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Effect of inorganic fertilizer applications on greenhouse gas emissions and microbial activity in shaded coffee of Mount Elgon, Eastern Uganda

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ABSTRACT

A study was conducted in non tilled coffee agroforestry fields of Eastern Uganda to understand the effects of application of inorganic fertilizers on soil nutrient loss in form of gas for mitigation of unsustainable agricultural practices. This study specifically i) assessed the effect of application of inorganic fertilizers on greenhouse gas emissions, ii) determined their effect on microbial carbon, nitrogen and phosphorus, and iii) determined their effect on leaf litter decomposition under Albizzia-coffee growing systems of the Mount Elgon. Soil gas emissions were measured with the static chamber method for twelve months in a field experiment with five different fertilizer treatments. The effect of treatments was separated using ANOVA in Genstat discovery version 13. Microbial carbon, nitrogen and phosphorus effect was separated using Mann-Whitney U test. Results showed that annual emissions ranged from 19.6 to 26.1 (t C/ha/yr), 3.5 to 9 (kg N/ha/yr) and 6.9 to 9.2 (kg C/ha/yr) for carbon dioxide, nitrous oxide and methane, respectively. Significant effects on soil emissions only occurred for nitrous oxide (P=0.017), microbial carbon (p=0.001) and microbial phosphorus ($p<0.001$) for the study period. The mixture of NPK fertilizers presented the lowest carbon dioxide loss and application of TSP presented the lowest nitrous oxide emission from soil. This study underscores the need for establishment of long-term experiments across several agro-ecological zones to confirm farmers' perceptions of their soil fertility levels and ascertain the contribution of farm practices towards the retention of nutrients in the soil with minimal emission, to inform decisions of small holder farmers, policy and development partners for sustainable production.

Key words: Arabica coffee, carbon dioxide, East African highlands, inorganic fertilizers, methane, Mt. Elgon, nitrous oxide, shaded coffee

RÉSUMÉ

Une étude a été menée dans des champs de café ombragés sans labour de l'Est de l'Ouganda pour comprendre l'effet de l'application d'engrais inorganiques sur la perte d'éléments nutritifs du sol sous forme de gaz pour l'atténuation des pratiques agricoles non durables. Cette étude a spécifiquement i) évalué l'effet de l'application d'engrais inorganiques sur les émissions de gaz à effet de serre et ii) déterminé leur effet sur le C, N et P microbiens. Une expérience factorielle avec 5 traitements d'engrais (250 kg/ha MOP, 50 kg/ha TSP, 250 kg/ha d'urée, 250 kg/ha de combinaison d'urée, de TSP et de MOP, 0 kg/ha de contrôle) et avec 4 répétitions a été

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établi sous 20X20m de caféiers ombragés d'Albizzia à Mount Elgon. Les émissions de gaz du sol ont été mesurées à partir de trois chambres statiques placées au hasard dans chaque jardin pendant douze mois. L'effet des traitements a été séparé à l'aide de l'ANOVA dans la version 13 de GenStat découverte. Le carbone, l'azote et le phosphore microbiens ont été séparés à l'aide du test U de Mann-Whitney. Les résultats ont montré que les émissions annuelles variaient de 19,6 à 26,1 (t C/ha/an), de 3,5 à 9 (Kg N/ha/an) et de 6,9 à 9,2 (Kg C/ha/an) pour le dioxyde de carbone, l'oxyde nitreux et le méthane respectivement. Des effets significatifs sur les émissions du sol se sont produits uniquement pour l'oxyde nitreux (P=0,017), le carbone microbien (p=0,001) et le phosphore microbien (p<0,001) pour la période d'étude. Le mélange d'engrais NPK a présenté la plus faible perte de dioxyde de carbone et l'application de TSP a présenté la plus faible émission d'oxyde nitreux du sol. Cette étude souligne la nécessité de mettre en place des expériences à long terme dans plusieurs zones agro-écologiques pour confirmer les perceptions des agriculteurs sur les niveaux de fertilité des sols et déterminer la contribution des pratiques agricoles à la rétention des nutriments dans le sol avec un minimum d'émissions, pour éclairer les décisions de petits exploitants agricoles, informer les partenaires politiques et de développement pour une production durable.

Mots clés: Engrais inorganiques, caféier ombragé, dioxyde de carbone, méthane, protoxyde d'azote, Coffea arabica, hauts plateaux d'Afrique de l'Est

INTRODUCTION

The need to increase agricultural production to satisfy the demand associated with population growth has resulted into horizontal expansion of cultivation even on marginal lands in Sub-Saharan Africa (Bekunda and Woomer, 1996; Kopittke *et al*., 2019). Subsequently, greenhouse gases (GHG) emission (Rosenzweig *et al.,* 2020) and other forms of environmental degradation (FAO, 2002) including soil fertility decline (Kopittke *et al.,* 2019) have increased. Various soil fertility management practices have been promoted across Africa including fertilization (Liniger *et al.,* 2011). However, this is likely to increase the greenhouse gas emissions (GHG) from agricultural land in SSA (Nisbet *et al.,* 2014; Musafiri *et al.,* 2020). It is therefore important to identify soil fertility management technologies that increase food production and play a fundamental role in GHG fluxes control since only a few integrated studies have tried to quantify gas released or to characterize the mechanisms involved in their release.

Carbon dioxide is the most important GHG, however, methane (CH_4) and nitrous oxide (N_2O) emissions also play a substantial role in global warming (Smith *et al.,* 2018). The net soil CO_2 emissions are produced by soil respiration (aerobic and anaerobic microbial and roots respiration) and decomposition of organic matter (Oorts *et al*., 2007; Sun *et al.,* 2019; Almagro *et al*., 2021). Net methane fluxes are the balance between two contending microbial processes that are methane production by methanogens, and methane oxidation by methanotrophs under anaerobic and aerobic conditions, respectively (Knief, 2019). Net soil N_2O fluxes occur as a result of heterotrophic and autotrophic nitrification, chemo-denitrification, nitrifier-denitrification, and co-denitrification (Gander *et al.,* 2012; Butterbach-Bahl *et al.,* 2013). The strength of these GHG emissions is affected by soil properties (soil organic carbon, soil nitrogen, texture, pH), land cover changes, vegetation type, environmental factors (soil temperature, soil moisture, drought, precipitation) and farm management practices (crop residue application, tillage, manure, agroforestry, fertilizer use) (Luo *et al.,* 2010; Powlson *et al.,* 2011; Tongwane *et al.,* 2016; Pelster *et al.,* 2017; Wang *et al.,* 2019; Dimitriou *et al*., 2021). Soil emissons are believed to be lower with organic carbon accumulation generally occurs in areas of low decomposition that thrives under low temperature, acid parent materials and anaerobic conditions. It enhances both unstable and stable macro aggregate formation (Denef *et al.,* 2013) vital for carbon sequestration (Plante and McGill, 2002; Six *et al.,* 2004).

