especially where fertilization results in high NH_4 concentrations [31]. However, the low NH_4 concentrations measured in this study suggest that fertilization had little effect on total CH_4 emissions. The steady increase in cumulative CH_4 flux as the mean soil moisture content increased from season 1 to season 3 suggests that soil moisture was the main driver determining the CH_4 fluxes in this study.

A number of studies have reported CH_4 oxidation from various ecosystems ranging from grasslands to croplands [32,33]. Whereas these studies were carried out in different regions, the crop growing season of [34] occurred in spring when prevailing atmospheric conditions were similar to the conditions of this study. The mechanism of CH_4 oxidation/emission greatly depends on SWC, temperature and soil conditions. SWC was positively correlated with CH_4 fluxes. Extremes of soil water content limited methanotrophic activities suppressing the CH_4 fluxes. Optimal SWC meant vibrant methanotrophic activity which led to higher CH_4 oxidation in season 2 compared with season 3 whose lower oxidation and emissions rates could be explained by limited gas diffusion at higher SWC [30,35]. Our study showed that atmospheric temperature was weakly correlated with CH_4 oxidation explaining only 20% of the CH_4 oxidation in agreement with [36] who also found that temperature was a minor co-factor in CH_4 oxidation

4.2. CO_2 Emissions

Cumulative soil CO_2 emissions recorded in this study were at the low end of an earlier study carried out in maize with agroforestry [29] where emissions ranged from 1.8 to 2.3 Mg CO_2-C ha^{-1} over a 99 d period, and also at the low end of the range of studies in Kenya and Tanzania where emissions ranged from 2.8 to 15.9 Mg CO_2 ha^{-1} yr^{-1} [14,21]. However, the emissions were at the high end of another study from Zimbabwe where 122d cumulative CO_2-C emissions ranged from 0.7 to 1.6 Mg CO_2 ha^{-1} [13]. The flux rates were generally low at the beginning of the seasons (average of 70 mg CO_2 m^{-2} h^{-1}) likely owing to the low root respiration of the young plants and increased during the plant growing stage (with average peaks of above 200 mg CO_2 m^{-2} h^{-1}). The last sampling shows the lowest observed flux rate (50 mg CO_2 m^{-2} h^{-1}) since the soil tended to be dry and the plants were at senescence stage with minimal root respiration [37]. The slight increase in soil respiration at the end of the first season can be attributed to increased microbial activity following the incorporation of the crop residues along with the arrival of some light rains (and increased soil moisture content) that occurred at the end of the season. Together, microbial activity and plant root respiration were the regulators of CO_2 emissions in this experiment.

We expected the MM treatment to experience the highest soil CO_2-C emission rates for all the three seasons because of the additional C applied as manure. While this was the case during season 3, this was not the case in seasons 1 and 2. Interestingly, treatment C had the highest initial soil C concentrations (Table 2) as well as similar or even higher emission rates as compared to the other treatments which had C inputs. Over time, it is expected that these soil C concentrations will decrease compared to the other treatments as there are no external C additions to the plots, and as the lower biomass yield (Table 4) will mean less C returned to the soil via residue incorporation. Reductions in soil C in the control plots may explain why soil CO_2-C fluxes decreased steadily from seasons 1 to 3 in the control plots, whereas the other plots did not show this steady decline in emissions.

This further supports the observation that plots with higher root respiration/biomass have more emissions [38]. Soil C:N ratio reduced with increase in N input which is consistent with earlier studies [39] where <100 kg N input resulted in C:N of 14 whereas >200 kg of N resulted in a ratio of <11 consistent with our findings. Additional N through fertilizations adds plant available N which at times is not utilized by the plant and ends up being mineralized. This coupled with additional nitrogen in the form of plant residue increases soil nitrogen and consequently reduces the ratio as seen in Table 2. The consistently low emissions from the MB treatment, meanwhile, could be related to the wider spacing of maize plants in MB as two consecutive rows were alternated with two lines of beans. This may have increased water loss through evaporation as beans have less ground cover thereby reducing the soil moisture and slowing organic matter decomposition and root respiration. Additionally, the lower plant density may have reduced root densities resulting in lower root respiration, while lower biomass results in reduced C returned into the soil (Table 2), which could also cause lower CO_2 emissions.

Table 4. Mean (±1 SD) above ground biomass (g) of 3 plants from maize plots near Nairobi Kenya with different fertilizer treatments taken during the mid-growing period of each of the three seasons. Different letters indicate significance at 0.05.

	Season 1	Season 2	Season 3
C	80.0 ± 0.64 a	81.7 ± 0.36 a	79.7 ± 1.30 a
Min	95.0 ± 0.11 a	85.8 ± 1.30 b	82.3 ± 0.80 a
MI	94.2 ± 2.80 a	88.8 ± 1.30 a	85.6 ± 0.59 a
MM	94.3 ± 1.50 b	91.9 ± 2.30 a	90.3 ± 0.38 a
MB	84.5 ± 0.95 a	81.8 ± 1.70 ab	89.3 ± 2.40 a

4.3. N_2O Emissions

Cumulative N_2O emissions were consistent with earlier studies where measured cumulative emissions from maize fields in Kenya ranged from 0.1 to 4.1 kg N_2O-N ha^{-1} over a 4-month period [40] and where cumulative emissions from a number of crop types in Kenya and Tanzania ranged from 0.4 to 3.9 kg N_2O-N ha^{-1} yr^{-1} [18]. However, with the exception of growing season 1 (with its overall low emissions), the emissions were higher than other studies from east Africa [13,41] where emissions were 0.62–0.81 kg N_2O-N ha^{-1} (over a 6-month period) and 0.1–0.5 kg N_2O-N ha^{-1} (over a 5-month period), respectively.

