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Multi-scale measurements show limited soil greenhouse gas emissions in Kenyan smallholder coffee-dairy systems

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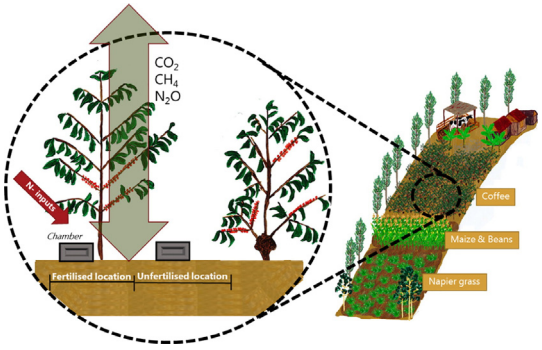
HIGHLIGHTS

- Smallholder coffee-dairy farms have low soil GHG emissions in Central Kenya.
- The inherent complexity of smallholder systems challenge GHG measurements.
- Stratification among farms, fields, and field locations can capture spatial variability.
- Sampling should match seasonal events to account for temporal variability.
- Fertilised spots in coffee plots registered the highest emissions during wet periods.

GRAPHICAL ABSTRACT



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ABSTRACT

Efforts have been made in recent years to improve knowledge about soil greenhouse gas (GHG) fluxes from sub-Saharan Africa. However, data on soil GHG emissions from smallholder coffee-dairy systems have not hitherto been measured experimentally. This study aimed to quantify soil GHG emissions at different spatial and temporal scales in smallholder coffee-dairy farms in Murang'a County, Central Kenya. GHG measurements were carried out for one year, comprising two cropping seasons, using vented static chambers and gas chromatography. Sixty rectangular frames were installed on two farms comprising the three main cropping systems found in the area: 1) coffee (*Coffea arabica* L.); 2) Napier grass (*Pennisetum purpureum*); and 3) maize intercropped with beans (*Zea mays* and *Phaseolus vulgaris*). Within these fields, chambers were allocated on fertilised and unfertilised locations to capture spatial variability. Cumulative annual fluxes in coffee plots ranged from 1 to 1.9 kg N_2O-N ha^{-1}, 6.5 to 7.6 Mg CO_2-C ha^{-1} and −3.4 to −2.2 kg CH_4 -C ha^{-1}, with 66% to 94% of annual GHG fluxes occurring during rainy seasons. Across the farm plots, coffee received most of the N inputs and had 56% to 89% higher emissions of N_2O than Napier grass, maize and beans. Within farm plots, two to six times higher emissions were found in fertilised hotspots – around the perimeter of coffee trees or within planted maize rows – than in unfertilised locations between trees, rows and planting holes. Background and induced soil N_2O emissions from fertiliser and manure applications in the three cropping systems were lower than hypothesized from previous studies and empirical models. This study supplements methods and underlying data for the quantification of GHG emissions at multiple spatial and temporal scales in tropical, smallholder farming systems. Advances towards overcoming the

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dearth of data will facilitate the understanding of synergies and tradeoffs of climate-smart approaches for low emissions development.

1. Introduction

Agriculture's carbon debt has considerably increased over the past two centuries (Sanderman et al., 2017). The sector – comprising agriculture, forestry and other land use (AFOLU) — currently contributes about a quarter of global anthropogenic greenhouse gas (GHG) emissions (Smith et al., 2014), of which more than a third result from soil GHG fluxes (Tubiello et al., 2013). Further agricultural expansion and intensification, driven by ongoing trends of population increases and dietary changes, are expected to result in the clearance of an additional one billion hectares of forest and increase agricultural GHG budgets by up to 80% by 2050 (Tilman et al., 2011). Meeting global food demand without increasing agricultural land and associated GHGs emissions will require transdisciplinary approaches such as sustainable intensification for yield gaps closure (Mueller et al., 2012); increase resource use efficiency (Foley et al., 2011); soil carbon restoration efforts (Lal, 2004); minimisation of food waste (Bajželj et al., 2014); and a shifting diets (Tilman and Clark, 2014), among others.

Crucial agricultural breakthroughs are thus needed to achieve the Sustainable Development Goals (SDGs) agenda (United Nations General Assembly, 2015). In Africa, targets to end poverty (SDG1) and end hunger, achieve food security and promote sustainable agriculture (SDG2), are of vital importance given the rapid population growth and rises in food demand, particularly in sub-Saharan Africa (Van Ittersum et al., 2016). Increased production largely depends on innovations within the AFOLU sector, which already releases >60% of the continental emissions (Valentini et al., 2014). Most of the SSA countries have ratified the Paris Agreement and made GHG reduction commitments for low-carbon development (UNFCCC, 2016). The lack of empirical data obliges these countries to report using Tier 1 default emission factors (EFs) (Hickman et al., 2014a, 2014b; Ogle et al., 2014), which were developed from global average data based primarily on monoculture cropping systems in temperate areas (Hickman et al., 2014a, 2014b; Olander et al., 2014).

Relatively few field studies have hitherto measured GHG emissions in agricultural soils in sub-Saharan Africa (Kim et al., 2016; Rosenstock et al., 2016a; Pelster et al., 2017). Insufficient, sparse empirical data present a challenge in evaluating the accuracy of the estimations (Kim et al., 2016), and may therefore lead to misdirected mitigation or regulation interventions (Rosenstock et al., 2013). For instance, there are no experimental data on common agroecosystems such as smallholder coffee systems, which in Kenya alone support >600,000 households (Monroy et al., 2012). Furthermore, the available accounting tools for carbon footprinting, such as GHG calculators, rely on EFs and empirical models that have not been calibrated for these regions. Since marketing low carbon products may benefit smallholder farmers producing global commodities such as coffee, accurate estimations are needed. Given the need for more data to inform programming and policy, efforts have recently made to develop harmonised low-cost methods to build EFs and parameterise models (Rosenstock et al., 2013).

While carbon dioxide (CO_2) from soils is produced by plant roots, soil fauna and microbial respiration, agricultural soils also emit or take up two major non-CO_2 gases: methane (CH_4) and nitrous oxide (N_2O). The former is emitted by methanogens under the anaerobic conditions in submerged soils – mainly in rice cropping systems (Zhang et al., 2016) – and taken up by methanotrophs in aerobic systems (Le Mer and Roger, 2001). The latter, N_2O, is currently the most important ozone-depleting gas (Ravishankara et al., 2009). N_2O is produced by nitrification and denitrification in microbial-mediated processes. Nitrification involves the aerobic oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-) (Webster and Hopkins, 1996), whereas denitrification causes the anaerobic reduction of NO_2^- and NO_3^- to N_2O and gaseous nitrogen (N_2) (Robertson and Tiedje, 1987). The amount of nitrogen cycled, together with environmental parameters such as climate (*e.g.* temperature, atmospheric pressure and rainfall) and soil factors (*e.g.* soil texture, moisture and oxygen content, drainage, soil organic-C and pH), control the nitrification and denitrification rates (Firestone and Davidson, 1989; Davidson et al., 2000; Bouwman et al., 2002; Butterbach-Bahl et al., 2013). Inorganic fertilisers and animal manure are the major contributors for N_2O production (Mosier, 2001).

The inherent heterogeneity of smallholder farming systems makes the design of GHG sampling approaches complicated (Rosenstock et al., 2016b). Complex landscapes of small farms, with multiple farm components (*e.g.* several crops), management practices (*e.g.* fertilisation) and seasonal events, accentuate spatial and temporal variabilities of GHG emissions (hotspots and hot moments). Hotspots are those precise spatial locations, within a determined scale (*e.g.* the landscape level), which show higher emissions rates than the surroundings (McClain et al., 2003). N_2O hotspots in agricultural fields depend on the interaction of nutrient patches and physical factors which controls oxygen diffusion and consequently denitrification (Groffman et al., 2009) Thus, the allocation of resources (*e.g.* N inputs), together with biophysical factors (*e.g.* plant and soils), needs to be considered in experimental designs. Hot moments, however, are temporal events that cause the convergence of factors (*e.g.*, drying-rewetting) with high emissions rates (Groffman et al., 2009). Targeting sampling periods within the day, season or year, under particular weather conditions (*e.g.* precipitation and temperatures) or farmers' practices (*e.g.* fertilisation periods), are critical to overcome temporal variability.