Besides, increasing soil N content generally leads to higher soil respiration facilitating higher net ecosystem exchange, if carbon is not limiting (Niu *et al.,* 2010; Peng *et al.,* 2011). According to Pilegaard *et al*. (2006), N_2O emissions are negatively correlated with the C/N-ratio (with N_2O emissions being lowest at C/N-ratios 30 and highest at a C/N-value of 11 (Christiansen *et al.,* 2012). Acidic soil conditions lead to lower soil emissions, with an optimal pH-value for methanogenesis (CH_4 production) that lies between pH 4 and 7 (Dalal and Allen, 2008). Carbon dioxide emissions are observed to be highest at neutral pH-values (Čuhel *et al.,* 2011). Methane emissions decrease only under acidic soil conditions while nitrification increases with higher pH-values, since the equilibrium between NH3 and NO_3 shifts to ammonia (Nugroho *et al.,* 2007). However, no significant correlations are found between N_2O emissions and pH-value (Pilegaard *et al.,* 2006). Saiz *et al*. (2006) found that young trees have higher respiration compared to old ones. Soil respiration decreases with stand age, caused by a lower fine root biomass. The authors added that in old forest ecosystems, the decrease levels out with stand age since lower root respiration rates are partly compensated for by higher microbial respiration due to higher organic inputs.

An increase of soil temperature leads to higher emissions and to higher soil respiration rates as a positive feedback response of increased microbial metabolism. Soil temperature and soil moisture explain 86% of the variations of N_2O emissions (Schindlbacher *et al.,* 2004). Methane emissions are additionally forced by increasing soil respiration rates with increasing soil temperatures, leading to decreasing O_2 concentrations in the soil (Butterbach-Bahl *et al.,* 2013). The positive temperature effect may be overlain by soil water stress, since water is needed as a transport medium for nutrients required by microbes (Fowler *et al.,* 2013). It is known that CO_2 emissions increase exponentially with temperature (Ludwig *et al.,* 2001; Tang *et al.,* 2003). Soil moisture is the single most important soil parameter for soil gas emissions, since it controls microbial activity and all related processes. Nitrifying bacteria require oxygen residing in soil pores. Therefore, soils with less water-filled pore space (WFPS) have higher emissions by nitrification, with a maximum at 20% WFPS (Ludwig *et al.,* 2001). Nitrification yields a higher potential for NO production than for N_2O production (Fowler *et al.,* 2013). In contrast, CH_4 and N_2O producing bacteria require anaerobic conditions. Also N_2O production is optimal around 60% WFPS and lowest when WFPS is below 30% (Gao *et al.,* 2014). Even an increase of WFPS above 80% can still lead to an exponential increase of N_2O emissions (Keller and Reiners,1994). On the other hand, CH_4 production requires strictly anaerobic conditions and correlates positively with soil moisture (Smith *et al.,* 2003; Gao e*t al.,* 2014). Long periods of drought can significantly reduce soil emissions and soils may then turn into a net sink for N_2O (Goldberg and Gebauer, 2009). Soils with a high proportion of large pores retain less water and therefore foster the emission of gases produced under aerobic conditions (van der Weerden *et al.,* 2012). Soils with dominant fine pores support the formation of CH_4 and N_2O produced under anaerobic conditions (Dutaur and Verchot, 2007; Gu *et al.,* 2013).

Soil texture and structure also influence GHGs indirectly through soil moisture. Higher CO_2 emissions are encountered with fine textured soils, especially compared to sandy soils during warm dry periods (Dilustro *et al.,* 2005). Stable soil aggregates (concretions, crusts) lead to lower soil emissions since C and N are less available for soil microbes (Wu *et al.,* 2012). Precipitation after extended dry periods causes the pulsing or Birch effect (Birch, 1958). Emissions increase within some minutes or hours after the onset of precipitation and return to background levels within a few days (Sponseller, 2007; Lado-Monserrat *et al.,* 2014). This is driven by the renewed mineralization and the availability of easily decomposable material (Borken and Matzner, 2009) for the metabolism of reactivated microbes (Ludwig *et al.,* 2001). The Birch effect decreases with higher frequencies of wet–dry cycles (Borken and Matzner, 2009).

Tillage practices influence particulate organic matter fraction (Hussain *et al.,* 1999, Liu *et al.,* 2014). Several authors (Curtin *et al*., 2000; Bauer *et al.,* 2006; Ussiri and Lal, 2009) have reported higher soil CO_2 emissions under conventional tillage compared to no-tillage. This is because no-tillage reduces the diffusion and content of air-filled pores in the soil, by which soil CO_2 emissions are very low or non-existing (Bilandzija *et al.,* 2016).

Agroforestry systems have similarly been seen as one of the promising management practices to increase soil C stocks, reduce soil degradation and mitigate greenhouse gas emissions (e.g., Frouz *et al.,* 2013; Ehrenbergerová *et al.,* 2016; Dollinger and Jose, 2018; Justine *et al.,* 2019; Solis *et al.,* 2020). Nitrogen fixing leguminous trees (such as *Albizzia* sp., *Inga* sp and *Erythrina* sp) have been commonly used to bring N and organic matter to the system in addition to other benefits (Vaast *et al.,* 2008; Verchot *et al.,* 2008). However, there is suspicion on N fixing leguminous species to increasing soil N_2O emissions (Rochette and Janzen 2005; Verchot *et al*., 2008) and reducing the soil CH_4 sink (Palm *et al.,* 2002) which is a growing concern in the sustainable development framework. For example, studies such as by Hergoulouch *et al*. (2008) and Verchot *et al*. (2008) showed that shaded coffee increased N_2O emissions by 34.8% compared to coffee monocrop. Such conflicting results compel us to investigate the response of soil microbial activity and production of GHGs during fertilization, since little is known about the how the type of the fertilizers applied affect soil emissions of CH_4, CO_2, and N_2O and the decomposition rate in agricultural systems (Amos *et al*., 2005; Mosier *et al.,* 2006; Sainju *et al*., 2008).

Various scholars (e.g. Bouwman *et al.,* 2002 a&b; Phillips, 2007; Phillips *et al.,* 2009) further found that the effects of fertilization on GHG fluxes at the soil surface tend to occur within the initial 8 to 10 weeks following N application. Since N_2O and CO_2 emissions tend to increase and CH_4 uptake tends to decline during the first few weeks following fertilization, it is generally accepted that GHG emissions tend to increase with additions of N (Bouwman *et al.,* 2002; Mosier *et al.,* 2006; Sainju *et al.,* 2008). Also, N-fertilization tends to increase CO_2 emissions (Raposo *et al.,* 2020). Effects of fertilizer N, P and K addition on fluxes of GHGs, however, are not consistent across studies. Sometimes fertilization of arable soil does not affect the strength of soil as a source of N_2O (Amos *et al.,* 2005) and CO_2 (Amos *et al.,* 2005) or the strength of the soil as a sink for CH_4 (Koga *et al*., 2017). Hence CO_2 released from soil to the atmosphere, referred to as soil respiration, is a combined activity of roots, micro and macro organisms decomposing litter and organic matter in soil (heterotrophic respiration) (Hanson *et al.,* 2003; Högberg *et al.,* 2020) and is influenced by temperature. Nevertheless, inorganic farming is reported to sequester less carbon than organic farming (Gattinger *et al.,* 2012).