The lower emission rates observed in the control were consistent with expected results where fertilized plots were expected to have higher emission rates than the unfertilized plot [42]. The start of each season had high emission rates that were caused by the high N concentrations due to the added fertilizer and the increased soil moisture content due to high rainfall (seasons 2 and 3) or irrigation in the case of season 1. During season 1, the N_2O released was likely from nitrification as the low amount of NO_3^-, relatively higher NH_4^+, and drier soil conditions were ideal for nitrification to take place [9]. The first few days of each season were also characterized by soil disturbances caused by ploughing and planting which may have created greater soil aeration and thus enhancing emission rates [43]. Soil NO_3^- in MB treatment was low (Figure 4), which might be due to uptake or rapid immobilization [7] by either the growing crop or the microbial community, likely reducing the emissions. Waterlogging which caused ponded water on the soil surface and increased soil moisture content at the start of seasons 1 and 2 (Figure 3) observed in the site with MB treatment affected most suggest the possible reason of low N_2O emission from the MB treatment as compared to others.

The strong correlation between cumulative N_2O emission and NO_3^- intensities in fertilized plots indicates a direct influence of fertilizer application on N_2O emissions consistent with our expectations [44,45]. High NO_3^- concentrations in the soils provided the N substrate required for the production of N_2O through microbial denitrification [46]. The positive correlation between mean soil moisture content and cumulative emissions was likely because denitrification requires anaerobic conditions, and soils will have more anaerobic microsites at higher soil moisture content resulting in high N_2O emissions [47].

Emission rates between different treatments were not consistent across growing seasons as the seasons were short and each season presented different weather conditions. However, a trend could be deduced from the average emissions over the three seasons. Zero N input resulted in lower emissions whereas optimal soil moisture through supplemented irrigation and increased N levels through manure addition in the soil led to higher emissions from the MI and MM treatments, consistent with previous research [9]. Similar levels of emissions in MB and Min treatments showed that type of plant cover did not affect the emission rates.

Lower precipitation in season 1 and the resulting low soil moisture content resulted in lower emissions for season 1 as compared to seasons 2 and 3, likely because denitrification, which is generally the primary source of N_2O emissions from agricultural soils [48,49], generally requires soil water content above 60% WFPS [50]. Consistent with previous studies, emissions increased during or slightly after precipitation episodes [14,51] as soil NO_3^- concentrations tend to increase after re-wetting of soils due to temporary mobilization of N that accumulated over the dry period [52]. This is characterized by an increase in soil microbial populations some of which are involved in biogeochemical cycles [53]. The high emission rates experienced at the start of seasons 2 and 3 was due to fertilization and consequently, higher inorganic N levels. High rainfall during this period might cause anaerobic conditions suitable for denitrification. The increase in N_2O emissions after the first (fertilization peak) was likely due to the combined effect of nitrification and denitrification which may have occurred simultaneously [54,55]. The reduced soil moisture content also allows for more rapid gas diffusion that results in less opportunity for N_2O to be reduced to N_2 and hence greater N_2O emissions [10]. Season 3 emissions were similar to season 2 with high emission rates observed during the periods after basal fertilization and top dressing as well as additional peaks seen around 11 May due to rainfall episodes. Consistently higher soil moisture content during season 3 likely caused slightly lower emissions than season 2, perhaps because the higher soil water content would result in more complete denitrification to N_2 [9,56].

Although there was no significant difference among different treatments for instantaneous fluxes, cumulative fluxes provided an overall picture from which significant differences could be seen. Spontaneous greenhouse gas measurements were noisy in some cases and did not provide a distinct trend between different treatments. The erratic nature of spontaneous emissions could be attributed to the extreme weather conditions especially high rainfall which caused a variation in distal and proximal emission drivers hence affecting the stability of emissions [9,57]. Increased moisture content affects all the three gases which were measured differently, and it was a key factor which was constantly changing. High rainfall episodes which were far apart made the soil shift from extremely dry to extremely moist. This also caused shifts to occur from denitrification to nitrification which produce different amounts of N_2O [58]. The decomposition rate which is critical in CO_2 emissions may have also been affected by the moisture/rainfall. Oxidation of CH_4 which is reliant on oxygen levels in the soil was also greatly influenced by the erratic rainfall. These factors together may have caused the erratic spontaneous fluxes. Long-term effects can easily be observed on specific treatments making long-term experiments more suitable to study field emission experiments in the region as indicated by the cumulative fluxes.

5. Conclusions

This study shows that agricultural soils from the dry uplands of central Kenya were CH_4 sinks when conditions were dry. However, under flooded conditions they have the capacity to become sources. Cumulative soil N_2O fluxes were correlated in two out of the three growing seasons with mean soil moisture content where emissions increased with N input. Precipitation was a factor where low precipitation led to low emissions, moderate precipitation had high emissions, while high precipitation caused moderate to high emissions. Therefore, as the region moves to intensify crop production through increased N input and irrigation, CH_4 and CO_2 fluxes are likely to have minimal increases while N_2O emissions are expected to increase but will remain below <1% of N applied if application rates remain below 100 kg N ha^{-1} season^{-1}. However, more long-term studies need to be conducted for more conclusive studies on annual emissions and estimation of regional emission rates.

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