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Smallholder cropping systems contribute limited greenhouse gas fluxes in upper Eastern Kenya

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ABSTRACT

The contribution of smallholder farming systems to the National greenhouse gas (GHG) budget is missing in most developing countries, including Kenya. Data on the contribution of smallholder cropping systems to the GHG balance is essential for realising Sustainable Development Goal 13 on climate action, i.e., on nationally determined contributions (NDCs) and in compliance with the Paris Agreement. Do smallholder farming systems act as nature-based solutions for greenhouse gas emissions reduction? This study evaluated GHG emissions from cropping systems under on-farm smallholder farming conditions. We had five cropping systems on two smallholder farms: sole maize, maize-bean intercrop, coffee, banana, and agroforestry. Gas samples were collected using three static chambers per cropping system. The gas samples were analysed using gas chromatography (GC) fitted with a ^{63}Ni-electron capture detector (ECD) for N_2O and flame ionisation detector (FID) for CH_4 and CO_2 using N as carrier gas. Cumulative annual fluxes of (CH_4, N_2O, and CO_2) varied significantly in farms one and two across the cropping systems. The cumulative soil GHG fluxes ranged from -1.34kg CH_4—C ha^{-1} yr^{-1} under agroforestry to -0.77kg CH_4—C ha^{-1} yr^{-1} under banana for CH_4, 0.30kg N_2O—N ha^{-1} yr^{-1} to 1.23kg N_2O—N ha^{-1} yr^{-1} for N_2O and 5949kg CO_2—C ha^{-1} yr^{-1} to 12,954kg CO_2—C ha^{-1} yr^{-1} for CO_2. The maize grain yields ranged from 0 to 3.38 Mg ha^{-1}. The N_2O yields scaled emissions ranged from 0.10 to 0.26g kg^{-1} maize and 0.68 to 1.30g kg^{-1} beans. Smallholder farmers in Upper Eastern Kenya contribute a limited amount of soil GHG emissions and thus could act as a nature-based solution for lowering agricultural emissions.

1. Introduction

Agriculture is an important entry point in the mitigation of greenhouse (GHG) emissions. However, agriculture contributes approximately 11 to 14% of the total annual anthropogenic GHG emissions globally, besides 17% from land-use changes [1,2]. In sub-Saharan Africa (SSA), 80% of farmland comprises smallholder farms. Hence, small farms are important in GHG inventories. Moreover, smallholder farming systems such as agroforestry could sink agricultural GHG fluxes, thus offering a nature-based pathway for lowering emissions. Although the region contributes minimal GHG emissions globally, rising temperatures and changes in rainfall have been projected and may affect

Abbreviations: ch4, methane; Co2, carbon dioxide; Ecd, electron capture detector; Fid, flame ionisation detector; Gc, gas chromatography; Ghg, greenhouse gas; Gwp, global warming potential; Ilri, internation livestock research institute; Ipcc, intergovernmental panel on climate change; LR, Long Rains; N_2O, Nitrous oxide; NDC, Nationally determined contributions; SR, Short rains; UM, Upper Midlands; UNFCCC, United Nations Framework Convention on Climate Change; WMO, World Meteorological Organization; YSE, Yield scaled emissions.

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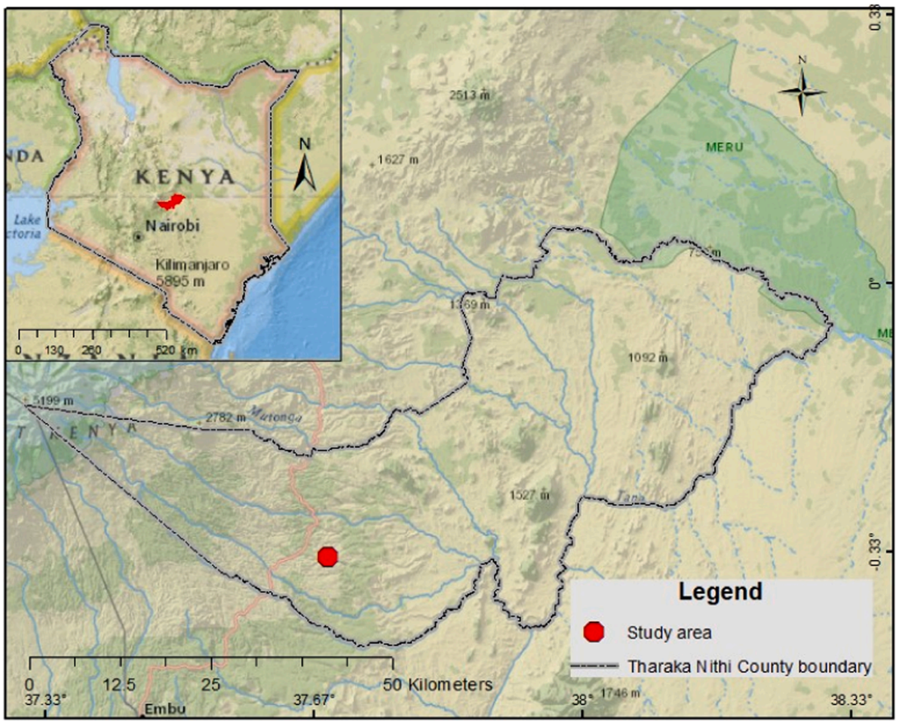

Fig. 1. Study area map.

agricultural production due to low-carbon development pathway alternatives [3]. Climate variability can adversely affect SSA, given that the region has a high poverty level and low adaptive capacity to climate change due to resource limitations [4,5].

The main agriculture-related GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). According to Sawa et al. [6], the GHG atmospheric concentration is 413.2ppm for CO_2, 1889 ppb for CH_4 and 333.2 ppb for N_2O. Agricultural CO_2 results from burning organic matter, autotrophic and heterotrophic respiration. The CH_4 is primarily the net balance between methanogens and methanotrophs [7, 8]. Nitrous oxide (N_2O) is produced through co-denitrification, chemo-denitrification, nitrifier-denitrification, heterotrophic nitrification and autotrophic nitrification [3]. The N_2O has a high global warming potential (GWP) of 265 and destroys the stratosphere ozone layer [9]. Similarly, agricultural intensification and application of nitrogen-based fertilisers also contribute to soil GHG emissions. The balance between the mineralisation of organic N and the immobilisation of N by microbes depends on soil biological activities, moisture and temperature, and the ratio of C: N in the soil. Methane (CH_4) is produced in oxygen-limited conditions by methanogens through the degradation of organic matter and can absorb infrared radiation 20 to 30 times more than CO_2 [8].