This information is very important particularly in the coffee-based farming systems where farmers have resorted to increased application of inorganic fertilizers to enhance coffee production. Coffee being one of the highest contributor to GDP in Uganda (De Beenhouwer *et al.,* 2016), it is important to identify best management practices which sustain its production and protect soil, water and air quality under fertilized shaded conditions. This study therefore i) assessed the effect of inorganic fertilizer application on greenhouse gas emission, ii) determined the effect of fertilizer application on microbial CNP, and iii) determined the effect of leaf litter decomposition under Albizzia-coffee growing systems of the Mount Elgon area in eastern Uganda.

METHODS

Description of the study area. This study was conducted in Manafwa District, on Mount Elgon in Uganda. Mount Elgon lies on the border of eastern Uganda and western Kenya. Manafwa district is bordered by Bududa District to the north, Kenya to the east and south, Tororo District to the south-west, and Mbale District to the west (Figure 1). It has an elevation of 1,354 metres. The geographical location, climate conditions, topography, geology, soils, vegetation and population are well described in Sebuliba *et al*. (2021).

The landscape of Manafwa mainly consists of smallholder farms (< 4 acres, i.e., 1.8 ha) with intensive and mixed coffee (*Coffee arabica*) agricultural systems and is characterized by a relatively high population density of approximately 250–300 inhabitants per km^2 (Gram *et al*., 2018). Coffee productivity in this district has declined below its potential due to low soil fertility and poor land and coffee tree management practices (Wang *et al*., 2015).

Manafwa district was selected because it offered adequate land for setting up the experiment under a homogenous environment (similar slope, vegetation, climate, age of coffee) and with minimum likelihood of mud or landslides events occurring on the site. Also, the farmers in the identified experimental site were willing to host the experiment.

Experimental design, treatment and replication. On farm, a completely randomized design was with four treatments (50P, 250N, 250K, 250N-50P-250K) kg ha^{-1} yr^{-1}, and a control. Each treatment was replicated four times. A total of 20 field plots, each of 20m-by-20m size, was laid out randomly on the ICRAF agroforestry experimental farmer sites.

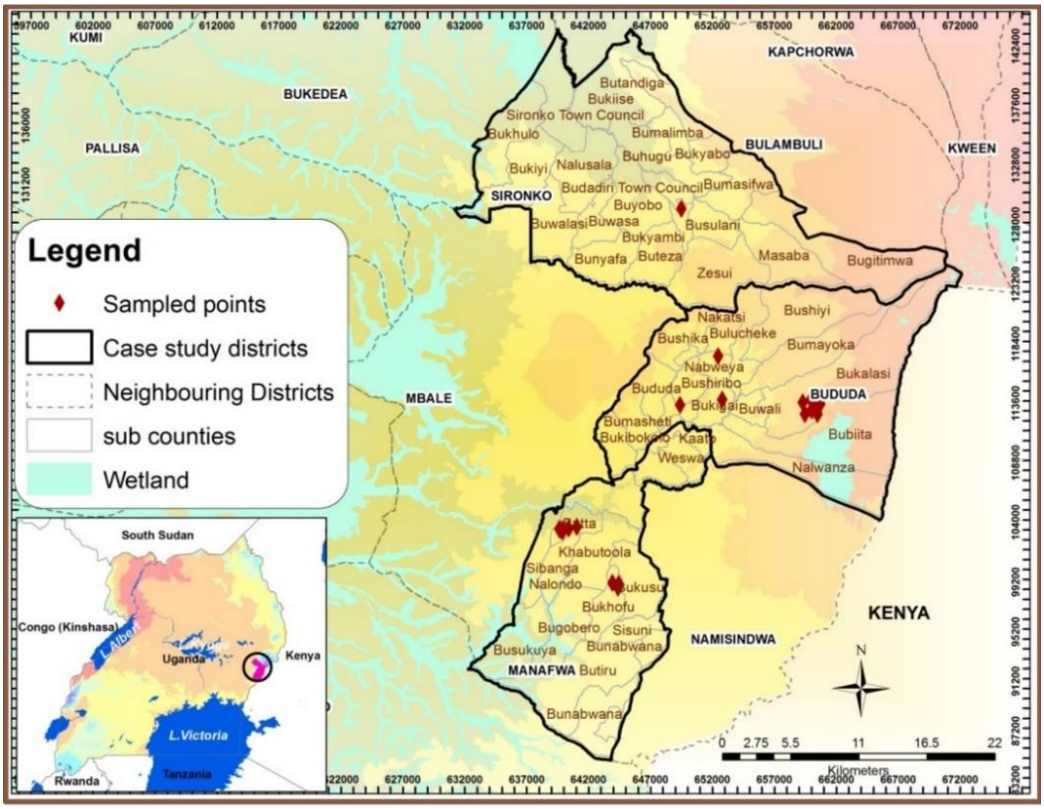

Figure 1. The study site around Mount Elgon, in Eastern Uganda showing Manafwa and neighboring districts

All plots were located on the same landscape positions and soil type. The experiment was established on quasi homogenous soils in terms of texture (sandy loam), pH, soil organic matter (SOM), soil organic carbon (SOC), Total nitrogen (TN), Available phosphorus (Av. P), extractable potassium (K) and sodium (Na) (Table 1). Urea, Tri-Super phosphate (TSP) and Muriate of Potash (MOP), NH_4NO_3 and NaH_2PO_4 solutions were annually applied to each plot at the beginning (August) of the short rain season. Each of the experimental plots was sub-divided into four cells/grids of 10 × 10 m. Each cell was also considered as a replicate and permanent chamber bases were installed. Chamber covers were placed on the bases and gas samples were collected four times at (10) minute intervals for determination of the trace soil gas fluxes. Soil gas fluxes (CO_2, CH_4 and N_2O) were measured monthly for twelve months. The samples were stored in pre-evacuated glass containers with Teflon-coated stopcocks and taken to University of Gottingen for CO_2, CH_4 and N_2O concentrations determination. Samples were analyzed using a gas chromatograph (Shimadzu GC-14B; Columbia, MD, USA) equipped with a flame ionization detector (FID), an electron capture detector (ECD) and an auto sampler (Koehler *et al.,* 2009, 2012; Corre *et al.,* 2014). The detection limits of this instrument were 50 ppm for CO_2, 43 ppb for N_2O and 45 ppb for CH_4. Annual and seasonal soil CO_2, CH_4 and N_2O fluxes were calculated as a sum of the twelve-monthly fluxes and the respective monthly fluxes for each gas. Relative change in comparision to the control for monthly fluxes was also computed using;

$$R = (F_k - F_c)\,\frac{100}{F_c}$$

where R is the relative change of the flux in the given month for the treatment K, Fk is the flux of a given month for the treatment K, Fc is the flux for the same month for the control.

