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Key Points:
- Animal manure increases maize yields while simultaneously reducing yield-scaled emissions
- N_2O emission factors (EFs) from this study suggests that the default IPCC EFs may overestimate N_2O emissions in sub-Saharan Africa
- Soil C, a key driver of GHG emissions, can be increased by the use of animal manure but may come at the cost of greater N_2O emissions

Correspondence to:
J. M. Macharia,
machariamjoseph@gmail.com

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Author Contributions:
Conceptualization: Felix K. Ngetich, Chris A. Shisanya
Data curation: David E. Pelster, Felix K. Ngetich
Funding acquisition: David E. Pelster, Felix K. Ngetich, Chris A. Shisanya
Methodology: David E. Pelster, Felix K. Ngetich
Project administration: Felix K. Ngetich, Monicah Mucheru-Muna, Daniel N. Mugendi
Resources: Chris A. Shisanya, Monicah Mucheru-Muna, Daniel N. Mugendi
Supervision: David E. Pelster, Felix K. Ngetich, Chris A. Shisanya, Monicah Mucheru-Muna, Daniel N. Mugendi
Validation: David E. Pelster, Felix K. Ngetich
Writing – review & editing: David E. Pelster, Felix K. Ngetich, Chris A. Shisanya, Monicah Mucheru-Muna

Soil Greenhouse Gas Fluxes From Maize Production Under Different Soil Fertility Management Practices in East Africa

Joseph M. Macharia[1,2], David E. Pelster[2,3], Felix K. Ngetich[4], Chris A. Shisanya[1], Monicah Mucheru-Muna[5], and Daniel N. Mugendi[4]

[1]Department of Geography, Kenyatta University, Nairobi, Kenya, [2]Mazingira Centre, International Livestock Research Institute, Nairobi, Kenya, [3]Now at Agriculture and Agri-Food Canada, Quebec, Quebec, Canada, [4]Department of Land and Water Management, University of Embu, Embu, Kenya, [5]Department of Environmental Sciences, Kenyatta University, Nairobi, Kenya

Abstract In sub-Saharan Africa (SSA), few studies have quantified greenhouse gas (GHG) emissions following application of soil amendments, for development of accurate national GHG inventories. Therefore, this study quantified soil GHG emissions using static chambers for two maize cropping seasons (one full year) of four different soil amendments in the central highlands of Kenya. The four treatments were (i) animal manure, (ii) inorganic fertilizer, (iii) combined animal manure and inorganic fertilizer, and (iv) a no-N control (no amendment) laid out in a randomized complete block design. Cumulative annual soil fluxes (February 2017 to February 2018) ranged from -1.03 ± 0.19 kg CH_4-C ha^{-1} yr^{-1} from the manure inorganic fertilizer treatment to -0.09 ± 0.03 kg CH_4-C ha^{-1} yr^{-1} from the manure treatment, $1,391 \pm 74$ kg CO_2-C ha^{-1} yr^{-1} from the control treatment to $3,574 \pm 113$ kg CO_2-C ha^{-1} yr^{-1} from the manure treatment, and 0.13 ± 0.08 to 1.22 ± 0.12 kg N_2O-N ha^{-1} yr^{-1} in the control and manure treatments, respectively. Animal manure amendment produced the highest cumulative CO_2 emissions ($P < 0.001$), N_2O emissions ($P < 0.001$), and maize yields ($P = 0.002$) but the lowest N_2O yield-scaled emission (YSE) (0.5 g N_2O–N kg^{-1} grain yield). Manure combined with inorganic fertilizer had the highest cumulative CH_4 uptake ($P < 0.001$) and N_2O YSE (2.2 g N_2O–N kg^{-1} grain yield). Our results indicate that while the use of animal manure may increase total GHG emissions, the concurrent increase in maize yields results in reduced yield-scaled GHG emissions.

Plain Language Summary The greenhouse gas (GHG) inventory of agricultural production systems in sub-Saharan Africa (SSA) remain uncertain. This emanates from the huge data gap as a result of the limited number of studies on GHG measurement, following soil amendments. This lack of data adds further difficulties for developing countries such as Kenya to accurately assess and report current GHG emissions from agriculture. Countries in SSA continue reporting to the United Nations Framework Convention on Climate Change on their current GHG emissions' status using default Intergovernmental Panel on Climate Change (IPCC) Tier I emission factors. Based on our measurements, we show that the previously reported GHG from fertilizer application may be highly overestimated. We also demonstrate the positive role played by animal manure in increasing maize yields and reducing yield-scaled GHG emissions (YSE). Our study, therefore, calls for revision of the emission estimates from agricultural production in SSA.

1. Introduction

Global atmospheric greenhouse gas (GHG) concentrations, notably methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) have risen over the last century causing an increase in average global surface temperatures (IPCC, 2014; Oertel et al., 2016). These three major GHGs contribute about 80% to the current global radiative forcing (Myhre et al., 2013). Agriculture contributes between 14% and 17% to the global anthropogenic GHG emissions (Ciais et al., 2013; Paul et al., 2017). Separated by gas species, agriculture accounts for 13% of global CO_2 emissions, mainly through land use change; 50% of the global CH_4 emissions, primarily from rice cultivation and enteric fermentation; and about 60% of global N_2O emissions, predominantly from the application of N fertilizers (Smith et al., 2014). GHG fluxes from agricultural systems may vary considerably depending on the soil properties, climatic conditions, and land management (Masaka et al., 2014; Pelster et al., 2012; Rosenstock et al., 2016).

Previous research in sub-Saharan Africa (SSA) has demonstrated that a decline in soil fertility is a major challenge affecting agricultural productivity (Mucheru-Muna et al., 2014; Mugwe et al., 2009; Place et al., 2003; Sanchez, 2002). Consequently, several soil fertility management interventions were found to improve not only soil fertility and overall soil health but also increase crop yields (Bationo et al., 2003; Vanlauwe et al., 2014). In the central highlands of Kenya, animal manure is one of the most widely used soil amendments and is used by approximately 80% of households (Macharia et al., 2014), with highly variable application rates between households (Mugwe et al., 2009). Application of inorganic fertilizers to counterbalance the existing low soil fertility is also done, although the relatively high costs of fertilizers have limited their use in the central highlands of Kenya (Mugwe et al., 2009). A third strategy is the integration of mineral with organic fertilizers to increase the agronomic efficacy of the inputs supplied, reduce the possibilities of soil acidification due to mineral fertilizer applications, and provide a more stable nutrient supply (Mugwe et al., 2009). However, none of the studies conducted in the central highlands of Kenya has so far quantified how application of these different fertilizer types affect soil GHG fluxes in maize production.

Net soil GHG fluxes are the result of complex soil processes involving many different biogeochemical reactions (Eugster & Merbold, 2015). As for net CO_2 emissions, it is the sum of autotrophic (plant roots and associated mycorrhizal fungi) and heterotrophic (soil CO_2 produced through the oxidation of soil organic matter) respiration (Jovani Sancho et al., 2017; Moyano et al., 2008). Net soil CH_4 flux results from two antagonistic processes, namely, methanogenesis, which is responsible for methane production under anaerobic conditions, and methanotrophy, which is responsible for methane consumption (Eugster & Merbold, 2015; Pazinato et al., 2010). Nitrous oxide (N_2O) emissions occur mainly due to microbial production processes in soils under oxygen (O_2) limiting environmental conditions including chemodenitrification, denitrification, codenitrification, and nitrifier-denitrification (Butterbach-Bahl et al., 2013) and as a by-product of nitrification, an aerobic process requiring NH_4 (Bateman & Baggs, 2005).

Accurate determination of soil GHG fluxes from croplands is critical in determining if a farming system is either a net source or sink of GHGs (Kirschke et al., 2013; Shaojuna et al., 2011). Due to the paucity of observational data of GHG emissions from typical farming systems in SSA, in particular from smallholder systems (Pelster et al., 2017), the GHG inventory of agricultural production systems remain largely uncertain (Ciais et al., 2011; Hickman et al., 2014; López-Ballesteros et al., 2018; Valentini et al., 2014). This lack of data adds further difficulties for developing countries such as Kenya to accurately assess and report current GHG emissions from the agriculture, forestry, and other land use sector to the United Nations Framework Convention on Climate Change as required under the Paris Climate Agreement 2015 (Horowitz, 2016).