Smallholder mixed farming systems – characterised by the integration of crops and livestock – are the backbone of African agriculture (Thornton and Herrero, 2001). The coexistence and redundancy between different farm components (*e.g.* crops, livestock, and trees) allow these systems to diversify farm production, promote resource interactions and increase farm resilience. For instance, livestock manure plays a crucial role in maintaining soil fertility by recycling plant nutrients removed by different crop residues and fodder (Rufino et al., 2007). At the same time manure quality depends on livestock feeding and manure management, which ultimately may affect soil N_2O emissions after manure application. In comparison with low-input systems (Pelster et al., 2015; Rosenstock et al., 2016a), integrated small farms with high livestock densities have relatively higher N inputs. Although previous studies have measured GHG at the field level, this is an attempt to upscale at farm-level by stratifying the farm on its different components, from the farm to the field and then to the specific location in the field (*e.g.* fertilised and unfertilised locations) (Fig. 1). Furthermore, despite the important role of manure as an endogenous resource in African smallholder systems, few studies have investigated N_2O emissions from manure handling and application. The present study aims to provide empirical measurements of soil GHG fluxes at multiple spatial and temporal scales in smallholder integrated coffee-dairy farms in Central Kenya.

2. Methods

2.1. Study area

Murang'a County is situated on the eastern slopes of the Aberdare Mountain Range in Central Kenya, one of the main coffee regions of

the country. The altitudinal gradient defines a series of agroecological zones in which Arabica coffee (*Coffea arabica L.*) is cultivated. The predominant coffee zone is situated in a belt between 1500 and 1800 m. a.s.l. The land above and below these limits is less suitable or profitable for coffee production and the major crops present are tea and food crops respectively. Average annual rainfall decreases with elevation from 2000 to 1200 mm due to the prevalence of south-east trade winds (Jaetzold and Schmidt, 1983). Mean annual temperatures increase from 18 °C in the upper zone to 20.7 °C in the lower areas of the county (Jaetzold and Schmidt, 1983). Soils are predominantly well-drained, reddish, deep nitisols (FAO, 1988).

2.2. Farming systems

Coffee farms in Murang'a are small (0.7 ha on average) and highly diversified (Ortiz-Gonzalo et al., 2017). A typical farm grows Napier grass (*Pennisetum purpureum*) as fodder for livestock, maize and beans (*Zea mais* and *Phaseolus vulgaris*, respectively) as staple crops, and coffee (*Coffee arabica* L.), banana (*Musa* sp.) and short-cycle vegetables as cash crops. Agroforestry shapes the landscape in Murang'a. Fruit and indigenous multipurpose trees are usually found in home gardens, whereas fast-growing exotic trees commonly delimit the farm perimeter (mainly *Grevillea robusta*) or are planted in woodlots (mainly *Eucalyptus sp.*).

Zero-grazing herds of improved dairy cow breeds, goats and sheep are present on almost all farms. Besides its economic and social functions, livestock contribute to nutrient cycling within the farm. Crop residues and fodder are collected to feed the animals in a "cut and carry" system. Manure is collected from the stall and stored using different manure storage systems. Although the most common method of storing manure is in heaps or pits, some farmers leave the manure in the stalls for long periods of time (unmanaged), while other farmers with sufficient capital build biodigesters. After storage, manure is then recycled to the cropping systems, which makes East African coffee systems unique in sourcing N inputs and incorporating considerable amount of organic matter into soils.

2.3. Farm selection

From the 125 households surveyed (see Ortiz-Gonzalo et al., 2017), two farms were selected for an observational study on soil GHG emissions over the course of two cropping seasons, one year (0°40′52″S – 36°59′13″E). To be representative of the main coffee zone, and thus to include a number of farm components, the following criteria were met by the two farms: 1) a zero-grazing system with integrated manure management, preferably in heaps; 2) a livestock herd of between 1 and 5 tropical livestock units (TLU); 3) arable land area of between 0.5 and 1 ha, with at least one plot of Napier grass and another plot of maize and beans (intercropped), with rotation between Napier grass and maize every few years; and 4) a minimum of 0.2 ha of Arabica coffee (coffee producers) established for > 20 years. Importantly, willingness to participate (due to the presence of chambers in their fields and monitoring of farm management) was also taken into account.

The first farm selected, "*Thara*" (which means napier grass in Kikuyu), is a farm focused on dairy, with 4 TLU and 0.8 ha of farm arable land, where the coffee area has been reduced over the last few years in favour of Napier grass production. The second farm selected, "*Kahua*" (which means Arabica coffee in Kikuyu), is a farm that is focused on coffee, with fewer livestock than the first farm (1.5 TLU) and 0.5 ha of arable land. Both farmers are associated with a coffee cooperative which provides best practices recommendation (Table S1, supplementary material). Farm management was followed throughout the year, especially with regard to the application of manure and inorganic fertiliser throughout during the two cropping seasons.

2.4. Soil characterisation

Soil samples were taken with a 5-cm diameter auger to 20 cm depth. In each of the plots, two composite samples were produced from fertilised and unfertilised locations. The fertilised composite consisted of 18 well-mixed samples taken within planted rows/holes or around coffee plants. The procedure was repeated for the unfertilised composite, but with sampling undertaken between planted rows/holes or

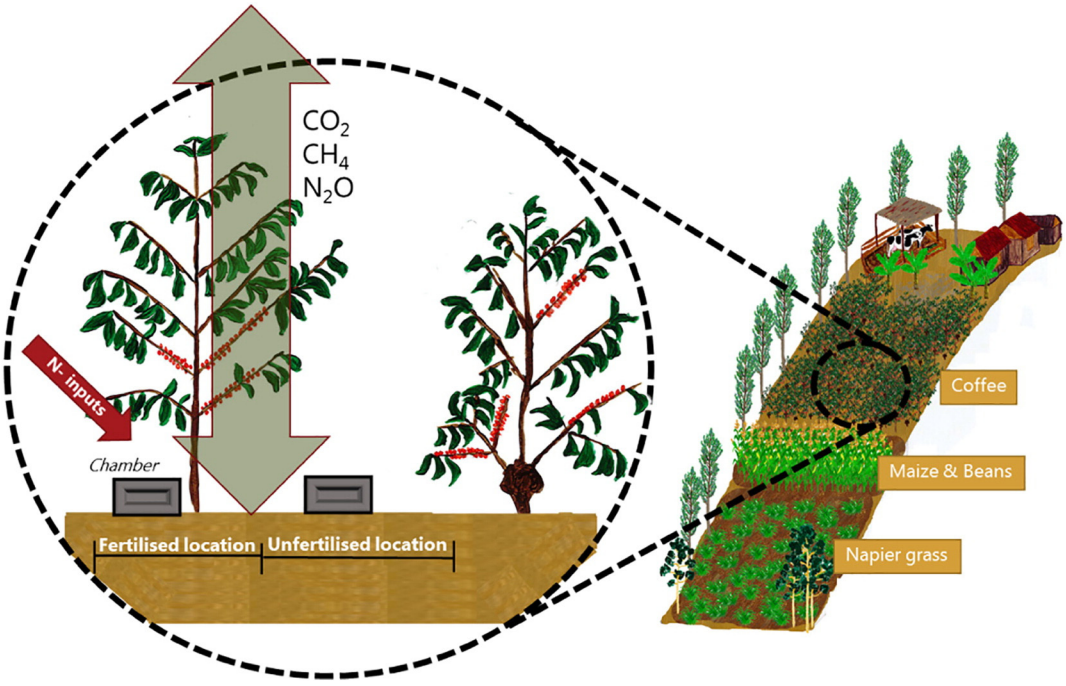

Fig. 1. A typical smallholder crop-livestock farm in Murang'a. Whole-farm GHG sampling designs shoud capture the spatial distribution of crops and nutrients use (between farms, among fields within the farm, between fertilised and unfertilised locations within fields).

coffee plants. For the incubation experiment, a composite was produced from nine coffee plots in the region.