Determination of leaf litter decomposition rate. Leaf litter of *Albizzia coriaria* was collected using the litterbag trapping method by placing traps on the floor of each plot at the beginning of March, April, May 2020. About 40 to 60g of collected leaf litter was placed in litter bags and buried in the soil at 10cm depth (Zhou *et al.,* 2008). Each plot received about 10 litter bags evenly distributed. Every three months, a litterbag was collected randomly, gently cleaned and leaf litter gently weighed using adhoc methods as described by Okalebo *et al*. (2002).

Incubation. A 72 hours' soils incubation was carried out in 50 ml plastic beakers with drainage holes at the bottom, lined with a glass filter and filled with field-moist soil (approximately 6 g dry weight) to allow inoculation (Okalebo *et al.,* 2002). A 16^o C growth chamber containing 1 L glass Mason Ball jars was used for storage and transportation of soil to the laboratory under field capacity conditions with sporadic additions of de-ionized water (Davis *et al.,* 2005).

Extractable and Microbial C, N, P. The chloroform fumigation–extraction method (CFEM) on sieved, undried splits of each sample was considered in measuring microbial C, N and P within a week of collection. A darkened vacuum desiccator fitted with fumigated soils was exposed to chloroform for 36–48h. Extraction of approximately 6 g fumigated or unfumigated (control) soil was done with Brays solution for

Table 1. Initial selected soil characteristics of the farmer fields used for the experiment (N=3)

Soil depth (cm)	pH pH units	N% %	Av P mg/kg	K cmol/kg	Na cmol/kg	SOC %	SOM %	Textural class
0-15	6.42	0.19	13.86	0.68	0.10	1.90	3.27	Sandy loam
15-30	6.36	0.13	9.12	0.53	0.11	1.41	2.42	Sandy loam

extractable P (Bray and Kurtz, 1945), using 50 ml or 75 ml extractant while 0.5 M K_2SO_4 was used for C and N (Brookes *et al.,* 1985; Vance *et al.,* 1987; Beck *et al.,* 1997). Beforehand filtered solutions of soil were shaken for 1h followed by refrigeration overnight. Extracts were analyzed for total N by Kjeldahl-digestion and total P by an Alpkem analyzer. A Shimadzu TOC-5050A was used to measure extracted carbon content. Unfumigated soils (control) measure represented the extractable C, N and P while microbial C, N, and P were calculated as the difference between the amount of unfumigated and fumigated soils.

Data analysis. The effects of treatments on CO_2, N_2O and CH_4 fluxes (annual, seasonal and monthly) and leaf litter decomposition rate were separated using ANOVA in Genstat discovery version 13. The microbial C, N and P were separated using Mann-Whitney U test. The least significant difference (LSD) test s for $P < 0.05$ was considered for this study.

RESULTS

Effect of inorganic fertilizers on annual fluxes of GHG under Albizzia shaded coffee in Manafwa District. Figure 2 shows the annual fluxes of CO_2, N_2O and CH_4. The results show that CO_2 emissions ranged from 19.6 to 26.1 (t C/ha/yr), N_2O emissions ranged from 3.5 to 9 (kg N/ha/yr) and CH_4 emissions ranged from 6.9 to 9.2 (kg C/ha/yr). Fertilizer applications had significant effect only on N_2O (P=0.017) emissions. The effect of the application of NPK was significantly higher than that of the control and P but similar to that of K and N applications. The average annual emission of CO_2 was 22.8 t C/ha/yr while that of CH_4 was 8.34 kg C/ha/yr.