According to the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2009), maize (*Zea mays L.*) ranks second, after wheat, in the order of importance among the world cereal crops. Moreover, maize is an important food and source of cash for most rural families in SSA (Midega et al., 2018; Valentini et al., 2014) and is the main staple food in Kenya (Schroeder et al., 2013). Consequently, this study investigated GHG fluxes from maize production in the central highlands of Kenya. The study objectives were to quantify soil GHG fluxes (CH_4, CO_2, and N_2O) and crop yields after application of three different fertilizer amendments and a no-fertilizer treatment in a typical maize field and investigate possible environmental drivers controlling the GHG fluxes. We hypothesized that (a) animal manure application would emit the most CO_2 because of the addition of labile C and the most CH_4 due to the addition of methanogens and the potential for degassing of CH_4 upon addition of goat manure; (b) animal manure combined with inorganic fertilizer would emit the most N_2O because of the addition of both labile carbon and nitrogen; and (c) CO_2 and CH_4 emissions would be controlled by soil moisture content while fertilizer type would be a key driver controlling N_2O emissions.

2. Methodology

2.1. Study Site

This study was carried out in Embu County, Kenya, which lies in the Lower Midland (LM5) agroecological zone (AEZ) on the eastern slopes of Mount Kenya (FAO, 1996) and within the upper Tana river catchment

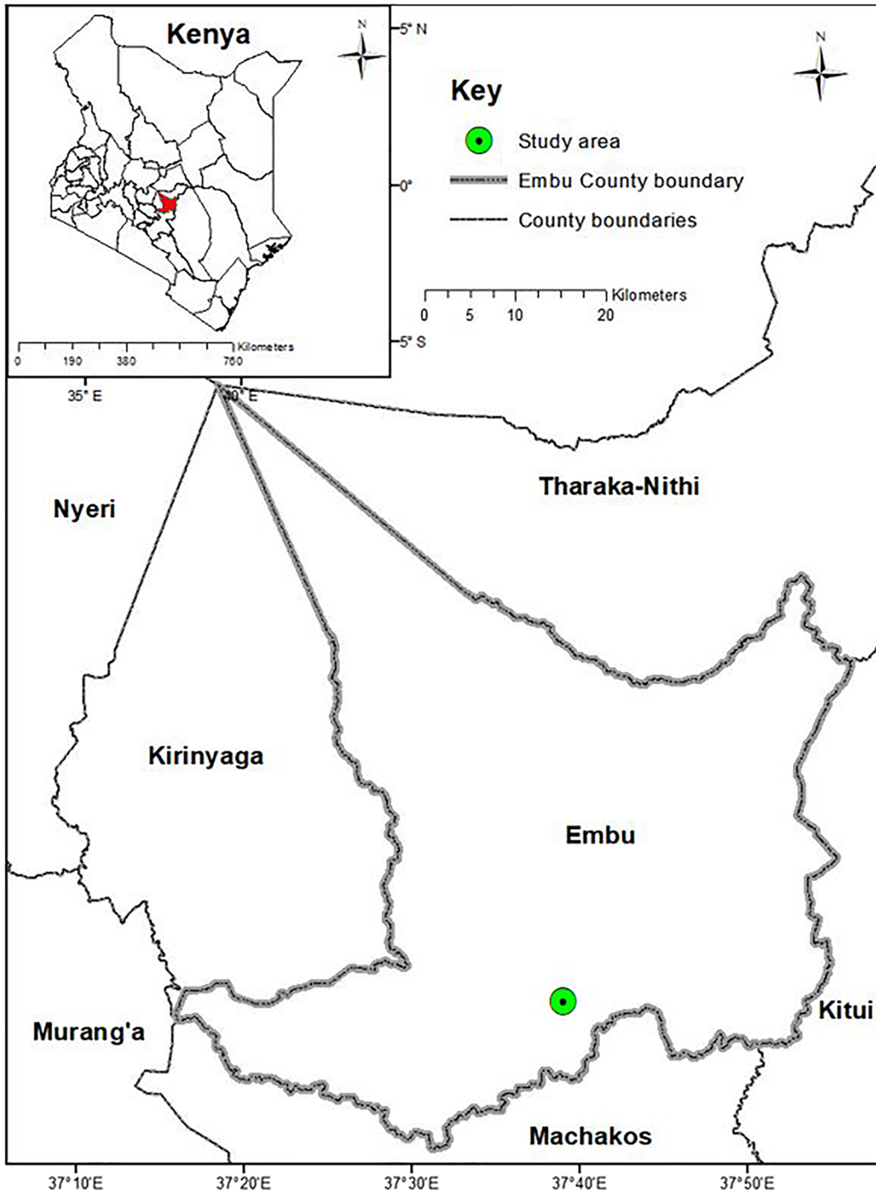

Figure 1. Map showing the location of the study site in Machang'a secondary school in Embu county, Kenya.

(Figure 1). The trial was established in 2004 at Machang'a secondary school (longitude 37°39′45.3″E; latitude 00°47′26.8″S), located at 1,030 m above sea level (Mucheru-Muna et al., 2009). The rainfall pattern in the study area is bimodal with long rains (LRs—averaging 430 mm rainfall) lasting from March through June and short rains (SRs—averaging 350 mm rainfall) occurring from October through December, thus supporting two complete cropping seasons in a year. The climate is categorized as tropical savanna using Köppen climate classification (Peel et al., 2007), with a mean annual temperature of 21.6°C (Jaetzold et al., 2007). The soils are predominantly sandy loam (Ngetich et al., 2014) less weathered, yellowish red, Xanthic Ferralsols (Jaetzold et al., 2007).

The study site lies in a marginal area characteristic of low agricultural potential and very short cropping seasons (Ngetich et al., 2014). Nevertheless, the zone is suitable for lowland hybrid maize (*Zea mays L.*), chickpeas (*Cicera rietinum*), green grams (*Vigna radiata*), common beans (*Phaseolus vulgaris*), sorghum (*Sorghum bicolor*), and cowpea (*Vigna unguiculata*) among other crops (Jaetzold et al., 2007). Most cropping systems in the region are maize-based (Okeyo et al., 2014) with common beans, as the favorite legume for intercropping (Kiboi et al., 2017).

2.2. Experimental Design

The experiment was laid out as a randomized complete block design replicated thrice. The details on trial establishment are explained in Mucheru-Muna et al. (2009). In brief, the full trial comprises 12 treatments of different organic and inorganic inputs, different assorted combinations, and a control (treatment without fertilizer input of nutrients). For this study on soil GHG fluxes, however, only four treatments were selected: (i) no fertilizer input (control), (ii) inorganic fertilizer (nitrogen [N] = 23% and phosphorus [P] = 23%; [NP]) applied at 120 kg N ha^{-1} yr^{-1}; (iii) goat manure applied at 120 kg N ha^{-1} yr^{-1}; and (iv) goat manure applied at rate of 60 kg N ha^{-1} yr^{-1} combined with the NP fertilizer at a rate of 60 kg N ha^{-1} yr^{-1}. It is worth noting that the three fertilizer treatments were applied at 60 kg N per growing season. These treatments were selected based on their popularity of use by the smallholder farmers in the study area (Macharia et al., 2014; Mugwe et al., 2009). The inorganic fertilizer used for this study was selected based on the recommendation by Mbuthia et al. (2015), who noted that the soils in the central highlands of Kenya are not K deficient. The experimental plots measured 6 m by 4.5 m with 1 m as a buffer between plots and at least 2 m between blocks (Mucheru-Muna et al., 2009).

The land was manually prepared with all aboveground fallow biomass removed from the plots at the beginning of each cropping season (February 2017 and September 2017, respectively) to minimize their interference with the individual treatments. Animal manure (locally sourced goat manure) was broadcast and immediately incorporated through hand-plowing approximately 2 weeks before seeding. The amounts of goat manure applied were calculated based on three composite samples of manure collected after thoroughly mixing the manure from two different farms and analyzed in the laboratories based on ground samples using a C/N analyzer (Thermal Scientific, Flash 2000 Analyzer, Waltham, MA USA). The manure had 2% $\pm$ 0.13 N, and therefore in order to supply the recommended 120 kg N ha^{-1} yr^{-1} (in plots treated solely with manure) and 60 kg N ha^{-1} yr^{-1} (in plots treated with manure + NP) (Fertiliser Use Recommendation Project (FURP), 1987), 6,000 and 3,000 kg ha^{-1} of dry goat manure were applied, respectively. The inorganic fertilizer was applied after the onset of the rains (6 April 2017 and 23 October 2017, respectively), directly in the maize planting holes and thoroughly mixed with the soils immediately before placing the seeds on top of the mixture (typical practice of local farmers). Dry highland maize (*Zea mays L.*) variety (DH 04) was planted (two seed per hole) at an interval of 0.9 m $\times$ 0.6 m, interrow and intrarow spacing, respectively. Weeds were regularly controlled using hand hoes with minimal soil disturbance.