Soil textures were determined by Laser Diffraction Particle Size Analysis (LDPSA, Horiba LA-960) at the ICRAF's Soil and Plant Diagnositic laboratory in Nairobi, Kenya. Soils samples were analysed using mid-infrared spectroscopy (MIRS, Tensor 27 HTS-XT). Calibration spectral models from ICRAF's database of >100 samples were used with the resultant spectra of the soil samples predicting soil attributes. Random forest (RF) algorithms were used to chemometrically estimate these attributes (Table 1).

2.5. Field soil GHG sampling

Soil CO_2, N_2O and CH_4 fluxes were measured over a 12-month period from 22 February 2015 to 22 February 2016 and included two cropping seasons. Gas samples were collected twice a week during the rainy season and once a week during the dry season. Fertiliser and manure applications were followed by daily measurements over the course of seven days. Gas samples were collected in the field using vented (non flowthrough non-steady state) static chambers (Hutchinson and Mosier, 1981; Parkin and Venterea, 2010). Sixty rectangular frames (0.355 m × 0.255 m) were inserted 5–10 cm into the soil – as chamber bases – on three fields/plots on each farm: coffee, maize intercropped with beans, and Napier grass. The chamber bases were placed in precise locations with and without fertilisation, matching the farmers' resource allocation. In each coffee plot, five frames for chambers were installed between the trees (unfertilised treatment) and five under the dripline (2-m radius) of the coffee tree (fertilised treatment). In maize and bean plots, five chambers were installed between the rows (unfertilised) and five within the rows (fertilised). Lastly, on each Napier grass plot, five chambers were installed between the plants (unfertilised) and another five within the rows (fertilised). Chamber bases were left in place for the year of measurements, except when they needed to be replaced (*i.e.* broken base) or when labour practices such as tillage required their removal. They were then reinstalled in the same location.

On each sampling date, an opaque, reflecting and insulated lid (0.355 m × 0.255 m × 0.125 m) was tightly fitted to the base. Air samples were collected from the headspace 0, 10, 20 and 30 min after closing using a propylene syringe (50 ml) through a rubber septum. Following the gas pooling procedure of Arias-Navarro et al. (2013), a sample of 10 ml was taken from each of the five chambers of the treatment. The combined 50 ml were mixed in the syringe, keeping the valve closed. Immediately afterwards, the first 20 ml of the sample from the syringe was used to flush the 20-ml sealed glass vials using a second needle through the rubber septum. The second needle was then removed and the final 30 ml were transferred into the vial. The 10 ml overpressure (50% vial capacity) minimised the risk of contamination and facilitated gas uptake by the chromatograph. Auxiliary measurements during each sampling event included chamber volume, air temperature in the chamber, soil temperature, atmospheric pressure (Garmin GPSmap 64 s), and daily rainfall (rain gauge).

2.6. Laboratory soil GHG incubations

We hypothesized that manure coming from different manure management systems (MMS) affects soil N_2O fluxes. Therefore, a parallel soil incubation experiment was carried out in the laboratory over a 42-day period. Manure was gathered from four MMS: unmanaged (no management), heaps (solid storage), pits (combination of solid and liquid slurry) and biodigesters (digestate resulting from anaerobic digestion). Three farms were sampled for each MMS (12 farms in total). Furthermore a synthetic fertiliser (calcium ammonium nitrate – CAN 25%) treatment was included (soil + CAN), along with a combination of manure (heaps) + synthetic fertiliser (CAN), mimicking the practices of local farmers. The incubation set-up consisted of 15 treatments each with four replications ($N = 60$).

The experimental soil (collected from 9 coffee plots in the field site) was sieved (2 mm) and air-dried for 1 week before the start of the experiment, and pre-incubated at experimental conditions for 48 h (75% of field capacity and 25 °C). Soil water content was kept constant during the experiment. Sixty 820-ml cylindrical glass jars were prepared with 400 g of soil at a bulk density of 1.26 g cm^{-3}. The manure treatments consisted of 55 g manure, whereas the fertiliser treatments received 1 g CAN. These amounts were calculated based on the coffee cooperative's recommendations.

GHGs were sampled every day during the first week, and every three days thereafter. The jar was closed and immediately afterwards a 50-ml propylene syringe was introduced through the rubber septum. The air was sucked up to the maximum syringe capacity and reintroduced into the jar to help mix the gases. Subsequently, a 15-ml air sample was taken from the jar and introduced into 10-ml vials. The process was repeated four times: at time 0 (immediately after the jar was closed), time 1 (20 min), time 2 (40 min) and time 3 (60 min). Room temperature was maintained at a constant 25 °C throughout the experiment.

2.7. Gas chromatography

Vials were analysed by gas chromatography on an SRI 8610C gas chromatograph (9' Hayesep D column) fitted with a 63Ni-electron capture detector (ECD) for N_2O (with pure N as carrier gas) and a flame ionisation detector for CH_4 and CO_2, after passing the CO_2 through a methaniser. Calibration vials of known N_2O, CH_4 and CO_2 concentrations were introduced into the chromatograph tray every 5 to 8 samples. The relation between the peak area from the calibration gas and its concentration was used to determine the N_2O, CH_4 and CO_2 concentrations of the chambers and jar headspaces.

2.8. Crop yield

In order to estimate crop production, both harvest units and whole plot harvests were sampled. Yields from individual coffee trees within rows were weighed during harvesting in June–July and November–December. Farmers were asked for their fresh coffee yields after the coffee

Table 1
Soil properties in *Thara and Kahua* farms.

		Bulk density (g cm^{-3})		pH		C (%)		N (%)		Clay		Texture (%) Silt		Sand	
Cropping system	Treatment	*Thara*	*Kahua*	*Thara*	*Kahua*	*Thara*	*Kahua*	*Thara*	*Kahua*	*Thara*	*Kahua*	*Thara*	*Kahua*	*Thara*	*Kahua*
Coffee	Fertilised	1.11	1.17	4.75	5.53	1.95	2.47	0.20	0.25	86.7	83.7	8.0	9.2	5.3	7.1
	Unfertilised	1.12	1.18	4.96	5.42	1.91	2.15	0.18	0.21	86.7	83.7	8.0	9.2	5.3	7.1
Maize & beans	Fertilised	1.14	1.08	5.08	5.27	2.17	1.89	0.20	0.19	87.8	88.6	7.6	9.4	4.6	2.0
	Unfertilised	1.13	1.12	5.01	5.27	2.20	1.91	0.22	0.19	87.8	88.6	7.6	9.4	4.6	2.0
Napier	Fertilised	1.19	1.19	5.26	5.29	2.06	1.99	0.20	0.20	74.9	86.2	13.8	6.9	11.2	6.9
	Unfertilised	1.07	1.28	5.22	5.21	2.08	1.96	0.20	0.20	74.9	86.2	13.8	6.9	11.2	6.9

berries had been weighed in the coffee cooperative. Similarly, whole-plot production of maize and beans was recorded after the plots were harvested and estimated in small parcels of 2 × 2 m inside the plot during harvesting for triangulation.

2.9. Data analysis

There is no consensus on the best method to calculate GHG fluxes from static chambers (Venterea et al., 2009). Though linear models can underestimate GHG fluxes if the underlying empirical data is non-linear, nonlinear models can also be very sensitive to sampling errors and outliers (Hutchinson and Mosier, 1981; Venterea et al., 2009). Given our aim of finding differences at temporal (*e.g.* wet and dry seasons) and spatial scales (*e.g.* fertilised *vs* unfertilised), we selected a linear scheme with an appropriate deployment times and chamber heights to reduce non linearity. Fluxes were thus calculated using linear regression of gas sample concentrations *versus* closure time of the chambers. Auxiliary measurements of headspace volume, internal temperature and ambient pressure were used according to the ideal gas law to convert concentrations into mass per volume. Calculations were automated using KNIME workflow (KNIME 2.9.2 software GmbH, Germany). The flux equation programmed in KNIME can be found below (Eq. 1).

$$Flux\left(\mu g\, m^{-2} h^{-1}\right) = \frac{m \cdot M_w \cdot V_{ch} \cdot 60 \cdot 10^6}{A_{ch} \cdot V_M \cdot 10^9} \quad (1)$$

where "m" is the slope, as the increase or decrease in concentration (ppb or ppm min^{-1}), "M_w" is the molecular weight of the component (g mol^{-1}), "V_{ch}" is the volume of the chamber (m^3), "A_{ch}" is the area of the chamber (m^2) and "V_M" is the corrected standard gaseous molar volume (m^3 mol^{-1}).

