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Carbon footprint of smallholder rain-fed sorghum cropping systems of Kenya: A typology-based approach

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ABSTRACT

Agricultural ecosystems are the main sources of soil-atmosphere exchange (methane-CH_4, Carbon dioxide-CO_2 and Nitrous oxide -N_2O) in sub-Saharan African countries, including Kenya. To feed the ever-growing population, there is a need to identify agricultural management practices to increase food production while reducing GHG emissions for climate change mitigation and adaptation. This study aimed to estimate the GHG balance at the farm scale and identify environmental hotspots and mitigation opportunities among smallholder sorghum farms in Western Kenya. The study hypothesized that different intensification levels influenced the GHG balance. The study collected data from 300 smallholder farms in western Kenya. The principal component analysis and hierarchical clustering analysis were used for farm typologies construction. Five farm types were constructed that ranged from no or minimal external inputs and highly intensified, small to large, and low to highly endowed in tropical livestock units. The Cool Farm Tool Excel program model was used to estimate GHG balances. that the sorghum cropping systems were net sinks of soil GHGs. The GHG balance, carbon footprint, and monetary footprint significantly varied across the farm types at $p = 0.025$, $p = 0.018$, and $p = 0.004$, respectively. The GHG balance ranged from – 818.76 kg CO2 eq. ha^{-1} in manure-intensive and low fertilizer-intensity small farms to 174.29 kg CO_2 eq. ha^{-1} in fertilizer-intensive and moderate manure application rates on small farms. Fertilizer production and direct and indirect emissions (fertilizer application) were the environmental hotspots accounting for 63 and 30 % of the GHG emissions. The carbon and monetary footprints ranged from -1.29 to 0.45 kg CO_2 eq. kg sorghum $^{-1}$ and -2.02 to 0.13 kg CO_2 eq. US$$^{-1}$ generated, respectively. The study established that sorghum cropping systems in Kenya produced limited greenhouse gas emissions.

Introduction

The global greenhouse gas (GHG) concentrations [carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)] have significantly increased over the last decades (IPCC, 2007, 2014; Ntinyari and Gweyi-Onyango, 2021). The GHGs CO_2, CH_4, and N_2O contribute approximately 60 %, 20 %, and 6 % of global warming, respectively (Dalal and Allen, 2008). Agriculture contributes 14–17 % of anthropogenic GHG emissions (Ciais et al., 2011; Paul et al., 2017). Agriculture has been identified as an essential entry point in GHG emissions mitigation (Ogle et al., 2014; Solinas et al., 2019; Leahy et al., 2020; Sapkota et al., 2021; Solinas et al., 2021). Few studies have quantified GHG emissions in most developing countries, including Kenya (Rosenstock et al., 2016; Pelster et al., 2017). Quantification of greenhouse gases from smallholder farming systems is accentuated. Direct quantifying agricultural GHG fluxes to inform the national and regional GHG budget is expensive and impractical (Giltrap et al., 2010; Musafiri et al., 2021) for such countries dominated by smallholder farming systems. Moreover, the smallholder farming systems are highly heterogeneous (Alvarez et al., 2014; Kamau et al., 2018; Musafiri et al., 2020a). Therefore, constructing farm typologies and using GHG emissions estimation approaches could be plausible for identifying GHG emissions

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hotspots and mitigation options.

Several tools, including Cool Farm Tool (CFT), EX-ACT, and Climate Change, Agriculture, Food Security Mitigation Options Tool (CCAFS-MOT), have been developed, tested, and validated for estimating GHG balance in tropical conditions. The GHG tools are designed to estimate global GHG emissions with minimal data requirements (Lata et al., 2020). The CFT (Hillier et al., 2011) is an open-source spreadsheet program that estimates GHG emissions from different input levels and management practices. Therefore, CFT combines other empirical models and uses them to calculate GHG emissions as carbon dioxide equivalents (Hillier et al., 2011). The CFT model uses empirical equations and the IPCC Tier 1 and 2 approaches. The CFT has been used to quantify GHG balance across different systems in Africa, including from smallholder farms in Western Kenya (Seebauer 2014), potato cropping systems in Zimbabwe (Svubure et al., 2018), crop-livestock systems in Central Kenya (Ortiz-Gonzalo et al., 2017) and from cacao production in the Republic of Côte d'Ivoire (Vervuurt et al., 2022). We thus used the CFT to estimate GHG balance across the different farm types in Western Kenya.