2.3. GHG Concentration Measurements

The three GHGs, methane—CH_4, carbon dioxide—CO_2, and nitrous oxide—N_2O, were measured using vented manual static chambers (Butterbach-Bahl et al., 2016). The chambers were made out of PVC plastic and consisted of a base (27 $\times$ 37.2 $\times$ 10 cm) and a lid (27 $\times$ 37.2 $\times$ 12.5 cm). Three chamber bases per plot were inserted into the soils to a maximum depth of 7 cm 2 weeks before the first sampling event (25 January 2017). The chamber bases were removed during land preparations and manure incorporation at the beginning of long rains (LR) and short rains (SR) (4 March and 5 October 2017, respectively) and returned immediately after the activities. The chamber lids were equipped with a fan to avoid concentration gradients in the chamber headspace; a digital probe thermometer (TFA thermometer, Zum Ottersberg, Wertheim, Germany) to record the internal chamber temperature; a sampling port sealed with a silicon septum; a vent to equilibrate pressure within the chamber during deployment; and a closed-cell foam gasket between the lid and the base to ensure airtight sealing. Chamber base and lid were tightly clipped together with large metal binder clips. Sampling was done after every rainfall event, during major field activities, once a week at the beginning of the season, and fortnightly toward the end of the season and during off-season period. Sampling was carried out in the morning between 9:00 a.m. and 12:00 noon to minimize the effects of diurnal variation in flux patterns as this time of the day typically represents the daily average temperature and thus the typical average daily flux as well (Meng et al., 2005; Parkin & Venterea, 2010). The chambers were closed for 30 min, and gas samples were taken four times (0, 10, 20, and 30 min) using syringes (60 ml propylene) fitted with Luer locks. A 20 ml sample from each of the three chambers in a plot was collected and pooled to form a single 60 ml composite sample (Arias-Navarro et al., 2013). The pooled gas was thoroughly mixed by repeated pumping while still in the syringe and the first 40 ml of the content transferred to 20 ml preevacuated glass vials. The gas samples were then transported to Mazingira Centre at the International Livestock Research Institute (ILRI), Nairobi, Kenya, for analysis.

Concentrations of CH_4, CO_2, and N_2O in each sampling vial were determined using gas chromatography (8610C; SRI Instruments, Torrance, CA, USA) fitted with a ^{63}Ni-electron capture detector (ECD) for determining N_2O concentrations as well as a flame ionization detector (FID) and a methanizer for CH_4 and CO_2 analysis. Nitrogen gas (N_2) was used as the carrier gas for both the ECD and FID channels at a flow rate of 20 ml min^{-1}. The gas samples' concentrations were determined by comparing the peak area obtained from the gas chromatograph to peak areas of four known calibration gas concentrations. A linear regression approach was used to calculate CH_4 and CO_2 concentrations, while a power function was used to calculate N_2O concentration.

2.4. GHG Flux Calculations and Data Quality Control/Quality Assurance

The instantaneous soil GHG fluxes were calculated using the change in concentration over time and corrected for pressure and temperature, following Pelster et al. (2017) as shown in Equation 1.

$$F_{\mathrm{GHG}} = (\partial c/\partial t) * (M/V_{\mathrm{m}}) * (V/A), \tag{1}$$

where F_{GHG} is the flux of the GHG in question, $\partial c/\partial t$ is the change in concentration over time, M is the molar mass of the element in question (C for CO_2 and CH_4, and N for N_2O), V_{m} is the molar volume of gas at the sampling temperature and atmospheric pressure, V is the volume of the chamber headspace, and A is the area covered by the chamber. Fluxes were calculated in mg C m^{-2} hr^{-1} for CH_4 and CO_2, and in μg N m^{-2} hr^{-1} for N_2O. These respective GHG fluxes were later converted to kg CH_4-C ha^{-1} yr^{-1}, kg CO_2-C ha^{-1} yr^{-1} and kg N_2O-N ha^{-1} yr^{-1}, respectively.

While calculating the change in GHG concentrations over time, it is generally known that nonlinear models are less biased than the linear models; though they tend to be oversensitive to outliers (Rochette, 2011; Venterea et al., 2009). Therefore, adopting only or mostly linear regression models underestimates GHG fluxes, thus affecting the GHG inventories obtained by using closed static chambers (Silva et al., 2015). For this current study, we considered both linear and nonlinear regression models in the calculation of GHG concentration change whereby whenever there was a strong correlation ($R^2 > 0.95$) for the nonlinear model, we used second-order polynomial; otherwise, we used a linear model following Pelster et al. (2017).

A linear regression of the simultaneous CO_2 concentration over time was fitted. If the R^2 for the CO_2 concentration relation was less than 0.90, the three flux measurements were considered unreliable. Where the R^2 value for the CO_2 concentration was higher than 0.90, the three flux measurements were assumed reliable including those below the minimum detection limit calculated following (Parkin et al., 2012). The minimum flux detection limits for the three GHG were 3.15 and 10.40 mg CO_2-C m^{-2} hr^{-1}, 3.91 and 13.49 μg N_2O-N m^{-2} hr^{-1}, and 0.03 and 0.11 mg CH_4-C m^{-2} hr^{-1} for the linear and nonlinear models, respectively. Flux values below the minimum detection limit were retained and used to calculate the cumulative fluxes of the three GHGs. Cumulative GHG fluxes for each growing season (i.e., long rains [LR 2017], 6 February to 6 July 2017, and short rains [SR 2017], 7 July 2017 to 7 February 2018) as well as annual cumulative fluxes for the entire study period (February 2017 to February 2018) were determined for each plot based on linear interpolation between sampling dates (Barton et al., 2015).

2.5. Soil and Meteorological Measurements

Soil bulk density for the top 5 cm of soils was determined once for each plot before land preparations at the beginning of the LR 2017 (1 February 2017) using soil sample core rings with a 100 cm^3 volume (Eijkelkamp Agrisearch equipment, Giesbeek, the Netherlands). The bulk density samples were oven dried at 105°C for 24 hr (Stoof et al., 2015) and weighed. A composite sample (three soil cores per plot) was collected to a depth of 0–20 cm using single gouge auger (3 cm diameter) (Eijkelkamp Agrisearch equipment, Giesbeek, The Netherlands). The soil samples were individually packed in labeled Ziplock bags. Any large clumps of soil were immediately crushed by hand before the samples were transported to the laboratory for further analysis. The soil samples were oven dried at 40°C for 3 days (72 hr) and then ground using a ball mill (Retsch ball mill, Haan, Germany). A slurry of soil:water (1:2) was used to determine soil pH from the suspension using a glass probe pH meter (Crison Instruments, Barcelona, Spain). Total carbon (C) and N concentrations were determined on the powdered samples using the same C/N analyzer used for the manure.

Inorganic N (NO_3-N and NH_4-N) concentrations were measured every 2 weeks for the period between February–July 2017 and October 2017–February 2018 (during the two cropping seasons) starting immediately after planting until physiological maturity. During sampling, a composite of three subsamples of undisturbed soils was collected to a depth of 20 cm using the single gouge auger described above. Soil samples were transported to the laboratory at Mazingira Centre, ILRI, using a standard commercial cool box filled with ice packs. The fresh soils were extracted within a day of sampling by mixing 10 g of fresh soils with 50 ml of 2 M KCL and shaking the slurry in an orbital shaker (Edmund Buhler model, Hechingen, Germany) for 1 hr at 100 shakes per minute. The samples were then centrifuged (Hettich Centrifuge, Tullingen, Germany) for 10 min at 3,000 rpm, after which the supernatant was passed through a 110 mm Whatman ™ filter (No. 42) enhanced with a vacuum pump. The extracted samples were frozen until further analysis.

Analysis for NO_3-N was done via reduction with vanadium, with development of color (540 nm) using sulfanilic acid and naphthyl ethylene-diamine and measurement of light absorbance on the photometric analyzer (Aquakem200: Thermo Scientific, Wilmington, US). The NH_4-N concentrations were measured using the green indophenol method (660 nm) using the same photometric analyzer (Bolleter et al., 1961). Cumulative intensities of ammonium (NH_4^+-N), nitrate (NO_3^--N), and total inorganic N (IN) (NH_4^+-N + NO_3^--N), which represent the integrated measure of NH_4^+, NO_3^-, and total IN concentrations in the soil over time, were calculated as the summation of their daily concentration in the soil over the study period using linear interpolation between sampling dates following Burton et al. (2008). A subsample of the composite fresh soil was further oven dried at 105°C until a constant soil weight was obtained to determine soil moisture content. Conversion of IN concentrations to soil mass was based on the soil moisture content determined as a percentage of the dry soil mass.