Cumulative GHG fluxes were calculated with the R package flux, which includes several functions for the estimation of GHG fluxes rates from closed-chamber concentration measurements (FLUX package, R 3.3.1). The function auc() integrates the curve formed by the fluxes of N_2O, CH_4 and CO_2 *versus* time, following the trapezoid rule. This provides the area under the curve — or cumulative flux — which was calculated for the whole year, for two cropping seasons (March to September and October to February), and for wet (long rains from March to June and short rains from October to mid-January) and dry periods (mid-January to March and July to September). CO_2 equivalent was calculated using the 100-year global warming potential (GWP) with inclusion of climate–carbon feedbacks (value of 298 for N_2O). Only cumulative N_2O emissions were included in the estimation of the coffee carbon footprint. Emission factors (EFs) were derived from N inputs and cumulative fluxes for 40 days after the fertilisation event (Eq. 2):

$$EF = \frac{\left[\left(N_2O{-}N_{fertilised}\right) - \left(N_2O{-}N_{unfertilised}\right)\right] \cdot 100}{N_{applied}} \quad (2)$$

where "N_2O- $N_{fertilised}$" is the cumulative emission of N_2O (kg N_2O-N) from the specific area fertilised or from the incubation treatment, "N_2O- $N_{unfertilised}$" is the cumulative emission from the unfertilised area or the incubation control, and "$N_{applied}$" is the inputs of N in the specific treatment (kg N).

Upscaling of GHG measurements to field and whole-farm scales was performed using the information in Table 2 (area under different treatments). Statistical analyses were carried out to identify spatial and temporal variabilities – hotspots and hot moments – considered respectively as spatial patches and temporal events which result in significantly higher emissions than the immediate surroundings (between farms, among fields within farms, and between fertilised and unfertilised locations within fields) and time periods (between cropping seasons, wet and dry periods). Seasonal differences and the effect of management (fertilised *vs* unfertilised) were assessed using the non-parametric Mann-Whitney-Wilcoxon (wilcox.test () in R, version 3.3.1). Two-way analysis of variance (ANOVA, aov () in R) was used to test the interaction between crops and wet/dry periods or first/second season.

In the case of the incubations, one-way ANOVA (aov in R) was carried out together with the *t*-test (t.test() in R). Cumulative emissions were previously log-transformed after the Kolmogorov-Smirnov test for normality. Correlations between N_2O fluxes and manure properties in the incubations were tested using Pearson correlation (cor.test () in R).

3. Results

3.1. Farm management

The management practices on both farms are shown in Table 2. The allocation of N resources, mainly through manure and fertiliser applications, is one of the main variables for predicting GHG emissions. The coffee systems received most of the manure, specifically 78–89% of total manure on *Thara* and 87–88% on *Kahua*. The maize and beans plot received 11% and 12% of the total manure on *Thara* and *Kahua* respectively. The Napier grass plot received manure only on *Thara* (9% of the total manure) during the first season, whereas on *Kahua* the farmer did not apply manure to the Napier grass at all during the year. Total manure application was higher during the long rainy season than during the short rainy season. *Thara*, with 0.8 ha of arable land, received an absolute amount of 59 and 42 kg of N in the first and second season respectively, whereas *Kahua* received 53 and 36 kg of N in 0.5 ha of arable land. The relatively similar amounts of manure on both farms, despite differences in livestock densities, were due to *Kahua* purchasing manure to meet coffee cooperative recommendations on manure applications. Imported N fertiliser was mainly applied to coffee plots (84 and 93% on *Thara* and *Kahua* respectively). The remaining fertiliser was applied to maize plots. The Napier grass plots did not receive any inorganic fertiliser on either farm. An amount of 30 and 31 kg N in the long rainy season was applied on *Thara* and *Kahua,* respectively. The second season accounted for an additional amount of 19 and 23 kg N on *Thara* and *Kahua.* Nitrogen fluxes within the farms were well represented by nutrient flows maps (Fig. S1, supplementary material).

3.2. Field soil GHG fluxes

3.2.1. N_2O fluxes

Fluxes of N_2O varied spatially and temporally throughout the two cropping seasons (Fig. 2). The different shape of the N_2O curves among the three cropping systems – coffee, maize and beans and Napier grass – indicates spatial variability at farm-scale. Downscaling, the plot-scale spatial variability is shown between fertilised and unfertilised areas. The Mann-Whitney *U* test showed differences between fertilised and unfertilised locations within coffee ($P < 0.001$) and maize and beans plots ($P < 0.001$). Average N_2O emissions around fertilised coffee trees were 26 and 43 μg N_2O-N m^{-2} h^{-1} on *Thara* and *Kahua* respectively. Emissions from unfertilised areas (between coffee trees) accounted for just 20% of those from fertilised areas on *Thara* (5 μg N_2O-N m^{-2} h^{-1}) and 33% on *Kahua* (15 μg N_2O-N m^{-2} h^{-1}). Maize plots registered lower average emissions than coffee plots, with 7 to 11 μg N_2O-N m^{-2} h^{-1} in fertilised planted rows and 1.7 to 3.3 μg N_2O-N m^{-2} h^{-1} in unfertilised inter-rows on *Thara* and *Kahua* respectively. The Napier grass plots did not present differences between fertilised and unfertilised areas ($P < 0.07$). Areas receiving manure inputs in *Thara*'s Napier grass plot produced an average emission of 12 μg N_2O-N m^{-2} h^{-1}, whereas *Kahua* – which did not receive manure in that year – emitted on average 3 μg N_2O-N m^{-2} h^{-1}.

The temporal variability in N_2O emissions occurred throughout the seasons, dry and wet periods and fertilisation calendar (Table 2).

Table 2
Cropping systems and microsite description.

Cropping system	Treatment	Microsite description	Fertilisation		Percentage of the plot (%)	
			Thara	*Kahua*	*Thara*	*Kahua*
Coffee	Fertilised	Application of manure and fertiliser around coffee trees (2 m radius)	March & October: a wheelbarrow of manure around coffee tree at 10.9 and 8.8 t DM ha^{-1} May: glass of CAN per coffee tree at 417 kg CAN ha^{-1} November: glass of NPK per coffee tree at 370 kg NPK ha^{-1}	March & October: a wheelbarrow of manure around coffee tree at 9.7 and 6.7 t DM ha^{-1} April & November: glass of NPK per coffee tree at 317 kg NPK ha^{-1} and 345 kg ha^{-1}	62	65
	Unfertilised	Corridors and spaces between coffee trees without fertiliser application	–	–	38	35
Maize & beans	Fertilised	Application of manure and fertiliser in planting rows or holes	March & October: buckets of manure in rows at 5.8 and 3.6 t DM ha^{-1} April: handful of CAN per plant at 112 kg ha^{-1} May & December: handful of DAP at 226 and 114 kg ha^{-1} Jan: handful of urea per plant at 114 kg ha^{-1}	March & October: two handfuls of manure in holes at 8.2 and 5 t DM ha^{-1} May & December: handful of CAN per plant at 94 and 100 kg ha^{-1} June: handful of DAP per plant at 115 kg ha^{-1}	15	15
	Unfertilised	Rows and spaces between plants without inputs	–	–	85	85
Napier grass	Fertilised	Application of manure in plant holes – no inorganic fertiliser registered	May & December: handful of manure in plant holes at 4.4 and 3.8 t DM per ha^{-1}	No fertilisation during the sampling period	9	8
	Unfertilised	Areas between plants without organic or inorganic inputs	–	–	91	92

While no differences in N_2O emissions were found between the first and second growing seasons ($P = 0.34$), wet periods had significantly higher emissions than dry periods ($P < 0.001$). Patterns were similar in both farms. In the second half of March, N_2O emissions increased with the first rains of the season. The higher peaks of N_2O after soil rewetting were observed on *Thara*'s coffee and Napier grass plots, with 72 and 52 μg N_2O-N m^{-2} h^{-1} respectively. Farmers took advantage of the first rains to prepare the land and apply manure. Manure applications to *Thara*'s coffee trees, in combination with wet conditions, caused a peak of 135 μg N_2O-N m^{-2} h^{-1} in mid-April followed by an application of NPK with a peak of 90 μg N_2O-N m^{-2} h^{-1} by the end of May. On *Kahua*, manure and inorganic fertiliser applied over a short time produced the highest peak observed in the experiment, with a value of 570 μg N_2O-N m^{-2} h^{-1} in early May. Emission peaks in the maize and beans and Napier grass plots were lower than those in the coffee plots. The highest peak registered in maize and beans was on *Kahua* after CAN fertilisation, with a value of 102 μg N_2O-N m^{-2} h^{-1}. *Thara*'s Napier grass plot, after receiving manure, registered the highest peak of Napier grass plots with a value of 80 μg N_2O-N m^{-2} h^{-1} in May. Peaks during the second cropping season were lower in magnitude, but followed similar trends. The rewetting of the soil occurred in October, at the start of the second cropping season. The cycle was repeated with manure and fertiliser applications and the consequent peaks in N_2O emissions.