Upper Eastern Kenya is one of Kenya's key food baskets. This region comprises smallholder farmers with diversified cropping systems under the same field. Cropping systems are rain-fed and non-mechanised [10]. Smallholder farmers use inorganic and organic resources such as mineral fertilisers, animal manure, crop residue and tithonia diversifolia for enhanced crop yields [1,9,11–13].). However, crop residue utilisation in the region is limited by crop-livestock competition [11,14]. Common crops grown in the region are maize (*Zea mays* L.*)* and beans (*Phaseolus vulgaris*) as staple crops, coffee (*Coffee arabica* L.*),* and banana (*Musa sp)* as cash crops. GHG emissions from different cropping systems, such as intercropping, mixed cropping, and cash crops, have been getting more and more attention. Despite the challenges of decline in soil fertility promoted by insufficient use of inorganic and organic resources [15,16], climate variability has also become an ailing issue in the region. For instance, Kiboi et al. [17] reported that farmers complained of poor harvests due to low precipitation. Therefore, smallholder farmers are faced with the triple challenge of improving soil fertility and responding to climate change through reduced GHG fluxes while improving food production. The soil GHG fluxes are mainly influenced by practices for enhancing crop yields, such as soil fertility management technologies [18,19]. Additionally, soil C content, tillage practices, N fertilisation, cover crops, aeration, and soil water content influence GHG fluxes [20, 21]. Therefore, there is a need to assess soil GHG fluxes across different cropping practices under smallholder management practice.

The vast data gap on the contribution of smallholder cropping systems to GHG emissions and the need by the Kenyan government to report her Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC) calls for regular in-situ GHG measurements. There is a likelihood of an increase in GHG emissions coupled with increasing GWP aided by agricultural lands due to low carbon development pathways. Additionally, the limitation of GHG measurements in smallholder farms further increases the uncertainty in GHG emissions. This study evaluated the effects of different cropping systems on soil GHG fluxes under on-farm conditions from two smallholder farms in Upper Eastern Kenya. We hypothesised that agroforestry cropping systems would have the lowest cumulative soil GHG fluxes due to carbon storage in the soil.

2. Methods and materials

2.1. Study area

The study was conducted in the Kangutu sub-location, Chukka /Igamba Ng'ombe sub-county, Tharaka-Nithi County, in Upper Eastern Kenya (Fig. 1). The study location is in the Upper Midland three (UM3) agroecological zone, on the eastern slopes of Mt. Kenya, and lies 1500m above sea level. The agroecological zone is predominantly a maize-growing area. The area receives annual rainfall between 1200 and 1400mm and a yearly average temperature of 20°C [22]. It experiences two rainfall seasons, the Long rains (LR) from March through to June and short rains (SR) from October through to December [22]. The soil type is predominantly *Humic* Nitisols, which are well-drained, very deep, dusky red to dark reddish-brown, friable clay with acidic topsoil, and moderate to high fertility.

Smallholder farming systems in the study area are highly heterogeneous [13]. Even within a single farm, the farm is diversified, with smallholders growing different crops. Therefore, to understand the contribution of farming systems to National Determined Contributions, there is a need to quantify the emissions from different cropping systems. This approach is referred to as whole-farm GHG quantification.

2.2. Cropping systems

The study area is predominantly smallholder, with small land parcels of 1.2ha with highly diversified cropping systems. Cropping systems in Chuka are mostly in small-scale farming for subsistence purposes. A typical farmer grows maize and beans as staple crops, coffee at the end of each farm. However, a majority of farmers have neglected it due to low coffee prices experienced in the recent past, and bananas mostly near the household as cash crops. Some farmers mix different crops in the same plot with fruit trees, such as mangos (agroforestry). Farm boundaries are marked by planted exotic trees such as *Grevillea Robusta* and Bluegum (*Eucalyptus sp*) woodlots.

2.3. Study set-up

In this study, we purposively selected two smallholder farms with typical diversified cropping systems. The main cropping systems considered for the selection of smallholder farms to be included in the study were i) sole maize, ii) maize-beans intercrop, ii) agroforestry, iv) banana and v) coffee. In both farms, banana cropping systems were planted near the homestead. Hence, they could benefit directly from kitchen-related refuse/waste. During farm selection, the key parameters for consideration were near homogeneity in inputs applied and alignment to the five cropping systems. Planting in both seasons was done at the same time on both farms. However, during the middle of the LR 2019 season, the farmer cleared the coffee cropping system, citing poor economic returns in farm one, but we continued determining the GHG fluxes. In each treatment, three static chambers were randomly installed (but closely for convenience during sampling) between the rows and within the rows.

2.4. Greenhouse gases concentration measurement

The greenhouse gas fluxes were measured using the circular vented static chambers technique. Round chambers with a radius of 0.2m and a height of 0.1m consisting of two parts (base and lid) were used, similar to Kibet et al. [23]. The bases were installed one week (23rd April 2019) before the first measurement and left intact throughout the experimental period (30th April 2019- 29th April 2020). The lid was equipped with a gas sampling port used during gas sampling and a vent to stabilise air pressure during gas deployment. Rubber tapes were used to close the joints during gas sampling to ensure an air-tight seal between the base and the lid. Soil GHG sampling campaigns were done following key farm operations like land preparation and fertilisation whenever it rained and fortnightly for two seasons, like in Pelster et al. [24] and Mairura et al. [12]. Gas was sampled per chamber using a 60mL syringe fitted with Luer locks at intervals of 0, 10, 20, and 30 min and transferred into 20mL pre-evacuated glass vials, ensuring over-pressurisation to avoid contamination from the external air. The gas vials were packed and transported to the laboratory for analysis.