Meteorological data were collected onsite and included rainfall at 3.5 m above ground, air temperature and relative humidity at 3 m above ground (S-THB-M002 sensor) (Onset Computer Corporation, Bourne, MA, USA). The data were averaged over 15 min and stored on a HOBO U30 NRC station data logger (Onset Computer Corporation, Bourne, MA, USA). Also, soil water content and soil temperature measurements were carried out adjacent to each chamber every time during gas sampling using a Procheck (ProCheck GS3 Sensor, Decagon Devices Inc. Pullman, Washington, USA).

2.6. Biomass Measurements

A sample of eight maize plants from four holes covering 2.16 m^2 (1.8 m × 1.2 m) near the middle of each plot (avoiding edge effects) was collected for biomass determination during the harvest of each cropping season (6 July 2017 and 7 February 2018, respectively). The aboveground samples were separated into individual components: leaves, stems, and grains. To determine total belowground biomass, the eight maize plants per plot were also dug up, mixed with water, and sieved with 2-mm wire gauze to ensure the roots were free of soils. The samples for the various plant components were weighed to measure their fresh weight and air dried for 3 weeks before weighing again to determine the air-dried weight and subsequent water content. The samples were then transported to the laboratory, dried for 48 hr at 60°C, and weighed again. A subsample of the roots, leaves, grains, and stems for long rains (LR) 2017 season (March–July 2017) were ground using a hammer mill (IKA mills, MF 10.2, Willington, N.C., USA) and analyzed for C and N content using the same C/N analyzer as described above for soil analysis. Maize grain yields were determined from a 19.9 m^2 (3.9 m × 5.1 m) harvest area (avoiding edge effects) at physiological maturity. Leaf area index (LAI) was measured using a ceptometer (Decagon Devices, Inc., Pullman, Washington, USA) on a weekly basis from the time the maize crop formed a canopy (at the sixth leaf stage or approximately 0.3 m above ground) until physiological maturity.

2.7. Yield-Scaled N_2O Emissions and N_2O Emission Factors

Yield-scaled N_2O emissions (YSE) (g N_2O-N kg^{-1} grain yield) were determined by dividing the cumulative N_2O emissions (g N_2O-N ha^{-1} yr^{-1}) of the study period by the total of grain yields (kg ha^{-1} yr^{-1}) covering both seasons (LR 2017 and SR 2017) following Van Groenigen et al. (2010). Nitrous oxide emission factors (EFs) were derived from N inputs and cumulative N_2O emissions as shown in Equation 2.

$$\mathrm{EF} = ((\mathrm{N_2O} - \mathrm{N_{fertilized}}) - (\mathrm{N_2O_{unfertilized}}))/\mathrm{N_{applied}} \tag{2}$$

where "N_2O-$N_{fertilized}$" is the cumulative emission of N_2O (kg N_2O-N) from the individual treatment, "N_2O-$N_{unfertilized}$" is the cumulative emission from the control treatment, and "$N_{applied}$" is the inputs of N in the specific treatment (kg N).

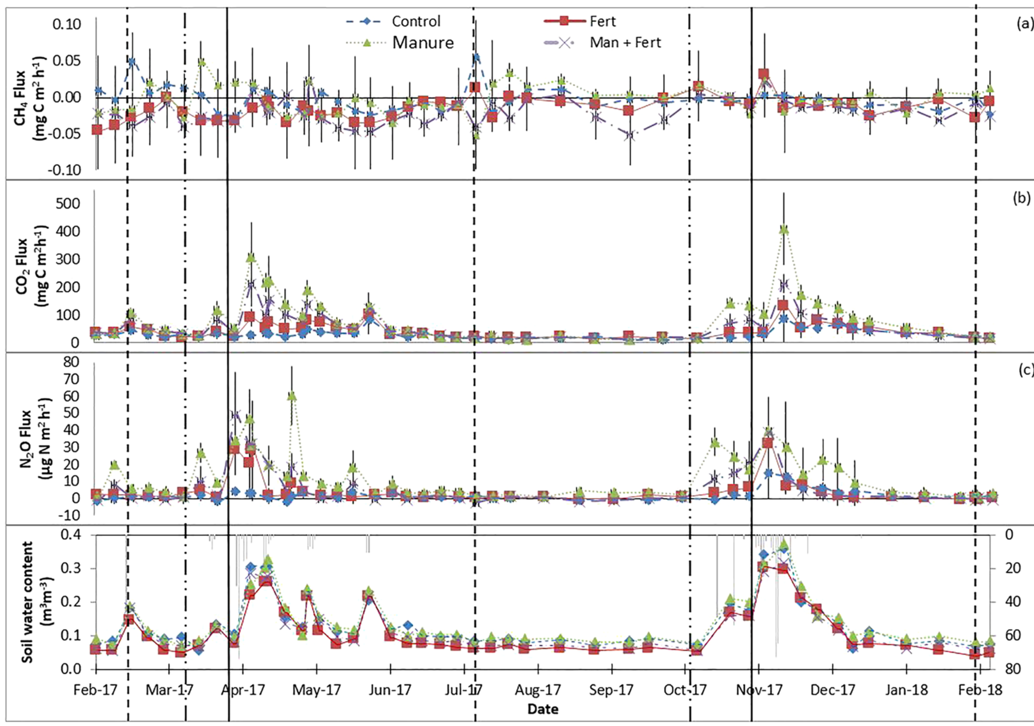

Figure 2. Soil (a) methane (CH_4-C mg m^{-2} hr^{-1}), (b) carbon dioxide (CO_2-C mg m^{-2} hr^{-1}), and (c) nitrous oxide (N_2O-N mg m^{-2} hr^{-1}) fluxes from February 2017 to February 2018. (d) Volumetric soil water content (m^3 m^{-3}) (SWC) at 10 cm depth and precipitation (mm). Treatment abbreviations are Control = no fertilizer input; Fert = inorganic fertilizer (120 kg N ha^{-1} yr^{-1}) from NP (N = 23%, P = 23%) applied at planting; Manure = goat manure applied at 120 kg N ha^{-1} yr^{-1}; Man + Fert = combination of goat manure and inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}. Manure was incorporated during land preparation. The vertical lines correspond to the harvesting of maize (dashed), land preparation and manure incorporation (long-dash dotted line), and planting of maize as well as inorganic fertilizers application (vertical continuous).

2.8. Statistical Analyses

The data were tested for normality using Shapiro-Wilk test (Shapiro & Wilk, 1965). Soil N_2O fluxes were not normally distributed and thus log transformed. We tested for effects of treatments, block, and seasons on the cumulative GHG fluxes using the mixed linear model of the lmerTest in the R package (R Core Team, 2016) with treatments as a fixed factor and season and block as random factors. Correlations between cumulative annual soil GHG fluxes (CH_4, CO_2, and N_2O) and soil properties (C, N, C/N ratio, and moisture), total annual biomass (roots, leaves, and stems), mean annual LAI, total annual grain yields, IN intensities (ammonium (NH_4^+-N) intensity, nitrate (NO_3^--N) intensity, and total IN (NH_4^+-N + NO_3^--N) intensity) for all plots during both seasons (n = 12) were examined using Pearson's correlation.