Negative N_2O fluxes were found in all cropping systems throughout the year. The highest N_2O uptake was found in the unfertilised areas of *Kahua*'s maize and beans plot, with −12.74 μg N_2O-N m^{-2} h^{-1} in April. *Thara's* fertilised maize and bean areas registered negative fluxes below −9 μg N_2O-N m^{-2} h^{-1} in August, as well as unfertilised areas in *Kahua*'s Napier grass plot in April and August. N_2O uptake rates below −5 μg N_2O-N m^{-2} h^{-1} in maize and bean plots were common between July and September, regardless chambers position in fertilised or unfertilised areas. The space between trees in coffee plots (unfertilised) registered negative fluxes below −2 μg N_2O-N m^{-2} h^{-1} in June, July and August, whereas in the areas adjacent to the coffee plants (fertilised) this occurred in August.

3.2.2. CH_4 fluxes

CH_4 fluxes ranged between −0.96 and 0.88 mg CH_4-C m^{-2} h^{-1}. However, most of the measurements were negative or close to zero (Fig. 3). Fertilised and unfertilised areas presented no differences within coffee plots ($P = 0.28$), maize and bean ($P = 0.26$) and Napier grass ($P = 0.49$). Average fluxes in coffee plots accounted for −0.04 to −0.02 mg CH_4-C m^{-2} h^{-1} on *Thara* and −0.05 to −0.03 mg CH_4-C m^{-2} h^{-1} on *Kahua*. Maize and beans plots registered average fluxes of −0.04 to −0.03 mg CH_4-C m^{-2} h^{-1} on both farms. The Napier grass plots averaged −0.04 to −0.05 mg CH_4-C m^{-2} h^{-1}.

3.2.3. CO_2 fluxes

Fluxes of CO_2 followed a similar trend to N_2O in the three cropping systems (Fig. 4). A first peak occurred with the Birch effect, immediately after the rewetting of the soil with the first rains in March (Birch and Friend, 1956). CO_2 fluxes generally stayed high during the long rainy season. A drop in CO_2 fluxes indicated the dry period from July to September. A new peak in October showed the rewetting of the soil. Significant differences were found between dry and wet periods ($P < 0.001$). During the wet periods, CO_2 emissions remained high, ranging between 90 and 320 mg CO_2-C m^{-2} h^{-1}. During the dry periods, CO_2 emissions reached minimum rates (21–56 mg CO_2-C m^{-2} h^{-1}). Fertilised locations registered higher fluxes than unfertilised locations ($P < 0.001$). Average fluxes in fertilised locations were above 100 mg CO_2-C m^{-2} h^{-1} in all plots, while in unfertilised locations they were below 90 mg CO_2-C m^{-2} h^{-1}.

3.3. Cumulative emissions

3.3.1. N_2O emissions

Differences in cumulative emissions were found between cropping systems at farm scale (F value = 9.2, $P = 0.01$), between dry and wet periods (F value = 31.7, $P < 0.001$), and in the interaction between cropping systems and dry-wet periods (F value = 5.8, $P = 0.03$). Table 3 presents a heat map for visual interpretation of fluxes, where darker colours indicate hotspots and hot moments at multiple scales. Coffee systems registered the highest annual cumulative emissions. Between 84% and 94% of the N_2O emissions occurred during the wet period. In the case of *Kahua*, most of the coffee plot emissions were concentrated in the first rainy season, whereas on *Thara* emissions were more homogeneously distributed during the year. With 0.69 kg N_2O-N ha^{-1}, the Napier grass plot of *Thara* registered the third highest cumulative emissions after the two coffee plots. Lastly the plot of maize and beans registered cumulative emissions with values of

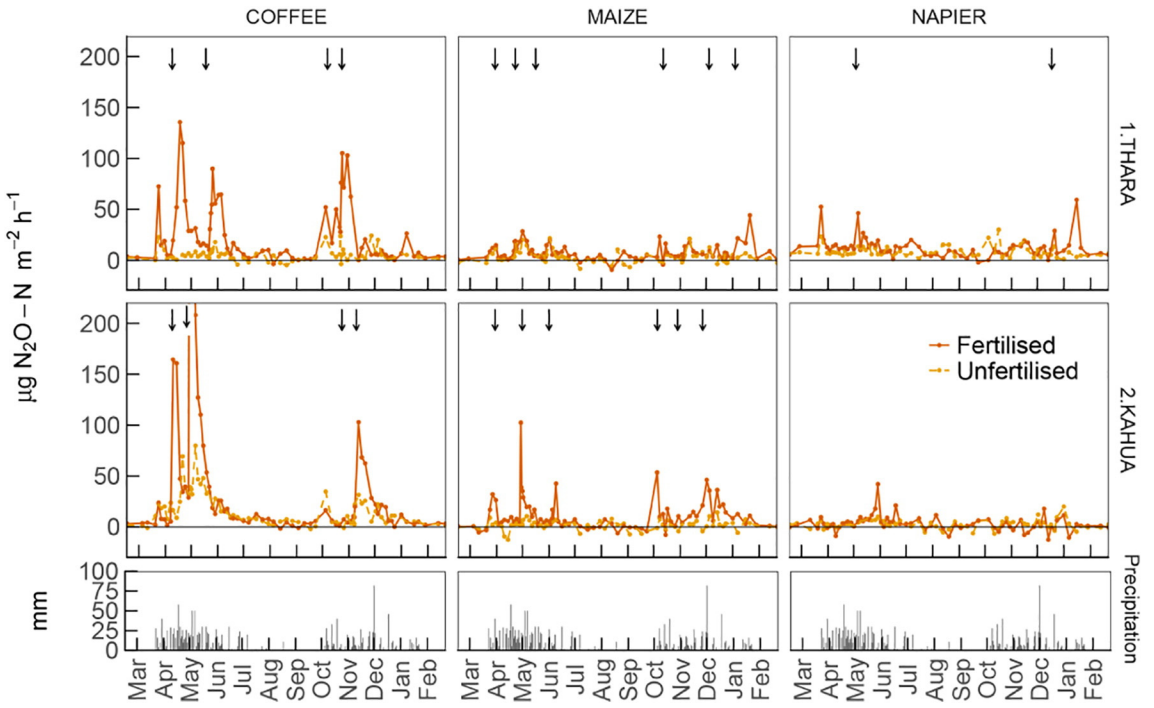

Fig. 2. Soil GHG emissions of N_2O in three cropping systems (coffee, maize – with beans intercropped – and Napier grass) on *Thara* and *Kahua*. Fertilised and unfertilised locations are represented by colour points linked by a line (fertilised) or a dashed line (unfertilised). Arrows on the top of the curves indicate N inputs. Grey bars in the bottom graphs show daily precipitation.

0.18 and 0.27 kg N_2O-N ha^{-1} on *Kahua* and *Thara* respectively. During the dry periods, however, the maize and beans plots of both farms registered negative cumulative emissions of −0.01 and −0.02 kg N_2O-N ha^{-1}.