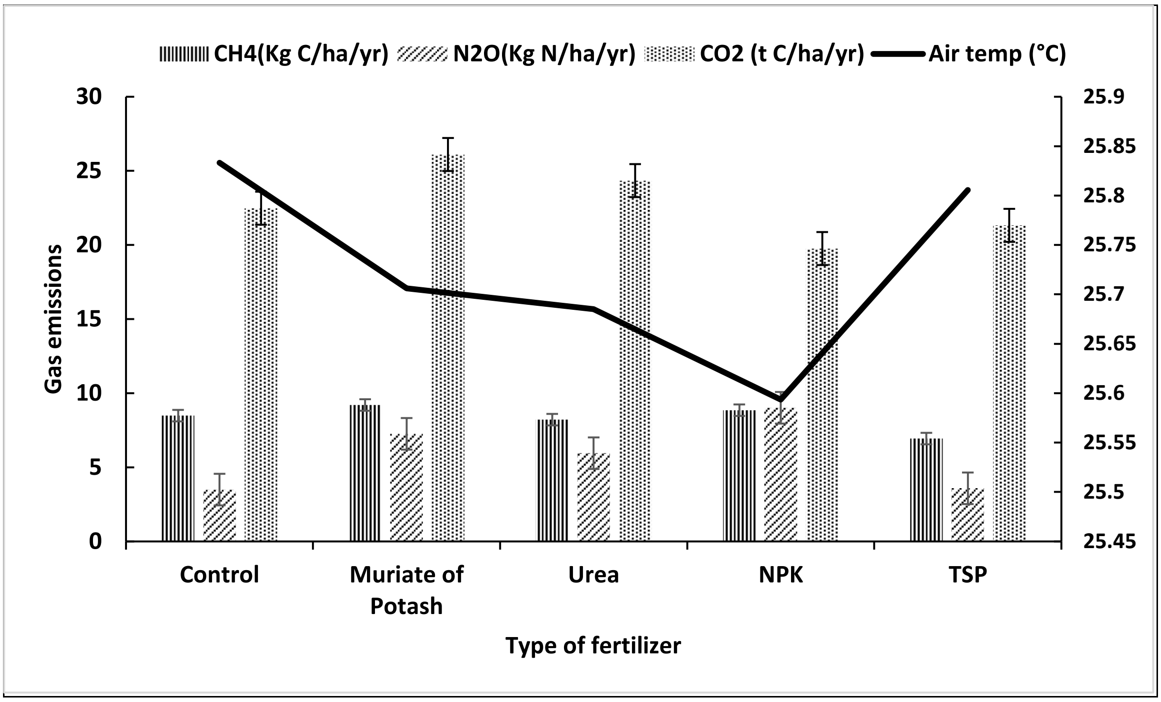

Figure 2. Annual GHG emissions from the different fertilizer applications

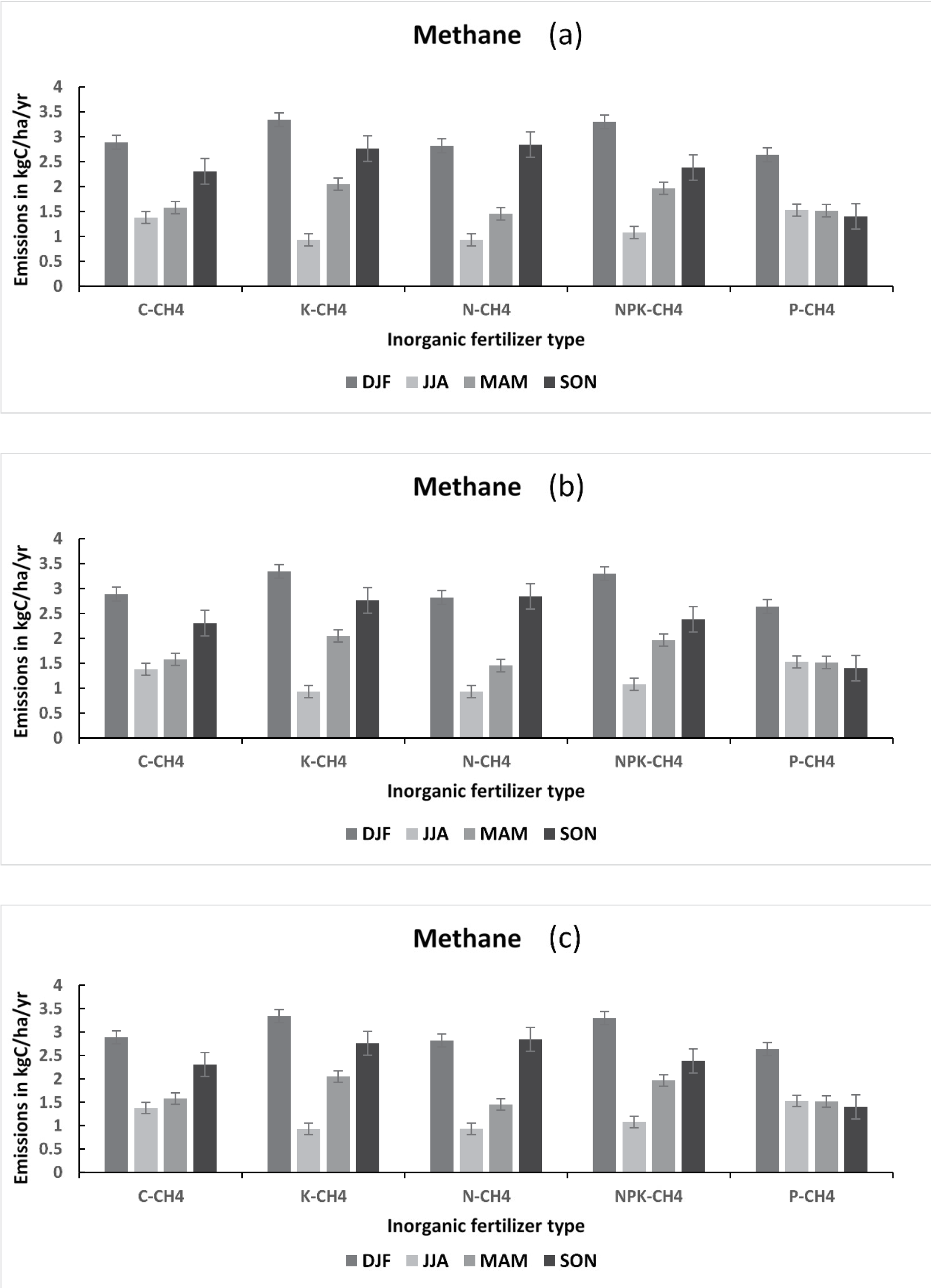

Figure 3. Seasonal GHG emissions from the different fertilizer applications

Effect of inorganic fertilizers on seasonal fluxes of GHG under Albizzia shaded coffee. Figure 3 presents the seasonal GHG emissions. The findings show that the GHG emissions varied from one season to the next (P<0.001) except for CO_2 in September, October and November and December, January and February that had significantly higher values than March, April, May and June, July, August for CH_4 emissions while only September, October and November was significantly higher than the rest of the seasons for N_2O emissions. There was no significant seasonal effect for CO_2 emissions with a mean of 5.68 t C/ha/yr. The monthly values for CH_4 emissions ranged from 1.38 to 2.88 kg C/ha/yr for the control, 0.93 to 3.34 kg C/ha/yr for K applications, 0.93 to

2.84 kg C/ha/yr for N applications, 1.07 to 3.3 kg C/ha/yr for NPK applications and 1.4 to 2.64 kg C/ha/yr for P applications. The monthly values for N_2O emissions ranged from 0.44 to 1.19 kg N/ha/yr for the control, 0.61 to 2.36 kg N/ha/yr for K applications, 0.71 to 1.96 kg N/ha/yr for N applications, 0.63 to 5 kg N/ha/yr for NPK applications and 0.45 to 1.07 kg N/ha/yr for P applications. While for $C0_2$ emissions, monthly values of emissions ranged from 0.44 to 7.27 t C/ha/yr for the control, 0.61 to 6.63 t C/ha/yr for K applications, 0.71 to 7.22 t C/ha/yr for N applications, 0.63 to 5.24 t C/ha/yr for NPK applications and 0.45 to 6.93 t C/ha/yr for P applications.

Effect of inorganic fertilizers on monthly fluxes of GHG under Albizzia shaded coffee. Figure 4 depicts the monthly GHG emissions.GHG emissions varied with month ($P<0.001$) for N_2O and CH_4 and at $P=0.014$ for CO_2. The monthly values for N_2O emissions ranged from 0.14 to 0.62 kg N/ha/yr for the control, 0.11 to 1.78 kg N/ha/yr for K applications, 0.2 to 1.05 kg N/ha/yr for N applications, 0.11 to 2.5 kg N/ha/yr for NPK applications and 0.09 to 0.58 kg N/ha/yr for P applications. For the case of $C0_2$ emissions, monthly values ranged from 0.88 to 3.48 t C/ha/yr for the control, 1.14 to 4.05 t C/ha/yr for K applications, 1.21 to 3.86 t C/ha/yr for N applications, 1.12 to 2.11 t C/ha/yr for NPK applications and 1.02 to 3.38 t C/ha/yr for P applications. The monthly values for CH_4 emissions ranged from 0.2 to 1.1 kg C/ha/yr for the control, 0.22 to 1.7 kg C/ha/yr for K applications, 0.22 to 1.41 kg C/ha/yr for N applications, 0.2 to 1.54 kg C/ha/yr for NPK applications and 0.23 to 1.09 kg C/ha/yr for P applications. For N_2O, October emissions were significantly higher than the rest of the months. September, March and December emissions had similar emission levels but higher than for May, June, July, August and November emissions.

For CH_4, December, November and February had significantly higher emission values compared to October, September, August, June, July, May and April emissions. Likewise, February, January, March, May, November and December had similar emission values. For CO_2, October emissions were significantly higher than those of April and February but similar to March, May, June, July, August, September, November and December emissions. Also, April emissions were significantly lower than those of March, May, July and August. Peaks in CH_4 were observed in June, October and November for the control; July, December and February for P applications; and May, November and February for NPK, K and N applications. Peaks in N_2O emissions were observed in May, October and December for the control; October and December for P applications; May, September, October, and December for NPK; May, October, January and March for K and N applications. Peaks in CO_2 emissions were observed May, August, October, January and March for the N, P, K applications; May, August and November for the control; May, October and December for NPK applications.