3. Results

3.1. Field Meteorological and Site Observations

Daily mean air temperature ranged from 19.9°C to 27.5°C (mean ± standard deviation = 23.4 ± 0.14°C), mean soil temperature at 5 cm depth ranged from 27.2°C to 38.4°C (mean ± standard deviation = 32.6 ± 0.39°C), and daily mean relative humidity ranged from 41% to 90% (mean ± standard deviation = 64 ± 0.5%). Total precipitation from 6 February 2017 through 7 February 2018 was 704 mm. Total rainfall for the long rains (LR 2017—February to July 2017), was 304 mm with 64% (194 mm) received during April. Total rainfall for the second season (SR 2017—October 2017 to February 2018) was 400 mm with 96% (384.5 mm) occurring during the first month (Figure 2d). Seasonal precipitation was 29% less and 14% more than long term averages (Jaetzold et al., 2007) for the LR 2017 and SR 2017, respectively. Volumetric soil water content (SWC), differed across treatments (P = 0.001) with control and NP treatments recording similar (lowest) amounts of SWC (0.11 m^3 m^{-3}), manure + NP recorded 0.12 m^3 m^{-3}, while manure treatment had the highest

Table 1
Soil Properties (±1 Standard Deviation) for 0 to 20 cm Depth, Sampled Immediately Before Initiation of Gas Sampling for the Different Treatments With Maize (DH 04 Variety) Crop in Embu County, Kenya

Treatments[a]	C content (%)	N content (%)	C/N ratio	pH	Bulk density (g cm^{-3})
Control	$0.54_c \pm 0.06$	$0.09_b \pm 0.01$	$6.17_c \pm 0.39$	$5.9_b \pm 0.44$	$1.40_a \pm 0.03$
NP	$0.71_c \pm 0.21$	$0.09_b \pm 0.02$	$7.44_c \pm 0.66$	$6.1_b \pm 0.66$	$1.39_a \pm 0.07$
Manure	$1.54_a \pm 0.16$	$0.14_a \pm 0.01$	$11.00_a \pm 0.06$	$8.0_a \pm 0.05$	$1.26_b \pm 0.06$
Manure + NP	$1.18_b \pm 0.05$	$0.14_a \pm 0.01$	$8.40_{ab} \pm 0.38$	$7.8_a \pm 0.05$	$1.28_b \pm 0.05$
P value	0.003	0.003	<0.001	<0.001	<0.001

Note. Same subscript letters in the same column denote no significant difference between the treatment means ($P \geq 0.05$).
[a]Treatment abbreviations: Control = no fertilizer input; NP = inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1} from NP ($N = 23\%$, $P = 23\%$); Manure = goat manure applied at 120 kg N ha^{-1} yr^{-1}; Manure + NP = combination of goat manure and inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}.

SWC (0.14 m^3 m^{-3}). Generally, SWC across treatments remained below 0.15 m^3 m^{-3}, although it did peak at 0.29 m^3 m^{-3} on 19 April 2017 and 0.34 m^3 m^{-3} on 15 November 2017 during the onset of the LR 2017 and SR 2017, respectively (Figure 2d). The soils were generally circumneutral, with C concentrations between 0.5% and 1.5%, N concentrations between 0.09 and 0.14%, C/N ratio from 6.17 to 11.00, and a bulk density between 1.26 and 1.40 g cm^{-3} (Table 1). Soil pH, C and N concentrations, and the C:N ratio were all higher in the plots treated with manure than in the NP or control treatments (Table 1). The soil bulk density of the manure treated plots were lower than the NP or control plots (Table 1).

3.2. Soil GHG Fluxes and Ancillary Information

Soil CH_4 fluxes were mostly negative across all treatments with uptake rates ranging from 0.001 to 40 μg CH_4-C m^{-2} hr^{-1} throughout the study period (Figure 2a). However, there were a few instances of CH_4 emissions, mainly from the manure treatment following key activities such as manure incorporation (Figure 2a). Soil CO_2 emissions remained low (<50 mg CO_2-C m^{-2} hr^{-1}) during the dry periods (June 2017 to October 2017) and increased after soil rewetting; up to 294 mg CO_2-C m^{-2} hr^{-1} during the onset of the LR 2017 (12 April 2017) and up to 390 mg CO_2-C m^{-2} hr^{-1} after the onset of the short rains (15 November 2017, Figure 2b). Soil N_2O emissions remained low for most of the year, with rates commonly below 10 μg N_2O-N m^2 hr^{-1} (Figure 2c). Peaks of N_2O emissions (up to 57 and 37 μg N_2O-N m^{-2} hr^{-1} for the onset of the LR 2017 (5 May 2017) and short rains (15 November 2017), respectively, occurred during the rainy season only (Figure 2c) and were observed across all treatments.

During both seasons, cumulative soil CH_4 fluxes, CO_2 emissions, and N_2O fluxes differed across treatments (Table 2). The application of manure + NP resulted in the highest cumulative CH_4 uptake, while the application of animal manure caused the highest CO_2 and N_2O emissions (Table 2). The CO_2 ($P = 0.008$) and N_2O fluxes ($P = 0.001$) differed between seasons, and there was also a significant treatment/season interaction (Table 2).

Annual cumulative soil CH_4 fluxes differed ($P < 0.001$) across the treatments with the highest CH_4 uptake measured in the NP manure plots (−1.03 kg CH_4-C ha^{-1}) and the least CH_4 uptake recorded in the sole animal manure plots (−0.09 kg CH_4-C ha^{-1}, Table 2). Cumulative soil CO_2 emissions also differed ($P < 0.001$) across treatments with control plots having the lowest (1,391 kg CO_2-C ha^{-1}) and animal manure the highest CO_2 emissions (3,574 kg CO_2-C ha^{-1}) (Table 2). Cumulative soil N_2O emissions were greatest from the animal manure plots (1.22 kg N_2O-N ha^{-1}) and lowest from the control (0.13 kg N_2O-N ha^{-1}, Table 2).

Inorganic nitrogen (IN) concentrations in the top 20 cm of the soil generally remained below 20 mg N kg^{-1} soil throughout the year. Concentrations peaked shortly after fertilization, but only upon rewetting, reaching a maximum of 57 mg N kg^{-1} soil on 26 April 2018 (LR 2017) and 66 mg N kg^{-1} soil on 7 November 2017 (SR 2017), from plots treated with NP (Figures 3a and 3b). Overall, soil IN consisted primarily of NO_3^--N (approximately 86%) with the rest of the soil IN composed of NH_4^+-N.

Table 2

Mean (±1 Standard Deviation) Annual Cumulative Greenhouse Gas (GHG) Fluxes for Two Full Cropping Seasons (Between February 2017 and February 2018) for Four Different Fertilizer Treatments of a Maize (DH 04 Variety) Crop in Embu County, Kenya

Season[a]	Treatments[b]	CH_4 (kg CH_4-C ha^{-1} yr^{-1})	CO_2 (kg CO_2-C ha^{-1} yr^{-1})	N_2O (kg N_2O-N ha^{-1} yr^{-1})
LR 17	Control	-0.02_{b}c ± 0.03	267_{b} ± 49	0.02_{c} ± 0.02
	NP	-0.22_{a} ± 0.09	379_{b} ± 75	0.08_{b} ± 0.04
	Manure	-0.03_{b} ± 0.02	723_{a} ± 68	0.24_{a} ± 0.04
	Manure + NP	-0.20_{a} ± 0.06	567_{a} ± 124	0.14_{b} ± 0.07
	P value	0.021	<0.001	0.002
SR 17	Control	-0.09_{c} ± 0.03	$1,124_{b}$ ± 26	0.11_{c} ± 0.06
	NP	-0.64_{b} ± 0.17	$1,530_{b}$ ± 33	0.31_{b} ± 0.09
	Manure	-0.06_{c} ± 0.01	$2,851_{a}$ ± 45	0.97a ± 0.08
	Manure + NP	-0.83_{a} ± 0.13	$2,136_{b}$ ± 39	0.49_{b} ± 0.17
	P value	0.04	0.005	0.002
Annual	Control	-0.11_{d}^{b} ± 0.06	$1,391_{c}$ ± 74	0.13_{d} ± 0.08
	NP	-0.86_{b} ± 0.26	$1,909_{c}$ ± 108	0.39_{c} ± 0.13
	Manure	-0.09_{c} ± 0.03	$3,574_{a}$ ± 113	1.22_{a} ± 0.12
	Manure + NP	-1.03_{a} ± 0.19	$2,703_{b}$ ± 163	0.63_{b} ± 0.24
	P value	<0.001	<0.001	<0.001
Seasonal *P* value[c]		0.121	0.007	0.001
Interaction[d]		0.024	0.001	0.001

Note. Same subscript letters in the same column denote no significant difference between the treatment means. [a]Season abbreviations: LR 17 = long rainy season 2017; SR 17 = short rainy season 2017. [b]Treatment abbreviations: Control = no fertilizer input; NP = inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1} from NP (N = 23%, P = 23%); Manure = goat manure applied at 120 kg N ha^{-1} yr^{-1}; Manure + NP = combination of goat manure and inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}. [c]Seasonal *P* value indicates whether there were differences between the seasons. [d]Effects of fixed factor (treatments) on GHG fluxes with season and block as random factors.