3.3.2. CH_4 emissions

Soils were mainly sinks of CH_4 throughout the experiment. By the end of the experiment, these small hourly fluxes resulted in cumulative annual fluxes ranging from −4.17 to −2.22 kg CH_4-C ha^{-1} y^{-1} (Table 3). No significant differences were found between crops (F value = 1.2, $P = 0.34$). However, methane oxidation was higher during the wet season than in the dry season (F value = 44.2, $P < 0.001$), with significantly higher uptake in the second season as well (F value = 23.5, $P < 0.001$). No interactions were found between crops and the wet/dry period (F value = 0.19, $P = 0.82$) or between crops and the first/second season (F value = 1.3, $P = 0.32$).

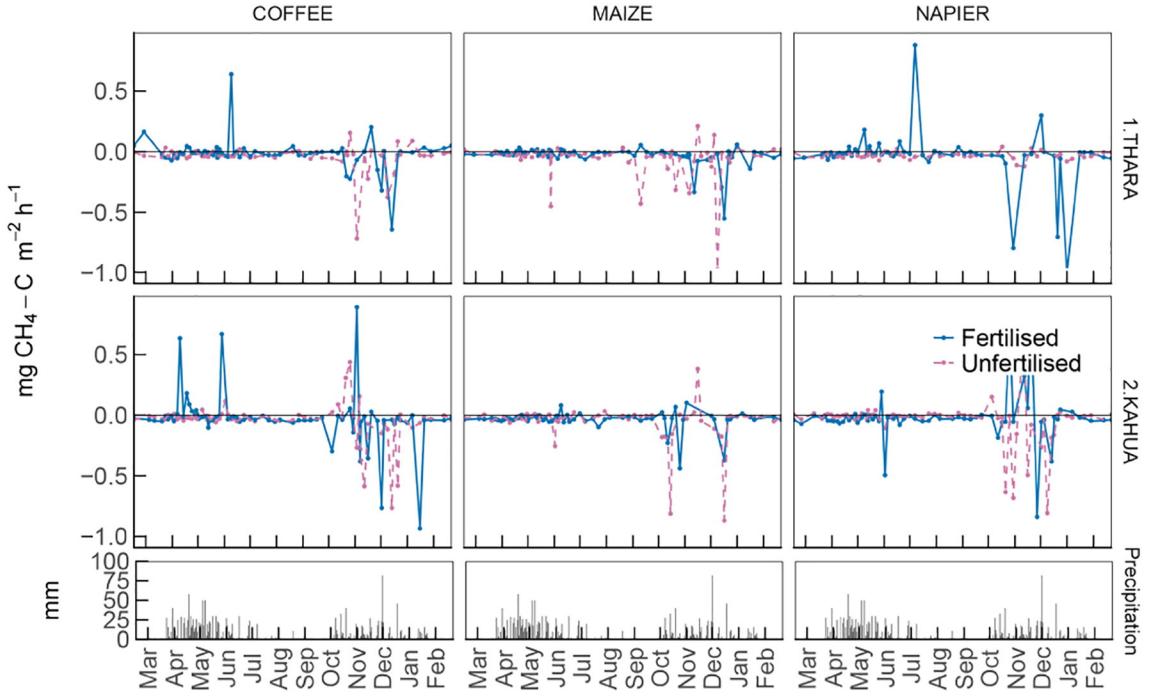

Fig. 3. Soil CH_4 emissions in three cropping systems (coffee, maize – with beans intercropped – and Napier grass) on *Thara* and *Kahua*. Fertilised and unfertilised locations are represented by colour points linked by a line (fertilised) or a dashed line (unfertilised). Grey bars in the bottom graphs show daily precipitation.

3.3.3. CO_2 emissions

Cumulative emissions of CO_2 (Table 3) were three to four times higher during the wet season than in the dry season ($F = 115.5$, $P < 0.001$). Similarly, significant differences were found between the first and second season ($F = 115.5$, $P < 0.001$). The first rainy season registered on average 40% higher emissions than the second rainy season. Between cropping systems, *Thara*'s Napier grass plot and *Kahua*'s coffee plot accounted for the largest value of CO_2 emissions within the whole year, however, no significant differences were found between cropping systems (F value = 4.6, $P = 0.05$). No significant interactions occurred between crops and the wet/dry period (F value = 2.4, $P = 0.17$) or between crops and the first/second season (F value = 0.8, $P = 0.46$).

3.4. Laboratory incubations

Although manure characteristics did not differ between MMS, a strong correlation was found between the initial manure NH_4 content and cumulative emissions ($R^2 = 0.81$, $P < 0.05$), a positive correlation between manure water content and cumulative emissions ($R^2 = 0.64$; $P < 0.05$) and a negative correlation between C/N ratio and cumulative emissions ($R^2 = 0.39$, $P < 0.05$) (Tables S2 and S3; Figs. S2 and S3 in supplementary material).

3.5. Yields and coffee yield-scaled emissions

Maize yields on *Thara and Kahua* were, respectively, 1.9 and 2.2 t ha^{-1} in the first cropping season and 3.2 and 3.4 t ha^{-1} in the second cropping season. Beans, intercropped with maize, accounted for yields of 1.1 on *Thara* and 1.4 t ha^{-1} in *Kahua* in the first cropping season and 0.8 and 1.3 t ha^{-1} in the second cropping season.

Thara and Kahua's coffee harvest by the end of the year resulted in yields of 5.8 and 7.2 t coffee berries ha^{-1} respectively, making it one of the best years for the farmers. The flowering at the onset of the short rainy season led to a "small harvest" in June–July. However, the main flowering occurred after the first rains in March, with 76% to 78% of the coffee berries being harvested in November–December. These yields resulted in a carbon footprint of 0.08 to 0.15 kg of CO_2 eq kg of coffee $berry^{-1}$.

4. Discussion

In recent years, a number of studies have carried out soil GHG measurements to enhance our understanding of hitherto uncertain emissions in sub-Saharan agroecosystems (Kim et al., 2016; Pelster et al., 2017; Rosenstock et al., 2016a). However, there is no experimental data from soil GHG fluxes on integrated coffee-dairy systems, despite this commodity's importance for livelihoods in the East African highlands. Furthermore, the diversity of smallholder agriculture challenges the mission of targeting GHG measurements at multiple scales (Rosenstock et al., 2016b). Despite their small areas, farms in our study include cash crops (coffee), food crops (maize and beans) and fodder (Napier grass) for livestock, with animal manure playing a crucial role for N sourcing. This study offers a first approximation of soil GHG emissions in these systems at multiple spatial (between farms, among fields within farms, and between fertilised and unfertilised locations within fields) and temporal scales (between seasons, wet and dry periods).

Restricted resources in smallholder farms lead to compromises on resource allocation (Giller et al., 1997). We hypothesized that these precise locations receiving resources are GHG hotspots at different scales (from the fertilised locations, to the fields receiving most of the resources, and to the farms with high resource endowments). Two to six times larger emissions were found in fertilised hotspots — around the perimeter of coffee trees or within planted maize rows — than in unfertilised locations between trees, rows and holes. Across the different fields in the farm, coffee had 56% to 89% larger emissions of N_2O than Napier grass, maize and beans. *Kahua*, with half of its farm arable land dedicated to coffee, almost doubled the N_2O emissions of *Thara's* coffee plot. However, the Napier plot of *Thara* — focused on dairy — tripled the emissions of *Kahua's* Napier plot. This suggests that farm production strategies influence emission profiles, which should be considered when upscaling at the landscape level.