Relative change in fluxes of GHG under Albizzia shaded coffee. Figure 5 shows the relative change of GHG emissions. The Emissions from other treatments were higher than the control in the months of July, November, December, February and March for CH_4. Emissions from applications of N, P, K and the mixture were higher than the control in September, October, February and March for N_2O. The CO_2 emissions from other treatments were higher than the control in April, July, October, January, February and March. For CH_4 and CO_2, the emissions from the control exceeded those where fertilizers were applied in June, August, September and January and November. The relative change for CH_4 emissions ranged from -60 to 82% for application of K, -74 to 133% for application of N, -46 to 99% for application of NPK, and -70 to 407% for application of P. The relative change for N_2O emissions ranged from -35 to 493% for application of K, -12 to 163% for application of N, -44.9 to 558% for application of NPK, and -54 to 153% for application of P. Also, the relative change for CO_2 emissions ranged from -63 to 106% for application of K, -58 to 108% for application of N, -62 to 28% for application of NPK, and -69 to 153% for application of P.

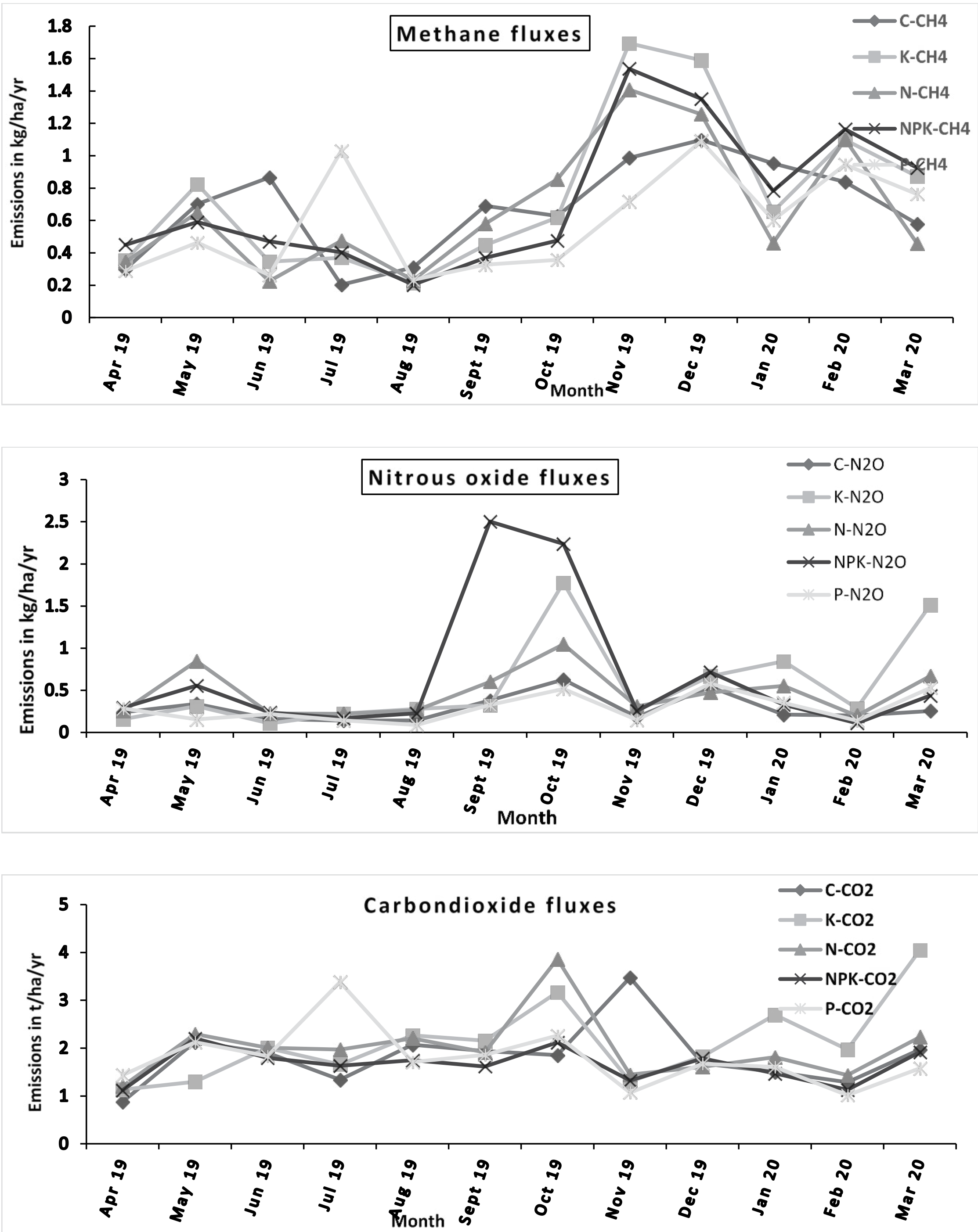

Figure 4. Monthly GHG emissions under different fertilizer applications in Mount Elgon