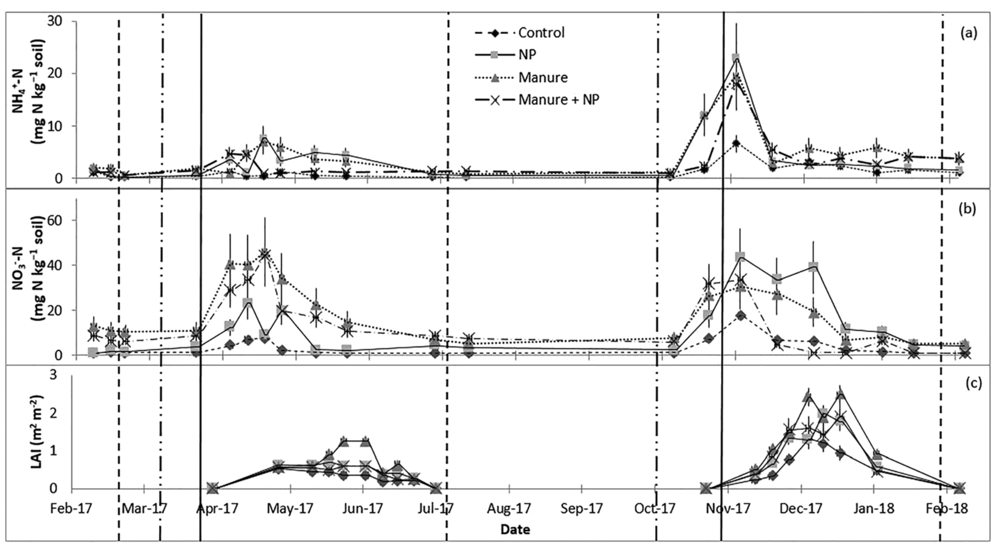

Figure 3. (a) Inorganic nitrogen concentrations of Ammonia (NH_4^+-N), (b) nitrate (NO_3^--N), and (c) leaf area index (LAI) from the four different treatments of maize (DH 04 variety) crop planted in Machang'a secondary school in Embu County, Kenya, between February 2017 and February 2018. Treatment abbreviations: Control = NO fertilizer input; NP = inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}from NP (N = 23%, P = 23%); Manure = goat manure applied at 120 kg N ha^{-1} yr^{-1}; Manure + NP = combination of goat manure and inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}. The vertical lines correspond to harvesting of maize (dashed), land preparation and manure incorporation (long-dash dotted line), and planting of maize as well as inorganic fertilizers application (vertical continuous).

Table 3
Mean (±1 Standard Deviation) Carbon and Nitrogen Content for Maize (DH 04 Variety) Plant Components During the Long Rainy Season (March–July) 2017 for Four Different Fertilizer Treatments in Embu County, Kenya

Plant component	Treatments[a]	C content (%)	N content (%)	C/N ratio
Grains	Control	43.4 ± 0.23	2.05 ± 0.08	21.2 ± 0.98
	NP	43.4 ± 0.10	2.26 ± 0.01	19.2 ± 0.09
	Manure	43.5 ± 0.12	2.14 ± 0.17	20.5 ± 1.59
	Manure + NP	43.5 ± 0.16	2.10 ± 0.23	20.9 ± 2.11
	P value	0.912	0.744	0.708
Leaves	Control	41.2 ± 0.79	0.96_c ± 0.16	44.0_a ± 7.00
	NP	40.9 ± 0.60	0.90_c ± 0.09	46.2_a ± 5.47
	Manure	40.7 ± 0.59	1.32_b ± 0.04	30.8_{ab} ± 0.94
	Manure + NP	41.5 ± 0.55	1.67_a ± 0.12	24.9_b ± 1.93
	P value	0.606	<0.001***	0.004**
Roots	Control	44.4 ± 0.97	1.18_b ± 0.13	38.1_a ± 4.95
	NP	44.8 ± 0.45	0.95_b ± 0.10	47.9_a ± 5.11
	Manure	44.9 ± 1.13	1.27_{ab} ± 0.08	35.6_a ± 3.22
	Manure + NP	44.5 ± 1.18	1.42_a ± 0.16	31.9_{ab} ± 4.13
	P value	0.947	0.027*	0.034*
Stems	Control	43.2_a ± 0.67	0.99_b ± 0.27	46.8_a ± 10.93
	NP	41.9_a ± 0.74	0.70_b ± 0.06	24.6_b ± 4.20
	Manure	40.7_a ± 0.13	1.58_{ab} ± 0.10	25.8_b ± 1.71
	Manure + NP	38.0_b ± 2.48	1.87_a ± 0.42	21.4_b ± 5.49
	P value	0.023*	0.007**	0.001***

Note. $N = 8$ maize plants per treatment. Same subscript letters in the same column denote no significant difference between the treatment means ($P \geq 0.05$).
[a]Treatment abbreviations: Control = no fertilizer input; NP = inorganic fertilizer applied at 120 kg N ha^{-1} yr¯1 from NP (N = 23%, P = 23%); Manure = goat manure applied at 120 kg N ha^{-1} yr^{-1}; Manure + NP = combination of goat manure and inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}. *Significant at 5% probability level. **Significant at 1% probability level. ***Significant at 0.1% probability level.

3.3. Maize Production

The nitrogen content for the various plant components (leaves, roots, and stems) across treatments were highest in manure + NP treatment (Table 3). The total, leaf, root, and stem biomass were highest in the animal manure plots for both the LR and SR 2017 seasons (Table 4). Grain yield in the manure plots was also higher than the other plots during the SR 2017 season, while there were no differences in grain yield during the LR 2017 season (Table 4). The total aboveground N (based on N content for leaves and stems, Table 3) was highest in manure treatment (165 kg N ha^{-1} yr^{-1}), approximately 45 kg N ha^{-1} yr^{-1} more than what was applied (Table 4). Plots treated with NP and manure + NP produced aboveground N equivalent to 60 and 108 kg N ha^{-1} yr^{-1}, respectively, and which was less than the application rate (Table 4).

3.4. YSE and N_2O EFs

YSE (g N_2O-N emitted per kilogram grain yield) were lowest from plots treated with animal manure (0.5 g N_2O-N kg^{-1} grain yield) and highest in plots treated with manure + NP (2.2 g N_2O-N kg^{-1} grain yield, Table 5). The NP plots had the lowest (0.2%) N_2O EFs, followed by manure + NP (0.4%) and were highest in animal manure treatment (0.9%, Table 5).

3.5. Drivers of GHG Fluxes

Annual cumulative CH_4 fluxes did not correlate with any of the measured soil and crop variables (Table 6). In contrast, annual cumulative CO_2 emissions were correlated with soil C content ($r = 0.997$, $P = 0.003$), soil N content ($r = 0.991$, $P = 0.009$), soil C/N ratio ($r = 0.985$, $P = 0.015$), soil moisture ($r = 0.967$, $P = 0.033$), and root biomass ($r = 0.981$, $P = 0.019$) (Table 6). Annual cumulative N_2O fluxes on the other hand were correlated with soil N content ($r = 0.958$, $P = 0.042$), C/N ratio ($r = 0.999$, $P = 0.001$), ammonium intensity ($r = 0.959$, $P = 0.041$), nitrate intensity ($r = 0.973$, $P = 0.027$), total IN intensity ($r = 0.993$, $P = 0.007$), root biomass ($r = 0.961$, $P = 0.039$), and LAI ($r = 0.963$, $P = 0.037$) (Table 6).

Table 4
Biomass Production and Nutrient Concentrations (±1 Standard Deviation) for the Long and Short Rainy Cropping Seasons (Between Planting and Harvesting, March–July 2017 and October 2017–February 2018) for the Four Different Fertilizer Treatments to a Maize (DH 04 Variety) Crop in Embu County, Kenya