2.5. Flux calculation and data quality and data assurance

Gases were analysed using gas chromatography (GC) fitted with a ^{63}Ni-electron capture detector (ECD) for N_2O and flame ionisation detector (FID) for CO_2 and CH_4 using N as carrier gas. Calibration was done using CO_2, CH_4, and N_2O standards, and their peak area and concentrations were applied to determine the sampled CO_2, CH_4, and N_2O. The GHG concentrations were converted to mass per volume using the ideal gas law and measured chamber volume, internal chamber air temperature, and atmospheric pressure as shown by Eq. (1). Fluxes were calculated using linear regression of gas concentrations versus chamber closure time, similar to Mairura et al. [12].

$$F = \frac{b \times Mw \times Vch \times 60 \times 10^6}{Ach \times Vm \times 10^9} \tag{1}$$

Where, F= flux rate (ug $m^{-2}\,n^{-1}$), Mw = molecular weight of component (g mol^{-1}), Vch = chamber volume (m^3), Ach = chamber area (m^2), Vm = correlated standard gas molar volume ($m^3 mol^{-1}$) and $Vm = 22.4 \times 10^{-3}$ $m^3 mol^{-1}$.

Data quality was validated using CO_2 concentrations, whereby if the coefficient of determination (R^2) of CO_2 was more than 90%, it was considered normal. However, if $R^2 < 0.90$, then the results were deemed contaminated and discarded.

2.6. Soil properties and meteorological data

We collected three soil samples (0–20cm depth) from each cropping system across the two farms at the beginning of LR 2019 and the end of the SR 19 season. The three soil samples from each cropping system were mixed in a zip-lock bag to make a composite sample. The soil samples were analysed for soil texture, total nitrogen, soil organic carbon, and pH at Mazingira Centre (ILRI-Nairobi, Kenya). The soil samples were oven-dried at 40°C for 72 h, ground using a ball mill (Retsch ball mill, Haan, Germany), and sieved through a 2mm aperture sieve. Grounded samples were used to determine C and N concentration using a C/N analyser (Thermal Scientific, Flash 2000 analyzer, Waltham, MA, USA). A glass probe pH metre determined soil pH at 1: 2, soil-to-water solution ratio (Crison Instruments, Barcelona, Spain). For bulk density, core rings with a 100 cm^3 vol (Eijkelkamp Agrisearch equipment, Giesbeek, The Netherlands) were used to collect undisturbed samples at each cropping system, oven-dried for 24 h at 105°C until a constant weight was obtained and the bulk density calculated. At each chamber, soil moisture was determined using the gravimetrical method, and temperature using a thermometer during gas sampling. The gravimetric results were then converted to the volumetric units (water-filled pores space) following Githongo et al. [18]. Precipitation data were collected using a manual rain gauge installed at Kangutu Primary School (S 37.6833°, E 0.3378°) adjacent to the two farms. Precipitation data was recorded daily at 09:00AM, and data was entered in an entry book. The data were extracted and managed in Excel during every gas sampling event.

2.7. Biomass measurement

During harvesting, a 2m x 2m sub-plot near each chamber was selected, and all the crops within the area were harvested. Both above and belowground biomass was harvested for food crops. Fresh weight for the plant components (grains, leaves, stems and roots) was determined using an electronic balance. A sub-sample for each plant component (leaves, stem, root, and grain) was weighed, air-dried for three weeks, re-weighed, and all components determined again. The grain weight was reported at 12.5% moisture content, similar to Ngetich et al. [10]. During the LR 2019, the biomass subsamples (grain, leaves, stems, and roots) were analysed for carbon and nitrogen content. The sub-samples were oven-dried at 60°C for 48 h in the laboratory. The sub-samples were ground using a hammer mill (IKA mills, MF 10.2, Willington, NC, USA) and analysed in a C/N analyser to determine the C—N concentration.

2.8. Greenhouse gas yield-scaled emissions

The greenhouse yields scaled emissions (YSE) were calculated by

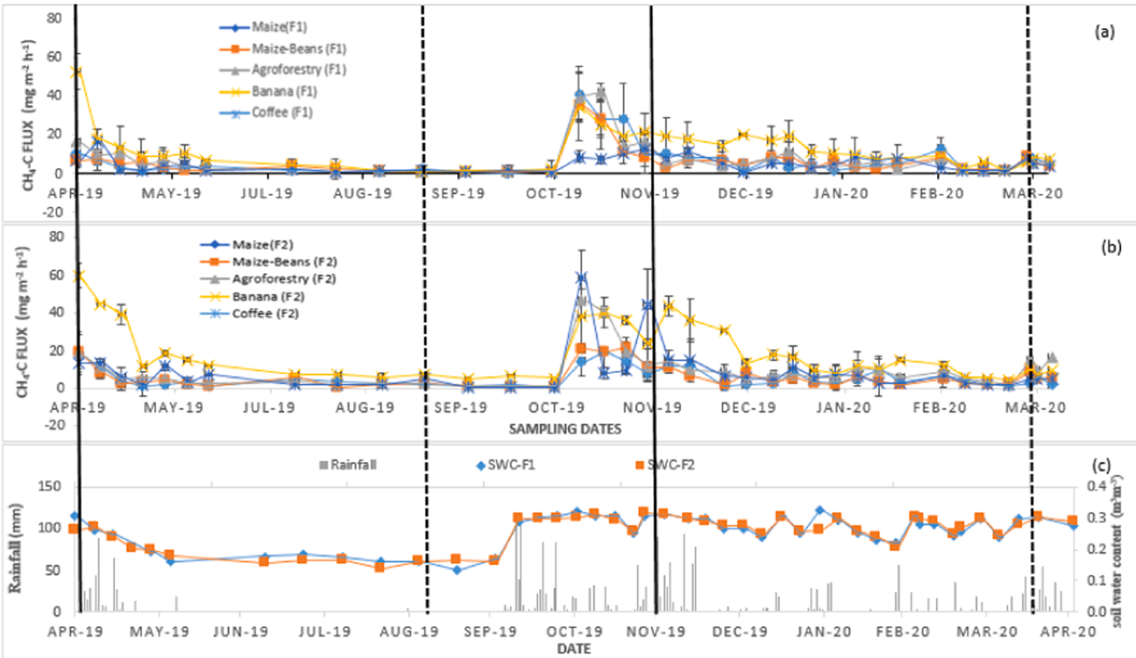

Fig. 2. Soil Methane Farm 1 (a), Farm 2 (b) and precipitation and soil water content (c) from different land utilisation types in Upper Eastern Kenya.