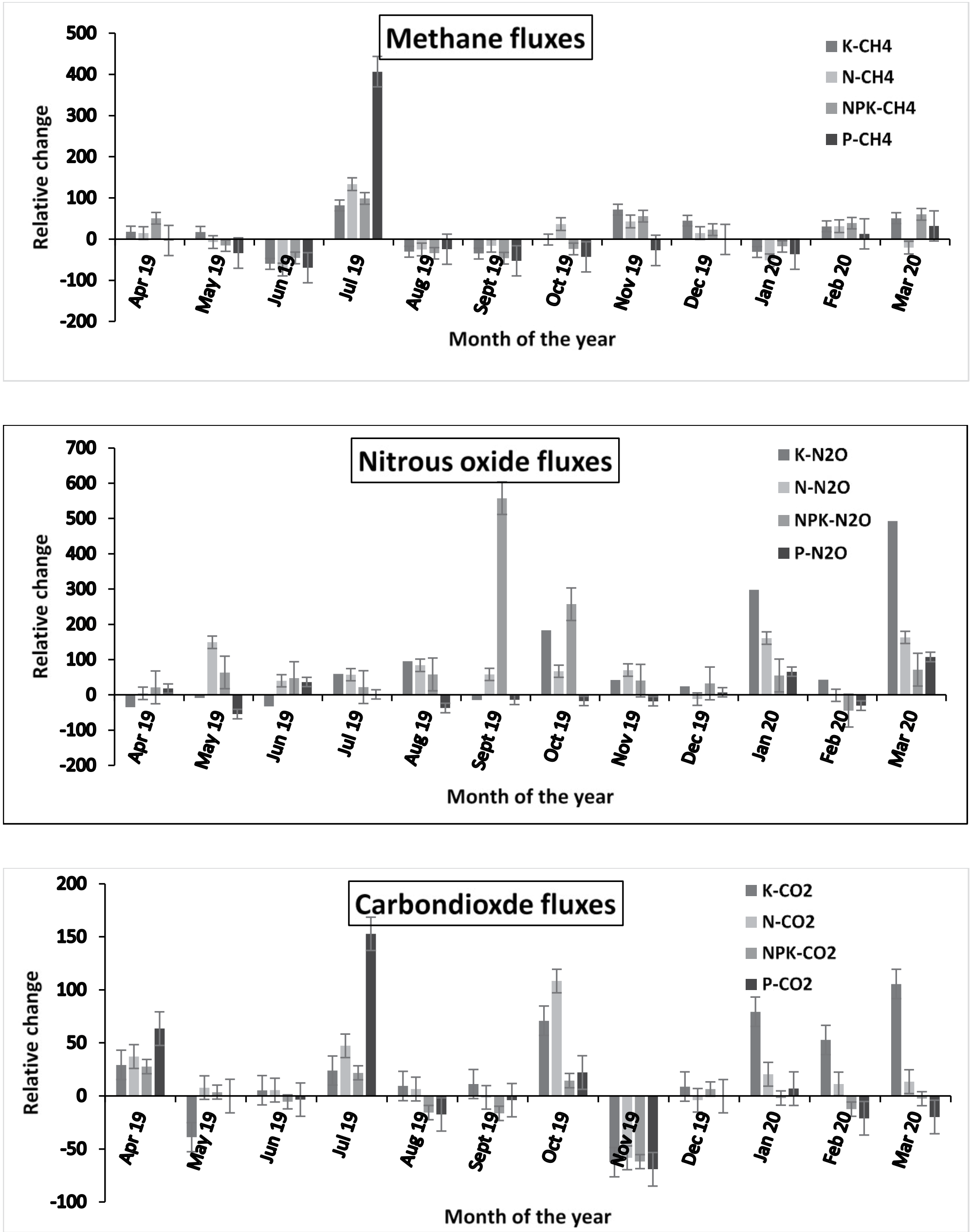

Figure 5. Relative change in the monthly GHG fluxes under different fertilizer applications in Mount Elgon

Effect of inorganic fertilizers on microbial carbon, nitrogen and phosphorus. Table 2 shows the microbial C, N and P under different treatments. Microbial C ranged from 0.022 to 0.028, microbial P ranged from 0.006 to 0.009 while microbial N ranged from 0.017 to 0.050. Statistical analysis shows that no treatment effect was detected (P<005; One-way ANOVA). The average microbial C, N and P were 0.024, 0.029 and 0.007, respectively.

Table 3 shows the change in microbial Carbon, Nitrogen and Phosphorus after one year of experimentation. Significant changes were observed for microbial C ($p=0.001$; One-way ANOVA) and microbial P ($p<0.001$; One-way ANOVA) while no changes in microbial N were seen after one year of nutrient application. The relative change in Microbial C was 66.7% and 1200% for microbial P.

Effect of inorganic fertilizers on decomposition rates. The decomposition rates of Albizzia leaves varied from 0.064 to 0.079 (Figure 6). However, no statistical difference was found between treatments (Mann Whitney U test). The average decomposition rate was 0.072 per day.

Table 2. Effect of fertilizer application on microbial C, N and P

Nutrient application	Microbial C	Microbial P	Microbial N
Urea-N	0.022	0.006	0.028
TSP- P	0.028	0.007	0.028
Muriate of Potash-K	0.022	0.007	0.050
NPK	0.026	0.007	0.017
Control	0.022	0.009	0.021
Mean	0.024	0.007	0.028

Table 3. Change in microbial Carbon, Nitrogen and Phosphorus after one year of experimentation

Period	Microbial C	Microbial P	Microbial N
Start of experiment	0.018+0.002	0.001+0.002	0.037+0.009
End of experiment	0.030+0.002	0.013+0.002	0.020+0.007

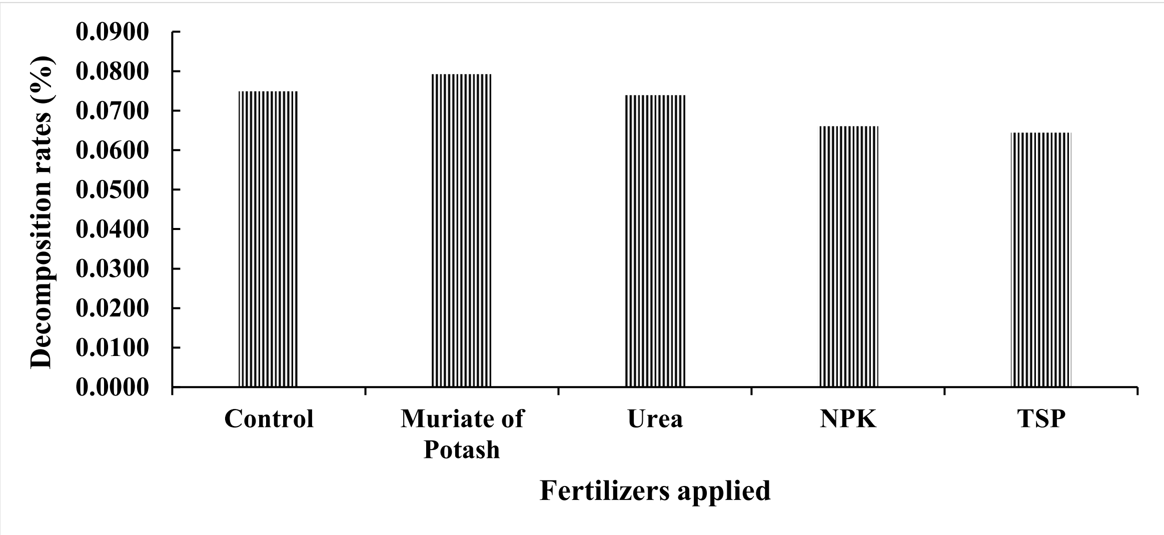

Figure 6. Leaf litter decomposition rate under different fertilizer treatments in Mount Elgon

DISCUSSION

Effect of fertilizer application on GHG emission under Albizzia shaded coffee in Mount Elgon.

Overall, relatively low emissions were observed with the application of a combination of the three inorganic fertilizers compared to other treatments. Li *et al*. (2022) also found that the combined application of K and N fertilizers significantly reduced the average N_2O emissions by 28.3% using agricultural soil from the suburbs of Wuhan, central China. This is attributed to the simultaneous enhancement in availability and uptake of all the three essential nutrients by the coffee plant (Finger *et al.,* 2019; Penueles *et al.,* 2023).

The increase in N_2O emissions due to fertilizer applications corroborates Owino *et al*. (2020) findings on smallholder rice paddy fields in Anyiko Wetland of Kenya. GHG emissions in the different fertilized shaded coffee of this study are comparable to the values observed by other scholars under coffee in the region for N_2O and CH4 (eg. Verchot *et al*., 2006; Hergoualc'h *et al.,* 2008; Capa *et al.,* 2015) except for CO_2 emissions whose values are almost triple the values observed by Hergoualc'h *et al*. (2008) in monoculture coffee systems of Costa Rica and four times that of de Urzedo *et al*. (2013) under reforestation conditions in Brazil. Verchot *et al*. (2006) found N_2O emissions of approximately 7 kg N/ha/year in 3-year-old coffee plantations fertilized with 100 kg N/ha/year in Southern Sumatra, India. The relatively higher magnitude of CO_2 and N_2O emissions could be attributed to no till conditions (Biland ija *et al.,* 2016).