Season[a]	Treatment[b]	Leaves (mg ha^{-1})	Roots (mg ha^{-1})	Stems (mg ha^{-1})	Grains (mg ha^{-1})	Total biomass (mg ha^{-1})	Total N[d] (%)	Total crop N[e] (kg N ha^{-1})
LR 2017	Control	$0.86_b \pm 0.37$	$0.11_b \pm 0.04$	$0.44_b \pm 0.30$	0.06 ± 0.08	$1.47_c \pm 0.79$	1.0	14
	NP	$1.93_b \pm 0.45$	$0.22_b \pm 0.02$	$1.05_b \pm 0.27$	0.07 ± 0.07	$3.27_b \pm 0.67$	0.9	26
	Manure	$2.38_a \pm 0.31$	$0.38_a \pm 0.09$	$1.77_a \pm 0.52$	0.09 ± 0.08	$4.62_a \pm 0.89$	1.3	60
	Manure +NP	$1.63_b \pm 0.31$	$0.27_b \pm 0.02$	$0.97_b \pm 0.04$	0.05 ± 0.04	$2.92_b \pm 0.96$	1.7	45
	P value	0.018	0.006	0.024	0.124	0.007		
SR 2017	Control	$1.57_b \pm 0.35$	0.27 ± 0.05	$0.69_b \pm 0.22$	$0.09_b \pm 0.08$	$2.62_c \pm 0.64$	1.0	26
	NP	$2.10_b \pm 0.38$	0.46 ± 0.18	$1.37_b \pm 0.37$	$0.31_b \pm 0.07$	$4.24_b \pm 0.87$	0.7	34
	Manure	$3.25_a \pm 0.64$	0.61 ± 0.10	$1.86_a \pm 0.31$	$2.41_a \pm 0.81$	$8.13_a \pm 0.58$	1.3	105
	Manure + NP	$2.20_b \pm 0.14$	0.43 ± 0.06	$1.23_b \pm 0.41$	$0.22_b \pm 0.27$	$4.08_c \pm 0.84$	1.4	63
	P value	0.022	0.069	0.044	0.001	0.016		
Seasonal *P* value[c]		0.342	0.001	0.80	0.258	0.004		

Note. Same subscript letters in the same column denote no significant difference between the treatment means.
[a]Season abbreviations: SR 17 = 2017 short rainy season, LR 17 = 2017 long rainy season. [b]Treatment abbreviations: Control = no fertilizer input; NP = inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}from NP (N = 23%, P = 23%); Manure = goat manure applied at 120 kg N ha^{-1} yr^{-1}; Manure + NP = combination of goat manure and inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}. [c]Seasonal *P* value indicates whether there were differences between the seasons. [d]Total (%) N in leaves and stems as described in Table 3. [e]Total N removal from fields under maize crop, calculated as N in mass per hectare of maize.

4. Discussion

4.1. Soil GHG Fluxes

Increased soil CO_2 emissions immediately following soil rewetting was similar to other studies (Ortiz-Gonzalo et al., 2018; Pelster et al., 2017; Predotova et al., 2010; Rosenstock et al., 2016) and is thought to be caused by increased decomposition and mineralization of soil organic matter (i.e., the Birch effect: Birch, 1958) following a physical pulse of CO_2 directly after a rainfall due to enhanced microbial activities (Huxman et al., 2004; Yan et al., 2014). The higher CO_2 emissions during the rainy season (Figure 2b) could be attributed to a stimulation of microbial activities (Gelfand et al., 2015); however, root respiration following plant growth also likely contributed to the increase in soil CO_2 emissions (Rochette et al., 1999) as indicated by the strong positive correlation between soil moisture, total root production, and cumulative annual CO_2 emissions (Table 6).

The delay in CO_2 fluxes from manure application was likely because it was initially too dry for any decomposition to take place but when water was added as rainfall, the manure began to mineralize (Dick et al., 2008). The high amounts of total soil C in the manure plots across the treatments (Table 1) could also explain the highest amounts of CO_2 emissions from the manure treatment as this native soil C could also be mineralized as a function of soil priming by the application of additional C (Kuzyakov et al., 2000).

Cumulative annual CO_2 emissions for all treatments in this study (Table 2) were on the lower range of the margin compared to findings from other studies carried out in East African soils where CO_2 emissions ranged from 1,000 to 15,900 kg CO_2-C ha^{-1} yr^{-1} (Ortiz-Gonzalo et al., 2018; Pelster et al., 2017; Rosenstock et al., 2016). The lesser CO_2 emissions from the current study could be as a result of the low soil C (Table 1) and the low rainfall (Figure 2d), resulting in less microbial activity and root production compared with the previous studies on maize fields in SSA. It is imperative to note that the CO_2 emissions reported in this study were solely from the soils as a result of root respiration and microbial decomposition of organic matter and does not represent neither net ecosystem exchange nor does it reflect amounts of C that can be sequestered by different treatments.

Table 5
Yield-Scaled N_2O Emissions (YSE, ±1 Standard Deviation) and Emission Factors (EFs) for Two Full Cropping Seasons (Between February 2017 and February 2018) for Four Different Fertilizer Treatments to a Maize (DH 04 Variety) Crop in Embu County, Kenya

Treatments[a]	YSE[b] (g N_2O-N kg^{-1} grain)	EF[c] (%)
Control	$0.8_c \pm 0.02$	—
NP	$1.1_b \pm 0.06$	0.2
Manure	$0.5_c \pm 0.10$	0.9
Manure + NP	$2.2_a \pm 0.54$	0.4

Note. Same subscript letters in the same column denote no significant difference between the treatment means.
[a]Treatment abbreviations: Control = no fertilizer input, NP = inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}from NP (N = 23%, P = 23%); manure = goat manure applied at 120 kg N ha^{-1} yr^{-1}; manure + NP = combination of goat manure and inorganic fertilizer applied at 120 kg N ha^{-1} yr^{-1}. [b]YSE = yield-scaled N_2O emission expressed as g N_2O-N emitted per kg grain yield. [c]Emission factors (EFs) calculated by dividing the amount of N lost as N_2O-N by the amount of N applied.

Table 6
Correlation Between Annual Cumulative Greenhouse Gas Fluxes and Soil and Plant Parameters in Embu County, Kenya

Soil and plant parameters	Annual CH_4	Annual CO_2	Annual N_2O
Soil pH	s	0.387	0.545
Soil C	0.268	**0.997****	0.639
Soil N	0.229	**0.990****	**0.958***
Soil C/N	0.301	**0.985***	**0.999****
Soil moisture	−0.426	**0.967***	0.648
Ammonium intensity	−0.137	0.721	**0.959***
Nitrate intensity	0.242	0.798	**0.973***
Total IN intensity	−0.216	0.741	**0.993****
Grain yield	0.450	0.789	0.757
Stem biomass	0.260	−0.473	−0.160
Leaves biomass	0.276	−0.084	0.250
Root biomass	−0.121	**0.981***	**0.961***
LAI	−0.132	0.656	**0.963***

Note. $N = 12$. Bold numbers represent the coefficient of determination (R^2) for the significant correlations.
**Correlation significant at 1% level. *Correlation significant at 5% level.

The low soil CH_4 uptake agrees with other studies carried out in East African maize fields that found upland agricultural soils to act predominantly as minor CH_4 sinks (Ortiz-Gonzalo et al., 2018; Pelster et al., 2017; Rosenstock et al., 2016). The low soil CH_4 consumption in the control plots could be because the limited C and N availability, due to years of no fertilizer application, can be detrimental to the methanotrophs (Bodelier et al., 2000; Subke et al., 2018). Furthermore, the control plots had the highest bulk density, which could have lowered the diffusion of CH_4 and O_2 from the atmosphere to the methanotrophic archaea in the soil (Castaldi et al., 2006; Konda et al., 2010). Similarly, the control plots had the lowest pH across treatments, which could also inhibit CH_4 oxidation (Konda et al., 2010). The low uptake in plots treated with goat manure could also be because the goat manure may contain CH_4 that could be released after application, while any lumps of manure could increase anaerobic microsites (Willén et al., 2015) resulting in short-lived CH_4 production. It should be noted that the differences in soil properties across treatments were a direct effect of the treatments over time (2004–2017). Results of the initial soil data, sampled in October 2004, did not show any significant differences across the treatments (Mucheru-Muna et al., 2009), and therefore the differences in treatment over the long term changed the GHG flux dynamics.

Application of inorganic fertilizer may have enhanced CH_4 oxidation, similar to Nyamadzawo et al. (2014) who noted that N application to sandy loam soils reduced CH_4 emissions. When N is applied as inorganic fertilizer in N-deficient conditions (Du et al., 2019), it relieves the N limitation of cell growth and subsequently increases the activity of methanotrophic microorganisms in the long term, increasing CH_4 uptake (Bodelier et al., 2000). Nitrogen application (either as ammonium or nitrate) also promotes the growth and activity of the nitrifying population, co-oxidizing atmospheric CH_4 thus increasing CH_4 uptake (Bodelier & Laanbroek, 2004; Reay et al., 2005). The soils from this study had low (0.09–0.14%) N content suggesting that the lower methane uptake in the control could be attributed to a lack of available N that could be ameliorated by fertilizer application.