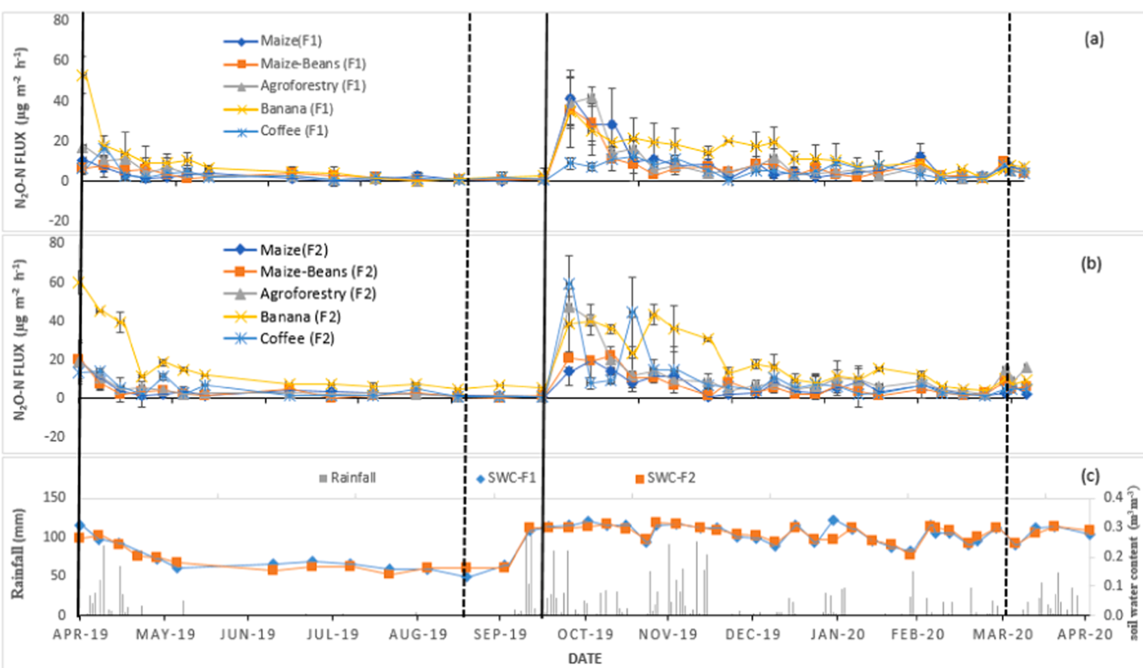

Fig. 3. Soil nitrous oxide Farm 1 (a), Farm 2 (b) and precipitation and soil water content (c) from different land utilisation types in Upper Eastern Kenya.

dividing cumulative annual N_2O fluxes with grain yields following Githogo et al. [18] and Musafiri et al. [1] as described in Eq. (2).

$$N_2O\ YSE = \frac{Soil\ N_2O\ fluxes}{Grain\ yield} \tag{2}$$

Where $N_2O\ YSE$ is soil nitrous oxide yield-scaled emissions (g N_2O—N kg^{-1} grain yield), *Soil N_2O fluxes* is cumulative annual soil nitrous oxide fluxes (g N_2O ha^{-1} yr^{-1}), and grain yields are annual grain yields (kg ha^{-1} yr^{-1}).

2.9. *Statistical analysis*

The data was tested for normality in distribution using the Shapiro–Wilk test. The soil N_2O fluxes were not normally distributed. The data were log-transformed following Musafiri et al. (2020). A linear mixed model was implemented in SAS 9.4 software to determine the influence of fixed factors treatments and random factors block and seasons on measured parameters. Soil GHG fluxes (CO_2, CH_4 and N_2O). Means separation was done using Tukey's Honest Significant test at $p<0.05$. The study utilised Pearson's correlation to test the association between soil GHG fluxes (CO_2, CH_4 and N_2O) and soil temperature, moisture,

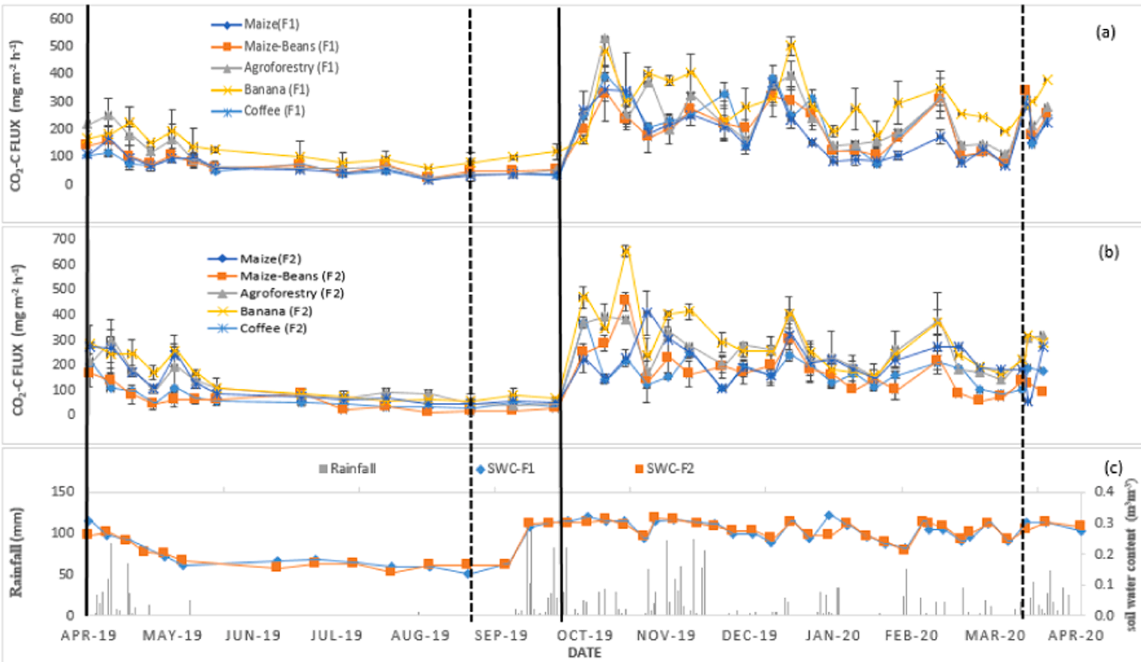

Fig. 4. Soil carbon dioxide Farm 1 (a), Farm 2 (b) and precipitation and soil water content (c) from different land utilisation types in Upper Eastern Kenya.