The implementation of no-tillage can increase soil GHG emissions due to the maintenance of higher water content and fewer air filled pore spaces in the soil surface layer that also favors greater soil biological activity (Biland ija *et al*., 2016). In fact, Linn and Doran (1984) reported 3.4- and 9.4-times greater CO_2 and N_2O production from surface no till soils as compared to plowed soils at sites in Illinois, Kentucky, Minnesota and Nebraska in the USA. The low N_2O emissions under P application is in line with Sundareshwar *et al*. (2003) report which attributed the reduction of soil N_2O emissions to stimulated N immobilization. Mori *et al*. (2013) also reported that P application reduced N_2O emissions under A*cacia mangium* plantation due to the enhancement of root uptake of soil N and water. Further, Zhang *et al*. (2014) also observed that P applications with N together significantly decreased N_2O emission. The relatively high amount of N in the studied soils then explains N_2O emissions reduction with P application observed in this study.

Capa *et al*. (2015) also found that N_2O emissions increased with the fertilizer application. Largely, the small variation in the observed emissions compared to other locations is attributed to, in addition to no till, other environmental and agricultural factors such as the uniform soil water content, availability of mineral nutrients in the soil, soil temperature, and climatic conditions (Hergoualc'h *et al*. 2008; Butterfly *et al.,* 2010; Hiel *et al.,* 2018; Rigon *et al.,* 2018). Besides, Kostyanovsky *et al*. (2019) observed that emissions of CO_2 only increased with an increase in moisture and temperature but decreased under fertilizer application. Accordingly, the lack of a difference in CO_2 emissions per season in this study indicates little variation in temperature and soil water content for those seasons (Rigon *et al.,* 2018; Kostyanovsky *et al.,* 2019) that minimized the photosynthetic activity by plants and microbial activity.

Also, the increased N_2O, CH_4 and CO_2 emissions observed upon soil rewetting in the wet months after the long dry spell collaborates with those of other studies carried out in East Africa and other regions (Vilain *et al.,* 2010; Ortiz-Gonzalo *et al.,* 2018; Macharia *et al.,* 2020; Musafiri *et al.,* 2020). The pulse of the emission following a rainfall event at the onset of the season could be attributed to the Birch effect (increased decomposition and mineralization of organic matter), since soil rewetting or high water content activates micro-organisms activity and enhances substrates supply and mineralization increasing emissions (Jarvis *et al.,* 2007; Butterfly *et al.,* 2010; Musafiri *et al.,* 2020) and contribution root respiration associated with plant growth especially for the increment in CO_2. But also, in addition to high water holding capacity, the moderate textured soils in the study area probably supported the higher emissions (Hiel *et al.,* 2018). However, low soil moisture associated with high soil temperatures in the severe dry spell could have restricted the flow of GHG particularly CO_2, possibly due to moderate soil microbial activity (Rigon *et al.,* 2018).

Furthermore, the highest N_2O emissions in October following fertilizer application corroborated observations of other authors (Hergoualc'h *et al.,* 2008; Koehler *et al.,* 2009), who reported that N_2O emissions are mainly produced within a few days after the addition of mineral fertilizers. Also, the relatively higher N_2O fluxes could also be attributed to the no till conditions because of the higher level of labile organic matter (Kostyanovsky *et al.,* 2019). Moreover, the low average soil C/N ratio of 10 also favored high emissions supporting findings of Gunderson et al. (2012) who reported that highest emissions occurred at the C/N ratio of 11.

Contrary to observations of Gu *et al*. (2013) that higher emissions were observed under fine textured soils, this study observed this in the sandy loam textured soils. Even an increase of soil water content or WFPS above 80% due to heavy rains especially in the last months of the experiments could have supported an exponential increase of N_2O emissions (Dencs *et al.,* 2020; Wu *et al.,* 2021).

Effect of inorganic fertilizer application on Microbial C, N and P of Mount Elgon. Significant changes were observed for microbial C and microbial P while no changes in microbial N were seen after one year of nutrient application. These changes corroborate Su *et al*. (2014) findings that chemical fertilization significantly increased soil microbial activity involved in C, N, P and S cycling, especially for the treatments NK and NPK in paddy rice. Several authors (Crecchio *et al.,* 2001; Marschner *et al.,* 2001) have however reported that short term fertilizer experiments had no significant effect on the microbial activity like in long-term experiments where fertilizer additions significantly affect function, community structure, and population of soil microorganisms (Cinnadurai *et al.,* 2013; Luo *et al.,* 2015) for brown soil in China. Besides, this could have been attributed to the low soil moisture at the beginning of the experiment that decreased microbial activity by reducing diffusion of soluble substrates, microbial mobility and intracellular water potential (Manzoni *et al.,* 2012) prompting a decrease in rates of organic matter decomposition. Likewise, the increased frequency of rains experienced towards March 2020, could have steered high soil water content reducing oxygen supply to the microbes favoring inactivity (Schjønning *et al.,* 2011).

Overall P fertilizer addition effect on microbial carbon is attributed to the high flux of P in microbial biomass (Teste *et al.,* 2021), due to enhanced microbial activity during microbial decomposition of organic matter particularly by the heterotrophs and symbionts (Yao *et al.,* 2016; Zhang *et al.,* 2022). On the other hand, overall K fertilizer addition increased microbial nitrogen probably because the addition of K+ altered soil N availability directly through competition with NH4+ for soil fixation sites (Nieder *et al.,* 2011) or indirectly through enhanced plant N uptake (Hou *et al*., 2019) and microbial activity since K is particularly responsible for the uptake, transport and use of nutrients. (Li *et al.,* 2021).

CONCULSION AND RECOMMENDATION

The magnitude of N_2O and CH_4 emissions are comparable to values observed in East Africa except for CO_2 that were relatively higher. The effect of inorganic fertilizer application on greenhouse gas emission was only significant for annual N_2O emissions and increased with wetness. In this study N_2O emissions peak was observed immediately after fertilizers application but decreased with time. Seasonal N_2O and CH_4 emissions were also high in the long rains which also coincides with the fertilizer application period. Furthermore, the December to February dry season had higher values than March-April -May and June-July-August for CH_4 emissions. Application of fertilizers significantly increased microbial carbon and phosphorus.

This study underscores the need for establishment of long-term experiments across several agro-ecological zones to confirm farmers' perceptions. This is needed to inform decisions of small holder farmers, inform policy and development partners for sustainable crop production. Proper management of N, P and K fertilizers can have minimal environmental damage (minimal emission and climate change effects) while at the same time ensuring optimal food production and security. There is a need to determine the actual microbes affected by inorganic fertilization in order to tailor remedial efforts towards preservation of those microbial communities (abundance, diversity and functioning) necessary for enhanced plant growth.

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STATEMENT OF NO CONFLICT OF INTEREST

The authors declare that there are no competing interests in this publication.

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