In the manure + NP treatment, the inorganic fertilizer could have enhanced the oxidation of methane (Bodelier et al., 2000), while the labile C from animal manure (Table 1) could have maintained a consistent supply of nutrients to help maintain the methanotrophic populations throughout the year (both seasons, i.e., LR 2017 and SR 2017) similar to Subke et al. (2018). More so, manure + NP plots had similar bulk densities (lowest) to the animal manure plots (Table 1), which could have enhanced the diffusion of CH_4 and O_2 from the atmosphere to the soil (Chi et al., 2016) resulting in greater CH_4 uptake across these two treatments (Table 2). The significant treatment/season interaction (Table 2) was because the control and manure plots had similar CH_4 fluxes regardless of the season, while the NP treatment had 3 times more CH_4 uptake during the SR and the manure + NP had 4 times more CH_4 uptake during the SR. The higher rainfall during the SR appears to have enhanced the growth of CH_4 oxidizers, which were further stimulated by the addition of mineral N from NP resulting in high CH_4 uptake rates (Bodelier, 2011).

Cumulative N_2O emissions from the current study were also on the lower range of the margin compared to other studies carried out on managed agricultural soils in East Africa (Hickman et al., 2014; Pelster et al., 2017; Rosenstock et al., 2016) and which ranged from 0.10 to 3.9 kg N_2O-N ha^{-1} yr^{-1}. The low N_2O emissions from the current study compared to other studies could be due to the low C content, which may be related to soil degradation and N mining and lack of adequate nutrient replenishment resulting to soil C depletion (Folberth et al., 2012). Some of the treatments in the study area have been undergoing nutrient mining at rates between 40 and 45 kg N ha^{-1} yr^{-1} and which were equally on the lower end of the average rate of N mining by maize crops in SSA which range from 14–110 kg N ha^{-1} yr^{-1} (Nandwa & Bekunda, 1998; Sommer et al., 2013; Zhou et al., 2014). It should be noted that the initial soil N pool from this study was higher in the manure plots than in the other treatments (Table 1), suggesting that even though the manure plot had low N concentrations, that some of this was bioavailable, which could account for the source of the additional N resulting in the highest N mining. There are still a few loss pathways that we did not measure including N_2, NO, NH_3 (gaseous losses), and NO_3 leaching and which could explain the differences in amounts of N applied, N_2O emission, and N removal.

The increase in soil N_2O emissions after fertilization is consistent with previous studies that measured a strong relationship between applied N and cumulative N_2O emissions (Shcherbak et al., 2014). However, the fact that the increase was not immediate and only occurred after rewetting indicates that the primary source of the N_2O would be denitrification (Davidson, 1992; Groffman & Tiedje, 1988). The rapid respiration and high soil water content concurrent with the increased IN likely provided sufficient anaerobic microsites for denitrification, resulting in enhanced soil N_2O emissions (Butterbach-Bahl et al., 2013; Pelster et al., 2012). The small peaks in IN concentrations and N_2O emissions in the no-N control after rewetting (particularly during the SR) suggests that the rewetting alone was sufficient to cause a release of IN (Birch, 1958) that resulted in the enhanced N_2O emissions (Jassal et al., 2011). The positive correlations between N_2O emissions and IN intensities (Table 6) implies that an increase in N availability resulted in an increase in N_2O emissions, consistent with Burton et al. (2008).

It is also worth noting that the N in plant components was significantly different across treatments and which if retained as crop residues could improve soil fertility, water retention, and crop yields (Anyanzwa et al., 2010; Gentile et al., 2009; Tongwane et al., 2016). Crop residue retention could also cause higher N_2O emissions (Basche et al., 2014; Peyrard et al., 2016); however, retention of crop residues on the field is not a common practice in the study area as the maize stalks are used as animal feeds and as fuel for cooking.

The significant treatment/season interaction was likely because of the different limiting factors in the different treatments. The SR had 32% more rainfall than the LR, causing higher soil water content, which tends to result in higher denitrification rates when NO_3^- is available (Linn & Doran, 1984). Many studies measured greater soil N_2O fluxes from animal manures (Chantigny et al., 2010; Ding et al., 2007; Sosulski et al., 2014; Zhang et al., 2018), while other studies show higher N_2O fluxes from inorganic fertilizers (Chantigny et al., 2010; Ellert & Janzen, 2008; Mukumbuta et al., 2017). According to Pelster et al. (2012), studies where manure applications caused more N_2O emissions than mineral fertilizers were largely on coarse-textured, well-drained soils with low C content, whereas studies with no differences or greater emissions from mineral N fertilizers tended to be from moderate to fine-textured soils with high C concentrations. As the soils in the current study were a sandy loam with low (0.5–1.5%) C content, denitrification may have also been limited by a lack of mineralizable C (Leip et al., 2011; Pelster et al., 2012) in the control and NP plots. Thus, denitrification in the manure plots, due to their higher C content, appears to be more responsive to increases in soil water content than the low C NP and control plots. In the current study, even though the manure plots had the lowest bulk density and the highest pH, both of which tend to lower N_2O emissions (Chi et al., 2016; Liu et al., 2010; Raut et al., 2012), they had the highest N_2O emissions likely because the added C provided the necessary environment for increased denitrification to take place.

4.2. Maize Production

The higher yields and biomass in all plots during the SR 2017 compared to the LR 2017 suggest that maize growth, particularly during the LR 2017 season, was limited by a lack of precipitation. Low crop production during the LR 2017 was likely caused by the low, erratic rainfall, characterized by three dry spells (13, 20, and 36 days) experienced between the first 2 weeks after maize emergence and harvesting. This agrees with other studies carried out in the study area that noted more reliable rainfall and higher yields during the SR season than in the LR season (Kiboi et al., 2017; Ngetich et al., 2014; Okeyo et al., 2014). The much greater response in grain yields in the manure plot compared to the other treatments to the higher precipitation during the SR 2017 season could be attributed to the buildup of soil organic carbon over time (Table 1). Soil organic matter has the ability to retain moisture into the dry period of the growing season (Ankenbauer & Loheide, 2017; Rawls et al., 2003). This suggests that proper water management is at least as important as nutrient management for ensuring crop production in the Kenyan central highlands.

4.3. YSE and N_2O EFs

The YSE from this study (Table 5) were at the low end of what has been measured from other studies in SSA (Nyamadzawo et al., 2014; Ortiz-Gonzalo et al., 2017; Pelster et al., 2017) which ranged between 0.7 and

41.6 g N_2O-N kg^{-1} N aboveground biomass. The relatively low YSE across the treatments was related to low emissions measured in the study area throughout the year, rather than to high yields.

The N_2O EF from this current study were all below the default Intergovernmental Panel on Climate Change (IPCC) Tier 1 EFs of 1% (0.2–0.9%, Table 5), which was consistent with other studies carried out in SSA that also reported N_2O EF below 1% (Mapanda et al., 2011; Ortiz-Gonzalo et al., 2018; Pelster et al., 2017; Tully et al., 2017). These low N_2O EF were likely due to the low soil C content as well as the low soil moisture through much of the year resulting to low microbial activity (Liu et al., 2014). The higher soil C content of the manure plots likely contributed to its slightly higher N_2O EF compared to the NP treatment.

5. Conclusions

In line with our initial hypotheses, our results showed that application of animal manure emits the highest amounts of CO_2 emissions across treatments probably due to addition of labile C. The CO_2 emissions were significantly influenced by moisture, while N_2O was significantly influenced by application of fertilizers. Unexpectedly, CH_4 fluxes were not significantly influenced by soil moisture. Contrary to our initial hypothesis, addition of manure did not always result to higher CH_4 emissions, as the manure + NP resulted in more CH_4 oxidation than any other treatment. Uptake of CH_4 was also relatively high in the NP treatment suggesting that the methanotrophic populations were likely N limited. Animal manure application had the highest cumulative N_2O emissions probably because denitrification was limited by not only N, but C as well. The low GHG emissions and crop yields from the current study were likely due to low soil C and low, erratic rainfall. While soil C concentrations can be increased through the application of animal manure (with or without inorganic fertilizer), this may come at the cost of greater N_2O emissions. However, the improved moisture retention in soils with higher organic C content may lead to greater yields that could reduce N_2O yield-scaled emissions of the agricultural system, suggesting a potential for mitigating agricultural GHG emissions in the region. Consistent with other studies from SSA, the N_2O EFs observed in this study were lower than the default IPCC EFs suggesting that the default EFs may overestimate N_2O emissions from fertilizer application in SSA. Establishment of similar studies across the various agroecological zones of Kenya and/or East Africa on farms with differing soil characteristics are essential to more accurately estimate Kenya's and other East African countries current GHG emission inventories and to determine the potential for mitigation of GHG emissions across the region.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data used in this study are archived in the figshare repository (DOI: 10.6084/m9.figshare.8868308. v1) (Macharia et al., 2019).

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