Table 1
Soil properties for 0 to 20cm depth sampled during the beginning and end line for both season.

		Farm 1					Farm 2				
Samples	Cropping Systems	BD g/cm^{-3}	pH	Total N (%)	SOC (%)	C/N ratio	BD g/cm^{-3}	pH	Total N (%)	SOC (%)	C/N ratio
Baseline	Maize	1.01	5.9	0.18	2.1	11.67	0.93	5.8	0.16	1.82	11.38
	Maize-Bean	1.02	5.7	0.22	2.46	11.18	0.97	5.5	0.17	1.8	10.59
	Agroforestry	1.05	5.4	0.2	2.28	11.40	0.94	5.3	0.17	1.93	11.35
	Banana	1.01	6.8	0.26	2.75	10.58	0.87	5.8	0.18	2.07	11.50
	Coffee	1.00	6.6	0.18	2.02	11.22	0.93	6.1	0.15	1.73	11.53
End of Experiment	Maize	1.15	5.8	0.21	2.37	11.29	1.06	5.8	0.22	2.43	11.05
	Maize-Bean	1.07	5.6	0.25	2.86	11.44	1.09	6.1	0.17	1.81	10.65
	Agroforestry	1.09	5.3	0.2	2.24	11.20	1.00	6.2	0.19	2.11	11.11
	Banana	1.08	6.6	0.28	3.06	10.93	0.95	6.1	0.18	1.89	10.50
	Coffee	1.04	5.6	0.2	2.2	11.00	0.89	5.8	0.18	2.05	11.39

BD is bulk density; SOC is Soil organic carbon; C/N is Carbon/Nitrogen; N is nitrogen. Soil texture 70% clay, 16% silt and 14% sand Kiboi et al. [25].

carbon, nitrogen, C: N ratio and bulk density.

3. Results

3.1. Meteorological and soil characteristics

The cumulative annual precipitation was 2027mm (Figs. 2–4c). The distribution of the precipitation was 460mm during the LR 2019 season and 1567 for the SR 2019 season. The rainfall distribution during the LR season was similar to the long term of 420 to 750 [22]. However, the SR season was higher than the long-term rainfall amounts of 250 to 450mm [22]. The mean soil moisture across the cropping systems was maize (0.24 m^3 m^{-3}), maize beans (0.26 m^3 m^{-3}), agroforestry (0.25 m^3 m^{-3}), and banana (0.27 m^3 m^{-3}), and coffee (0.26 m^3 m^{-3}) in farm 1. In farm 2, the soil moisture content was maize (0.25g^{-1} soil), maize-beans (0.25 m^3 m^{-3}), agroforestry (0.24 m^3 m^{-3}), banana (0.26 m^3 m^{-3}) and coffee (0.27 m^3 m^{-3}) Figs. 2–4c).

At the start of the experiment in farm one, bulk density ranged from 1.00 to 1.05g/cm^{-3}, soil pH from 5.38 to 6.75, total nitrogen from 0.18 to 0.26%, total soil organic carbon (SOC) from 2.02 to 2.75%, and C/N ratio from 10.58 to 11.67 across the cropping systems (Table 1). In farm two, bulk density ranged from 0.87 to 0.97g cm^{-3}, soil pH ranged from 5.26 to 6.14, total nitrogen from 0.15 to 0.18%, total SOC from 1.73 to 2.07%, and C/N ratio from 10.59 to 11.53 across the cropping systems (Table 1). At the end of the experiment, farm one had a bulk density ranging from 1.04 to 1.15g cm^{-3}, soil pH from 5.56 to 6.63, total nitrogen from 0.2 to 0.28%, total SOC from 2.2 to 3.06%, and C/N ratio from 10.93 to 11.44. In farm two, bulk density ranged from 0.89 to 1.09g/cm^{-3}, soil pH from 5.75 to 6.2, total nitrogen from 0.17 to 0.22%, total SOC from 1.81 to 2.43%, and a C/N ratio from 10.50 to 11.39 across the cropping systems (Table 1).

3.2. The GHG fluxes

Throughout the study period, soil in all the cropping systems predominantly acted as a CH_4 sink (Fig. 2a, b). In farm 1, The CH_4 fluxes in farm one differed significantly ($p=0.0002$) during LR 19 and ranged between −0.72 and −0.32kg CH_4—C ha^{-1}. During the SR, the CH_4 varied greatly ($p=0.0008$), ranging between −0.65 and −0.42kg CH_4—C ha^{-1} (Table 2). We observed a significant ($p<0.0011$) difference in annual CH_4 fluxes where the variation was between −1.34 and −0.81kg CH_4—C ha^{-1}yr^{-1}. Additionally, the seasonal interaction was significant ($p<0.0015$). In farm 2, the methane uptake significantly ($p<0.05$) varied across the cropping systems. During the LR 209, the methane uptake

Table 2
Seasonal and annual cumulative greenhouse gas (GHG) fluxes for two cropping seasons between April 2019 and April 2020 for different cropping systems in Upper Eastern Kenya.