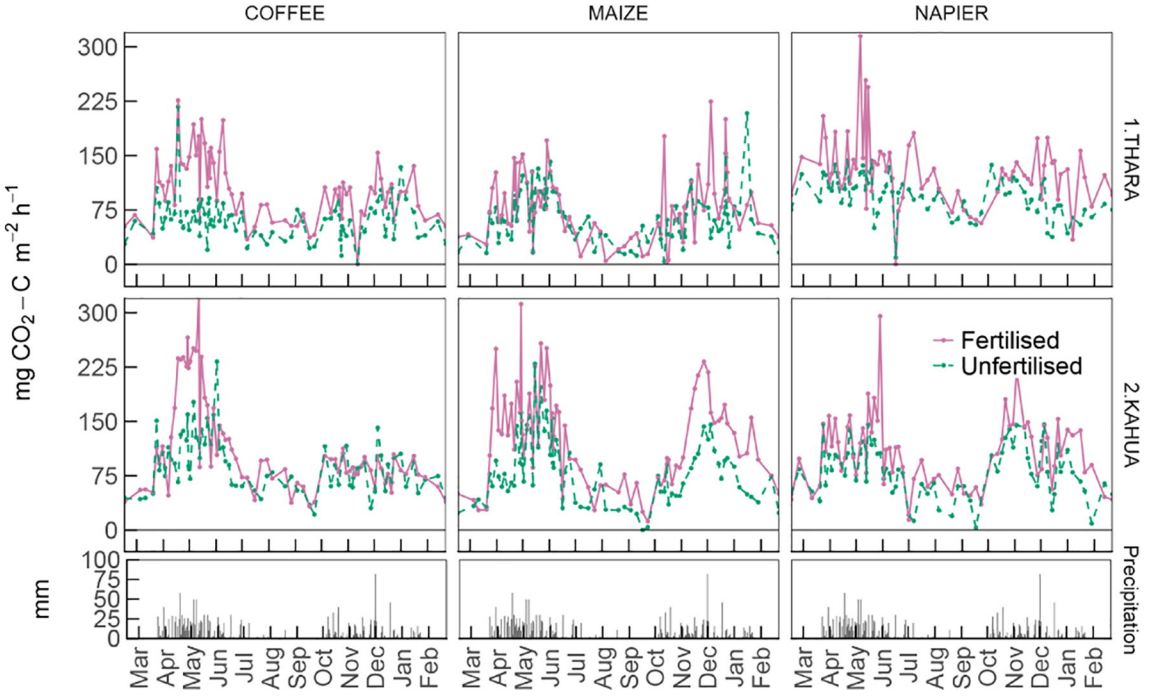

Fig. 4. Soil CO_2 emissions in three cropping systems coffee, maize – with beans intercropped – and Napier grass on *Thara* and *Kahua* farms. Fertilised and unfertilised locations are represented by colour points linked by a line (fertilised) or a dashed line (unfertilised). Grey bars in the bottom graphs show daily precipitation.

Table 3
Heat map of cumulative temporal and spatial emissions (hot moments and hotspots). Darker colours indicate higher emissions.

			N_2O [kg N_2O-N ha^{-1}]					CH_4 [kg CH_4-C ha^{-1}]					CO_2 (t CO_2-C ha^{-1})				
Farm	Cropping system	Treatment	First season	Second season	Dry period	Wet period	Annual	First season	Second season	Dry period	Wet period	Annual	First season	Second season	Dry period	Wet period	Annual
Thara	Coffee	Fertilised	0.94	0.62	0.1	1.41	1.53	0.53	−1.88	0.49	−1.83	−1.34	4.88	2.88	1.65	5.69	7.55
		Unfertilised	0.17	0.18	0.04	0.29	0.33	−1.4	−2.32	−0.79	−2.77	−3.64	2.98	2.05	1.24	3.48	4.87
		Total plot	0.65	0.45	0.08	0.98	1.08	−0.2	−2.04	0	−2.19	−2.22	4.16	2.56	1.5	4.85	6.53
	Maize and beans	Fertilised	0.26	0.32	0.04	0.5	0.56	−0.67	−2.21	−0.45	−2.24	−2.78	3.07	2.64	0.9	4.52	5.57
		Unfertilised	0.11	0.11	−0.03	0.25	0.22	−1.97	−2.48	−1.31	−3.07	−4.41	2.8	2.16	0.86	3.86	4.83
		Total plot	0.13	0.14	−0.02	0.29	0.27	−1.77	−2.44	−1.18	−2.94	−4.17	2.84	2.23	0.86	3.96	4.95
	Napier grass	Fertilised	0.63	0.41	0.24	0.73	1.01	1.06	−5.69	0.24	−5.37	−4.88	6.65	3.79	3.08	6.59	10.06
		Unfertilised	0.42	0.26	0.2	0.43	0.65	−1.6	−1.03	−0.89	−1.55	−2.53	5.05	2.77	2.51	4.8	7.56
		Total plot	0.44	0.27	0.21	0.46	0.69	−1.36	−1.45	−0.79	−1.89	−2.75	5.19	2.86	2.56	4.96	7.79
	(All)	Total farm	0.48	0.31	0.15	0.60	0.77	−1.03	−1.72	−0.58	−2.07	−2.70	4.66	2.71	2.08	4.84	7.15
Kahua	Coffee	Fertilised	1.89	0.49	0.11	2.24	2.37	−0.09	−3.22	−1.23	−1.87	−3.20	5.6	2.73	1.74	6.17	8.12
		Unfertilised	0.74	0.3	0.1	0.9	1.02	−1.14	−2.63	−0.71	−2.9	−3.69	4.35	2.62	1.64	4.88	6.74
		Total plot	1.49	0.42	0.11	1.77	1.89	−0.46	−3.02	−1.05	−2.23	−3.38	5.16	2.69	1.7	5.72	7.64
	Maize and beans	Fertilised	0.28	0.38	−0.02	0.65	0.64	−1.47	−1.42	−0.91	−1.87	−2.84	5.28	4.22	1.48	7.52	9.24
		Unfertilised	0.04	0.07	−0.01	0.11	0.10	−1.11	−2.47	−0.51	−2.87	−3.47	3.49	2.45	1.00	4.69	5.81
		Total plot	0.07	0.11	−0.01	0.19	0.18	−1.16	−2.31	−0.57	−2.72	−3.38	3.76	2.72	1.07	5.11	6.33
	Napier grass	Fertilised	0.2	0.02	0.05	0.16	0.22	−1.82	0.12	−0.94	−0.56	−1.60	4.84	3.83	1.86	6.4	8.46
		Unfertilised	0.1	0.09	0.01	0.17	0.18	−0.43	−2.89	−0.12	−3.1	−3.27	3.63	2.83	1.44	4.78	6.34
		Total plot	0.11	0.08	0.01	0.17	0.19	−0.54	−2.65	−0.18	−2.9	−3.14	3.73	2.91	1.47	4.91	6.51
	(All)	Total farm	0.79	0.25	0.05	0.97	1.03	−0.59	−2.78	−0.67	−2.54	−3.29	4.45	2.77	1.52	5.34	7.05

The Central Highlands of Kenya receive some of the highest N inputs of East Africa. However the GHG emissions in the present study were in the range of the low-input smallholder systems of other East African studies. Rosenstock et al. (2016a) found cumulative N_2O emissions ranging from 0.4 to 3.9 kg N_2O-N ha^{-1} yr^{-1} depending on the cropping system and region. Pasture sites in that study emitted above 2 kg N_2O-N ha^{-1} yr^{-1}, which is higher than the emissions recorded in the present study's coffee plots at 1.08 to 1.89 kg N_2O-N ha^{-1} yr^{-1}. High cumulative emissions are partially due to large pulses of N_2O during certain events. While in pastures these peaks are explained by animal urea and faeces deposition, animals in our study were kept in zero-grazing stalls and the N inputs in soils were human-driven. N_2O fluxes from fertilisation ranged from 20 to 570 μg N_2O-N m^{-2} h^{-1} in the present study, thus within the range of other Kenyan studies, *e.g.* Millar et al. (2004); slightly higher than in low-input smallholder systems (Rosenstock et al., 2016a; Pelster et al., 2017); and lower than dung and urine applications in Western Kenya pastures (up to 1076 mg N_2O-N m^{-2} h^{-1}) (Tully et al., 2017).

Soil CO_2 fluxes were clearly seasonal, with emission rates increasing from rewetting to a decrease after the onset of the rainy seasons. Low CO_2 fluxes during dry periods are due to minimal microbial activity, but also to the absence of plants (not yet planted) and thus no root respiration. This may be the reason why the fluxes remained slightly higher in perennial plots (coffee and Napier grass) than in annuals (maize and beans). The cumulative CO_2 fluxes in the present study ranged between 4.4 and 7.8 t CO_2 -Cha^{-1} yr^{-1}, which is within the range of other smallholder East African studies (Rosenstock et al., 2016a; Pelster et al., 2017).