Season[1]	Treatment	Farm 1			Farm 2		
		CH_4 (kg CH_4—C ha^{-1})	N_2O (kg N_2O—N ha^{-1})	CO_2 (kg CO_2—C ha^{-1})	CH_4 (kg CH_4—C ha^{-1})	N_2O (kg N_2O—N ha^{-1})	CO_2 (kg CO_2—C ha^{-1})
LR 19	Maize	−0.39a[2]±0.04	0.04c±0.01	1844b±83	−0.51b±0.02	0.11b±0.01	1764bc±64
	Maize-Bean	−0.69b±0.04	0.08b±0.01	2394ab±82	−0.47b±0.04	0.11b±0.01	3510a±316
	Agroforestry	−0.72b±0.02	0.04c±0.01	1992ab±120	−0.44ab±0.03	0.08b±0.01	1668c±67
	Banana	−0.43a±0.01	0.13a±0.01	2503a±191	−0.35a±0.02	0.48a±0.02	3748a±426
	Coffee	−0.32a±0.03	0.05c±0.01	1900ab±36	−0.49b±0.01	0.08b±0.01	2818ab±97
	P *value*	*0.0002*	<0.0001	*0.04*	*0.0044*	<0.0001	0.0011
SR 19	Maize	−0.42a±0.01	0.28b±0.01	6659ab±190	−0.52bc±0.03	0.43b±0.01	5438cd±133
	Maize-Bean	−0.65b±0.02	0.32a±0.02	7220a±150	−0.57bc±0.03	0.23c±0.01	7522b±451
	Agroforestry	−0.62b±0.03	0.26b±0.01	6298ab±325	−0.35a±0.05	0.40b±0.02	4281d±402
	Banana	−0.43a±0.03	0.32a±0.03	6825b±599	−0.42ab±0.01	0.75a±0.03	9210a±191
	Coffee	−0.6b9±0.05	0.27b±0.01	5536b±171	−0.60c±0.04	0.39b±0.02	5782c±173
	P *value*	*0.0008*	*0.03*	*0.02*	*0.0108*	<0.0001	<0.0001
Annual	Maize	−0.81a±0.05	0.33bc±0.01	8504ab±251	−1.03b±0.05	0.54b±0.01	7202cd±194
	Maize-Bean	−1.34b±0.05	0.40ab±0.01	9614a±221	−1.04b±0.07	0.34c±0.01	11032b±767
	Agroforestry	−1.34b±0.03	0.30c±0.02	8290ab±441	−0.79a±0.06	0.48b±0.03	5949d±400
	Banana	−0.87a±0.04	0.45a±0.03	9328a±692	−0.77a±0.03	1.23a±0.01	12958a±439
	Coffee	−1.01a±0.08	0.32bc±0.01	7436b±199	−1.09b±0.03	0.48b±0.03	8599b±269
	P Value	*0.0011*	*0.005*	*0.04*	*0.0035*	<0.0001	<0.0001
	p value[3]	0.0015	<0.0001	<0.0001	0.003	<0.0001	<0.008
	Interaction[4]	<0.0001	0.1083	<0.0001	<0.0001	0.09	<0.0001

[1] Season LR 2019 indicates the long rain 2019 season, SR 2019 indicates the short rain 2019 season.
[2] Soil GHG emissions with the same letter are not significantly different at p=0.05.
[4] Seasonal p-value
[5] Interaction between season and different cropping systems.

ranged from −0.51 and −0.35kg CH_4—C ha^{-1}. Methane uptake ranged from −0.60 and −0.35kg CH_4—C ha^{-1} during the SR 2019. The cumulative annual methane uptake ranged from −1.09 and −0.77kg CH_4—C ha^{-1} yr^{-1}. The seasonal p-value of the CH_4 uptake was significant at p=0.0015 and $p < 0.0001$ in farms one and two.

The N_2O fluxes ranged between 0.22μg N m^2 h^{-1} (23rd July 2019) and 60.12μg N m^2 h^{-1} (30th April 2019) during the study period (Fig. 3a, b). We observed low N_2O from May to September 2019. However, the daily N_2O fluxes peaked in October 2019 following the onset of rainfall on 10th October, reaching a maximum of 59.20μg N m^2 h^{-1}. Cumulative seasonal N_2O differed significantly ($p < 0.0001$) across cropping systems during LR19 in farm one. The N_2O fluxes ranged from 0.04 to 0.13kg N_2O—N ha^{-1} and 0.08 to 0.48kg N_2O—N ha^{-1} in farm one and two, respectively. We observed a significant (*P=0.03, P=0.01*) difference during SR 2019 in N_2O fluxes ranging from 0.26 to 0.32kg N_2O—N $ha^{-1}yr^{-1}$ in farm one and 0.23 and 0.75kg N_2O—N ha^{-1} in farm two. In farms one and two, the annual N2O fluxes differed significantly (p=0.005, p<0.0001). The range was between 0.30 and 0.45kg N_2O—N $ha^{-1}yr^{-1}$ in the farm and 0.34 and 1.23kg N_2O—N $ha^{-1}yr^{-1}$ in farms one and two, respectively. The seasonal value was significant at p<0.0001 in the two farms.

Soil CO_2 emission varied across cropping systems during the study period (Fig. 3a, b). The daily CO_2 fluxes ranged from 10.10 to 680.24mg C m^{-2} h^{-1} across cropping systems and farms. We observed peak CO_2 fluxes at the onset of rainfall (30th April 2019 and 7th May 2019) across all the cropping systems, ranging from 108 to 256 and 135 to 274mg C

Table 3
Crop production during the two cropping seasons in the Upper Eastern Kenya.

Season[a]	Cropping	Farm 1					Farm 2				
	System	Grain	Stem	Root	Leave	Total	Grain	Stem	Root	Leave	Total
LR 2019[b]	Maize	0	0.02	0.03	0.01	0.06	0.05	0.02	0.02	0.03	0.12
	Maize-Beans	0.06	0.01	0.03	0.03	0.13	0	0.01	0.01	0.02	0.04
	Agroforestry	0.04	0.01	0.03	0.02	0.08	0	0.01	0.01	0.03	0.05
	Banana	-[f]	–	–	–	–	–	–	–	–	–
	Coffee	–	–	–	–	–	–	–	–	–	–
SR 2019[b]	Maize	3.38	0.29	0.03	0.25	3.95	2.37	0.18	0.02	0.2	2.77
	Maize-Beans	2.65	0.22	0.03	0.25	3.15	3.02	0.16	0.01	0.29	3.48
	Agroforestry	2.88	0.06	0.03	0.26	3.23	1.84	0.31	0.09	0.24	2.48
	Banana[c]	–	–	–	–	–	–	–	–	–	–
	Coffee[d]		–	–	–		–	–	–	–	–
SR 2019[e]	Maize	–	–	–	–	–	–	–	–	–	–
	Maize-Beans	0.31	0.21	0.03	0.02	0.57	0.44	0.12	0.02	0.11	0.69
	Agroforestry	0.37	0.31	0.02	0.14	0.7	0.76	0.18	0.01	0.16	1.11
	Banana	–	–	–	–	–	–	–	–	–	–
	Coffee	–	–	–	–	–	–	–	–	–	–

[a] Season LR 2019 is the long rain 2019 season, SR 2019 is the short rain 2019 season.
[b] Maize harvest during the season except for the coffee.
[c] Banana yields not harvested.
[d] Reported are the coffee berry yields.
[e] Reported are the beans yields (during the long rain 2019 season, we experienced total crop failure for the beans).
[f] The sign indicates that the crop was no harvested.

m^{-2} h^{-1} in farms one and two, respectively. Additionally, from 10th October 2019, CO_2 fluxes in all cropping systems peaked in the first four weeks. Conversely, we observed lower emissions<163mg C m^2 $h^{-1)}$ during the dry period from June to the first week of October (Fig. 4a, b). However, during this period, mean CO_2 fluxes in banana cropping systems and agroforestry were higher than in other cropping systems.

We observed a significant (P<0.0001) difference in cumulative CO_2 fluxes during LR 2019 in farms one and two. The variation in the CO_2 emissions across the cropping systems ranged from 1844kg CO_2—C ha^{-1} under maize monocrop to 2503kg CO_2—C ha^{-1} under banana and 1668kg CO_2—C ha^{-1} under agroforestry to 3748 under banana in farm one and two respectively. During SR, the CO_2 emissions varied significantly across the cropping seasons (p=**0.02**, p<0001) in farms one and two, respectively. The range of variation was 5536kg CO_2—C ha^{-1} under coffee to 7220 CO_2—C ha^{-1} under maize beans in farm one. The CO_2 emissions in farm two ranged from 4281kg CO_2—C ha^{-1} under agroforestry to 9210kg CO_2—C ha^{-1} in the banana cropping system. The annual CO_2 fluxes differed significantly (p=0.04, p<0.0001) in farms one and two, respectively. The range of CO_2 fluxes in farm one was 8504 to 9614kg CO_2—C $ha^{-1}yr^{-1}$, while the range in farm two was from 5949 to 12,958kg CO_2—C $ha^{-1}yr^{-1}$.

3.3. Crop production

In farm one, during the LR 2019 we experienced crop failure (Table 3) because of limited rainfall amounts. The grains of beans crop and maize on the maize monocrop cropping system totally failed (Table 3). During the LR 2019, the crop yields ranged from 0.04 Mg ha^{-1} under agroforestry and 0.06 t ha^{-1} under maize beans. During the SR 2019, the maize grain yields ranged from 2.65 Mg ha^{-1} under maize beans to 3.38 Mg ha^{-1} maize monocrop. During the SR 2019, the bean grain yields were harvested in the two cropping systems maize-beans (0.31 Mg ha^{-1}) and agroforestry (0.37 Mg ha^{-1}).

In farm two, maize grain yields were 0.05 Mg ha^{-1} under maize monocrop, and the crop failed in the maize beans and agroforestry during the LR 2019 (Table 3). We experienced total crop failure for beans during the LR 2019. In the SR 2019, maize grain yields ranged from 0.16 Mg ha^{-1} under maize beans to 0.31 Mg ha^{-1} under agroforestry. The bean grain yields ranged from 0.44 Mg ha^{-1} to 0.76 Mg ha^{-1} during the SR 2019.

3.4. Yield-scaled emissions

The maize yield scaled emissions ranged from 0.10g kg^{-1} Maize to 0.15g kg^{-1} maize in farm type one. The beans yield scaled emissions ranged from 0.82g kg^{-1} beans to 1.30g kg^{-1} beans. In the farm, the maize grain yields ranged from 0.11g kg^{-1} to 0.26g kg^{-1}, and the beans N_2O yield scaled emissions ranged from 0.68g kg^{-1} beans to 0.78g kg^{-1} beans.

3.5. Correlation of greenhouse gas fluxes and soil properties

Soil CH_4 uptake was negatively correlated with soil bulk density and positively correlated with soil moisture (Table 5). Soil N_2O fluxes were positively correlated with soil moisture and negatively correlated with soil bulk density and nitrogen content. Soil carbon dioxide emissions were positively correlated with soil moisture and organic carbon content.

4. Discussion

4.1. Soil greenhouse gas fluxes under different cropping systems

Smallholder farms emit a limited amount of soil GHG fluxes [20,24,26]. We observed uptake for CH_4 emissions consistent with other studies conducted in SSA, which also reported that upland soils predominantly uptake CH_4 [1,24]. The CH_4 fluxes were < −1.39kg CH_4—C $ha^{-1}yr^{-1}$ across all cropping systems. We observed a slight increase in CH_4 fluxes at the onset of the first rain in all cropping systems. This might have resulted from increased water content in soil pores, limiting oxygen availability and favouring anaerobic conditions, thus lowering the CH_4 uptake [24].

The low uptake of CH_4 can be attributed to gas diffusivity. Conversely, the CH_4 uptake is high during the dry period, possibly due to high gas diffusivity, which favours aerobic conditions. The most increased cumulative CH_4 uptake in maize-bean and agroforestry could have been attributed to different levels of N concentration in soils that ultimately inhibit methanotrophic activities in soil compartments [26]. The significant difference between banana and maize-beans intercrop cropping systems could be attributed to rooting systems. In banana cropping, deep rooting allows water absorption, creating a wet microsite that encourages CH_4 production compared to maize cropping, which only becomes activated during rainy systems. Through the continuous accumulation of leaf litter, agroforestry cropping systems might have also contributed to significant changes in CH_4 uptake. As observed in farm two, the low uptake in banana cropping systems could have been due to increased methanogenic archaea, reducing the CH_4 uptake.

Further, dropping plant litter in bananas may serve as mulching on the ground, limiting evaporation and thus creating a moist environment for CH_4 emission [27]. The seasonal interaction between the cropping systems reflects the influence of precipitation on the CH_4 fluxes [26]. In addition, the variability in soil bulk density and variation in soil pH (Table 3) could have contributed to the seasonal difference in CH_4 fluxes.