The cumulative N_2O emissions found in the present study in Central Kenya were lower than those found in other Arabica coffee regions globally. For instance, with inorganic fertilisation rates above 250 kg N ha^{-1} in Costa Rica, Hergoualc'h et al. (2012) found 4.3 to 5.8 kg N_2O-N ha^{-1} yr^{-1} in coffee monoculture and coffee agroforestry systems shaded by N_2-fixing trees respectively. These emissions are 2–2.5 times higher than the ones found in Central Kenya. Low N_2O fluxes in the present study may be due to low-quality inputs driving N immobilisation (*e.g.* manure with a high C/N ratio). N immobilisation is seen in African pastures, where grasses with poor N content may lead to high C/N excreta in livestock (Giller et al., 1997). This feedback loop may lead to even higher C/N ratios in following seasons (Haynes and Williams, 1993;

Tully et al., 2017). In zero-grazing or semi zero-grazing systems of Kenya, livestock diets and feeds often also have low N and low digestibility (Rufino et al., 2006). On top of that, the addition of crop residues and weeds to the manure heap also increases the C/N ratio of the manure. Therefore, poor livestock diets and crop residues may lower N_2O emissions from manure applications in soils. The availability of labile C may also be a factor to consider in the control of N_2O emissions (Hickman et al., 2014a, 2014b), and differences in manure qualities originating from different composting practices may induce further variability in terms of emissions. Although no differences were found in the quality of manure from different systems, a high NH_4 content, high water content and low C/N ratio were likely to induce higher emission rates.

Soils with low pH result in higher losses of N in the form N_2O (Bakken et al., 2012), due to N_2O reductase inhabitation during denitrification leading to a higher N_2O:N_2 ratio (Knowles, 1982). High manure loadings may increase soil pH in the acidic soils of the area of the present study, thus acting as a buffer for N_2O emissions. However, manure applications are also expected to increase soil organic carbon, thus stimulating microbial activity and reducing the N_2:N_2O ratio during denitrification (Davidson et al., 2000). Low N_2O emissions may be also explained by a decrease in gas diffusivity, which even leads to N_2O consumption (Arah et al., 1991). The soils in the present study are heavily textured, with clay content above 70%. This could lead to significant N_2O consumption in periods of no N applications. Negative N_2O fluxes were found in our study, especially during dry periods which coincide with no N fertilisation. N_2O can be consumed during nitrification, but also during denitrification (Schlesinger, 2013; Wrage et al., 2004; Wu et al., 2013). Net negative fluxes have been broadly reported in the literature, but with little information on the extent of the reasons behind them (Chapuis-Lardy et al., 2007).

Dick et al. (2008) found that cereals systems, fertilised with both organic manure and urea, emitted significantly less N_2O (0.8 kg N_2O-N ha^{-1} per year) than plots receiving no organic manure (1.5 kg N_2O-N ha^{-1} per year). However, the present study found that manure and fertiliser applications added together had the highest peak and cumulative fluxes in both the incubation experiment and coffee field conditions. This was probably due to the highest N application of all treatments, combined with changes in soil moisture. An optimum water-filled pore space (WFPS) of 60–80% could partially explain these field observations (Davidson et al., 2000; Van Lent et al., 2015), which occurred in the middle of the long rainy season combined with an optimum substrate for denitrification. Rewetting of the soil from dry periods behaves in a similar way to the Birch effect for soil respiration (Birch and Friend, 1956), and contributes to hot moments for N_2O (such as those from fertilisation) since it offers ideal conditions for the transition from microbial oxygen to NO_3 respiration (Groffman et al., 2009). During high rainfall, higher soil moistures may be reached, with the major end product of denitrification being N_2 (Butterbach-Bahl et al., 2013).

N_2O emission factors can range from 0 to 7.8% globally (Bouwman, 1996), with 1% suggested by IPCC for its Tier 1 approach. Our study is consistent with most of the studies in SSA, which have shown N_2O EF to be under 1% of total N inputs (Baggs et al., 2006; Brümmer et al., 2008; Chapuis-Lardy et al., 2007; Chikowo et al., 2004; Kimetu et al., 2006; Mapanda et al., 2011; Pelster et al., 2017; Tully et al., 2017). Since emission factors are annual estimates, they should account for hot moments. Capturing hot moments requires experimental designs which follow management practices (*e.g.* fertilisation through the year) (Oktarita et al., 2017). Furthermore they can be improved by taking soil texture, crop type and precipitation regime into account, but there are still few measurements in SSA to account for these variations (Hickman et al., 2014a, 2014b).

GHG calculators are usually fed with default EF and model parameters coming from developed countries (Olander et al., 2014) and thus may not accurately estimate soil GHG emissions in SSA farming systems (Richards et al., 2016). Almost 90% of the field measurements and incubation experiments in the present study were below CFT and the IPCC default Tier 1 estimations. This study found coffee carbon footprints (*CF*) one order lower than those estimated with GHG calculators (Noponen et al., 2012; Ortiz-Gonzalo et al., 2017). Since marketing sustainable low-carbon coffee may benefit smallholder farmers, these tools and EFs need to be revised for tropical regions.

The relevance of the experimental design should be noted, with chambers allocated in different farms, crops and fertilised and unfertilised areas in order to capture spatial variability at multiple scales. It is known that smallholders allocate resources in different ways and there is an intrinsic fertility range even within plots and farms (Tittonell et al., 2010). The emission factors being developed take into account the fluxes from both the treatments and the controls. High emissions in the controls may induce a low EF in the treatments, since the control is subtracted from the treatment. The present study did find spatial differences between fertilised and unfertilised areas in coffee and maize and bean plots, suggesting that low EFs are not an artefact of controls with high fluxes. However, N is quite mobile, and some other methodological issues in this analysis may reduce the accuracy of the estimates. Some pulses of N_2O may be not captured ("hot moments" within a day), and therefore cumulative emissions may be underestimated. To overcome this issue, measurements were taken daily for seven days after fertilisation during the central hours of the day. Since denitrification hotspots have large spatial variability, the samples covered much of the area with 10 chambers per plot in fertilised and unfertilised treatments, with the variance between replicates then estimated. However, gas pooling was not suitable to pick up differences at smaller scales such as those within fertility treatments (*e.g.* rows or plants). Variability at small scales also reside in biophysical differences such as soil bulk density and texture, micro-environmental conditions (temperatures and moisture), micro differences of soil organic carbon, root systems and microbial activity, among others (Butterbach-Bahl et al., 2016).

Mitigation options in smallholder systems should be achieved without adversely affecting the yield. Improvements in coffee management would further reduce yield-scaled emissions while increasing production of coffee (Noponen et al., 2012). Although more long-term studies are needed, balancing organic manure-N and inorganic N may increase yields and mitigate soil N_2O emissions, as found in some other sub-Saharan African studies (Dick et al., 2008; Nyamadzawo et al., 2017). Furthermore, the recycling of nutrients in smallholder crop-livestock is largely dependent on manure. Given its importance in the region, further studies should explore manure management systems (MMS) and how to achieve good quality manures while reducing nutrient losses.

5. Conclusions

This study is a first attempt to estimate soil GHG emissions in smallholder integrated dairy-coffee systems in East Africa. Although intensification processes are already occurring in Murang'a – small farms sizes, livestock in zero-grazing stalls and increased N inputs in cropping systems – GHG emissions in our study remained low, within the range of low-input, rain-fed systems in East Africa. Given the complexity of smallholder farming systems – with numerous farm components and resource interactions – capturing temporal and spatial variability becomes a challenge. We applied a stratification of farms on its different production systems, targeting fields with different resource allocations, and continuously measuring in fertilised and unfertilised locations throughout seasonal events. Our results showed significant differences in magnitudes of fluxes across space (within the field, between farm fields and between farms) and time (between seasons). However, this approach is costly and labour intensive. Recent empirical data generated along sub-Saharan Africa will help to calibrate emission factors (EFs) and models to reduce uncertainties of soil GHG emissions estimations. Our results are consistent with most of the GHG studies which showed

limited soil EFs below the default IPCC's 1% in the region. Advances toward accounting for multifunctionality in integrated systems are also needed to guarantee a comprehensive understanding of synergies and trade-offs of low-emission development in sub-Saharan Africa.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.247.

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