The peak cumulative soil N_2O fluxes following precipitation were consistent with previous studies in Kenya [11,18]. The peak N_2O fluxes could be attributed to the birch effect [1]. The cumulative soil N_2O fluxes aligned with previous studies in SSA [18,24]. There were high N_2O fluxes in the banana cropping systems across the seasons. This can be explained by the inclusion of manure around the base of crops, which increases the N levels in soils, thus favouring a heterogeneous phylogenetic group of microbes that increases denitrification [3]. Banana roots boost the soil's root respiration, and optimal moisture content in soils favours denitrification. The addition of nitrogen to grounds increases soil respiration and net ecosystem exchange, provided carbon is not limiting. Therefore, there was a general increase in N_2O fluxes after fertilisation, coinciding with rainfall events. Musaifiri et al. [1] reported the same observation, where there was an increase in N_2O upon the addition of fertilisers and rainfall events. There was a mixed observation in N_2O fluxes across the cropping systems in different seasons. Maize and coffee had the lowest emissions compared to all cropping systems. This could have been attributed to low nutrient availability, continuous cropping coupled with low residue availability due to completion by humans and animals for fibre [11]. Emissions of N_2O only occur when microbial N immobilisation and plant N requirement are balanced [28].

The cumulative soil CO_2 emissions were in the range of those observed in previous studies in Kenya [13,1,24]. We observed high soil CO_2 emissions from different cropping systems that could be attributed to the high soil organic carbon in the study (Table 1). The soil CO_2 emissions reported in the current study resulted from root respiration and decomposition. The study underscored the need to study the total CO_2 budget from respiration and photosynthesis.

4.2. Maize yields

The crop failure observed in the current study was consistent with previous studies in Upper Eastern Kenya Githongo et al. [18] and could be attributed to low precipitation. The mean maize grain yields were lower than those reported in previous studies in the study area [11,1,10,18]. The maize crop was mixed with the beans, and the yields were low. The low crop yield could be attributed to low soil fertility and precipitation.

Table 4
Yield scaled emissions under different cropping systems in Upper Eastern Kenya.

Cropping System	Farm 1				Farm 2			
	Annual grain yields (kg ha^{-1} yr^{-1})		YSE[1] (g kg^{-1} grain)		Total grain yields (kg ha^{-1} yr^{-1})		YSE (g kg^{-1} grain)	
System	Maize	beans	Maize	Beans	Maize	beans	Maize	Beans
Maize	3380		0.10	–	2420	–	0.22	
Maize-Beans	2710	310	0.15	1.30	3020	440	0.11	0.78
Agroforestry	2920	370	0.10	0.82	1840	760	0.26	0.63
Banana	–	–	–	–	–	–	–	–
Coffee	–	–	–	–	–	–	–	–

[1] N_2O Yield scaled emissions.

Table 5
Correlation between soil greenhouse gas fluxes and soil properties.

Parameter	Methane	Nitrous oxide	Carbon dioxide
Soil moisture	0.58**	0.61***	0.54**
Soil pH	0.19	−0.05	0.01
Soil bulk density	−0.58**	−0.73***	−0.26
SOC	−0.13	−0.08	0.67***
Nitrogen	−0.12	−0.51**	0.17

Rho values, ***$p<0.01$ and **$p<0.05$, SOC soil organic carbon.

4.3. Yield-scaled emissions

The yield-scaled emissions were consistent with those of the previous studies in Upper Eastern Kenya [1,11,18]. The low N_2O yield scaled emissions in the study area could be attributed to the reduced N_2O emissions.

5. Conclusion

The study investigated the influence of selected cropping systems on greenhouse gas emissions. As per our hypothesis, soil GHG fluxes (CH_4, N_2O and CO_2) differed across the cropping systems. The soil acted as the CH_4 sink in all cropping systems. Greenhouse gas emissions were also found to be affected by rainfall availability, which increases soil water content. Banana cropping systems emitted the highest soil CO_2 compared to other cropping systems. Crop production was significantly affected by the availability of rainfall, where LR 19 registered a lower yield than SR 19 due to precipitation differences. Fertiliser application to the cropping systems determines GHG emissions. However, smallholder farmers in SSA apply little inorganic fertiliser to their farms. Only a few treatments received inorganic fertiliser, especially in the first season, while in the second season, almost all treatments received less than 25kg N ha^{-1}yr^{-1}. This may have been attributed to lower GHG emissions, given that soil in the study area has low soil fertility. Applying recommended nutrients to soil helps increase yield production while reducing GHG emissions. Using recommended soil nutrients in consideration of crop requirements should be a major issue for farmers. Given the low emissions across cropping systems, smallholders could act as a nature-based solution for lowering agricultural emissions.

NBS impacts and implications

- We found that smallholder cropping systems produce a limited amount of greenhouse gases, hence environmentally friendly.
- Greenhouse gas emissions differed across smallholder cropping systems.
- Smallholder cropping systems contribute to climate change adaptation and mitigation.
- Soil physicochemical properties influenced soil greenhouse gas emissions.

Smallholder cropping systems can significantly contribute to enhancing food security as well as climate change adaptation and mitigation through reduced greenhouse gas emissions. The agroforestry cropping system, which has the potential to enhance biodiversity protection, significantly lowered greenhouse gas emissions while producing both maize and beans, thus acting as nature-based solutions. The smallholder cropping systems could also reduce malnutrition leading to enhanced human well-being. Therefore, smallholders cropping systems such as agroforestry are nature-based solutions for climate change adaptation and mitigation (Table 4).

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Availability of data and materials

All the data used is presented in the main paper.

CRediT authorship contribution statement

Shaankua E. Lemarpe: Conceptualization, Writing – original draft. **Collins M. Musafiri:** Conceptualization, Methodology, Writing – original draft, Data curation. **Milka N. Kiboi:** Validation, Writing – review & editing, Supervision. **Onesmus K. Ng'etich:** Validation, Supervision, Visualization, Investigation. **Joseph M. Macharia:** Data curation, Visualization, Investigation. **Chris A. Shisanya:** Writing – review & editing. **Esphorn Kibet:** Data curation, Writing – review & editing. **Abdirahman Zeila:** Supervision, Writing – review & editing. **Paul Mutuo:** Data curation. **Felix K. Ngetich:** Writing – original draft, Supervision, Visualization, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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