Climate change is one of the main challenges facing smallholder farming systems in African countries, including Kenya (Musafiri et al., 2020a; Mairura et al., 2022). It exacerbates the hurdle to feeding the ever-growing population projected to double by 2050 from the current 1.3 billion persons in African countries while mitigating and adapting to climate change. Ortiz-Gonzalo et al. (2017) suggested that to feed the growing population, there is a need to shift from land expansion to intensification. Growing climate-smart crops such as sorghum provides novel opportunities to enhance food security (Mwadalu and Mwangi, 2013; Ogeto et al., 2013) and tackle adverse climate change effects. Soil fertility management practices, including animal manure, inorganic fertilizer, animal manure and inorganic fertilizer integration, and mulching, could be considered as options for counteracting the vagaries of climate change (Musafiri et al., 2022a,b). However, the application rates (amounts) among smallholder farming systems are low (Waithaka et al., 2007; Tittonell et al., 2008; Musafiri et al., 2020a; Mairura et al., 2022). Given the differences in the level of intensification among smallholder farms, the smallholders' sorghum cropping systems are highly heterogeneous. Constructing farm typologies is an essential strategy to group the smallholder sorghum cropping systems into homogenous farm types. The homogenous farm types could aid in the identification of GHG hotspots and mitigation options.

In Western Kenya, sorghum is grown by approximately 80 % of farming households (MoALF, 2016). Though sorghum farming is mainly subsistence, there are concerted efforts by different organizations such as One Acre Fund, Cereals Growers Association (CGA), and Farm to Market Alliance (FtMA) to commercialize sorghum farming (MoALF, 2016; CGIAR, 2021). The commercialization of sorghum productivity encourages increased use of soil amendments such as mineral and organic inputs. Though the external inputs lead to increased sorghum yields, they come with additional costs of GHG emissions, thus increasing climate variability. Climate disturbance due to the increased use of soil amendments could threaten food security and smallholders' livelihoods. To enhance greener production, sustainable utilization of soil amendments is essential. The GHG balances under different intensification levels will be necessary to inform potential GHG mitigation options in sorghum cropping systems.

Given that direct quantification of GHG fluxes to inform the national and regional budgets is expensive, previous studies have used a modeling approach to quantify the carbon footprint (CFT) to assess the impact of management practices on climate change (Rakotovao et al., 2017; Ortiz-Gonzalo et al., 2017). The CFT has been used to evaluate the GHG balance at the farm level (Farm-gate), as influenced by different agricultural management activities (Zhang et al., 2017; R. Chen et al., 2020). Using the CFT methodology, agriculture has been assessed for GHG mitigation in different management practices (Rakotovao et al., 2017; Huang et al., 2017). Documentation of Nationally Determined Contributions (NDCs) of GHG emissions is essential in meeting Kenya's obligation to the United Nations Framework Convention on Climate Change (UNFCCC) and the 2015 Paris Agreement on climate change. Carbon footprint (CFP) estimation could be used to report the GHG budget. This study assessed the CFT of sorghum production in Western Kenya to improve GHG reporting from climate-resilient crops.

There is limited information on the influence of intensification levels on farm-scale GHG balances in sorghum cropping systems of Western Kenya. This study aimed to estimate the GHG balance of sorghum cropping systems under different soil input intensification levels (no external inputs to highly intensified systems) in Western Kenya. The study was based on the hypothesis that farm-level GHG balances vary across different intensification levels defined as farm types. Secondly, the study identified the environmental GHG emissions hotspots by assessing the contributions of various components to the GHG balance. The analysis was implemented using CFT methodology the assess the potential different intensification levels on climate change mitigation and crop productivity.

Methodology

Study area description

We implemented the study among smallholder sorghum farmers in Alego-Usonga and Ugenya sub-counties, Siaya County, Western Kenya (Fig. 1).

Alego-Usonga and Ugenya sub-counties cover 599 km^2 and 324 km^2 and have a population of 224,343 and 134,354, respectively (Kenya National Bureau of Statistics (KNBS), 2019). The population density is 375 and 415 persons per km^{-2} for Alego-Usonga and Ugenya, respectively. The sub-counties lie at an altitudinal range of 1140 and 1500 m above sea level in Western Kenya. The two sub-counties experience similar climatic conditions varying from semi-humid to semi-arid and are located within six agroecological zones; lower midland (LM 1–5) and upper midland (UM1) (Jaetzold et al., 2010). The sites receive bimodal precipitation with the long rain (LR) season experienced between March and June and the short rain season between September and December. The annual precipitation amounts range from 800 to 2200 mm. The long-term temperature ranges from 20.9 to 22.3 °C. The primary soil type is *Ferrasol*, with moderate to low soil fertility.

Smallholders' cropping systems

The main economic activities in Alego-Usonga and Ugenya sub-counties are rainfed agriculture, fishing, and livestock keeping. However, agricultural production is negatively affected by low soil fertility and climate change, including insufficient and erratic rainfall in the study area. The main climate-smart crops cultivated by the smallholders' include; sorghum (Sorghum bicolor), cassava (*Manihot esculenta*), green gram (*Vigna radiata*), cowpea (*Vigna unguiculata*), groundnuts (*Arachis hypogaea*), millet (Panicum miliaceum) and chickpea (*Cicer arietinum)*. Other crops grown in the sub-counties include maize (*Zea mays*), beans (*Phaseolus vulgaris*), and sugarcane (*Saccharum officinarum*). Sorghum, a drought-resistance crop, is the widely grown climate-smart crop by approximately 80 % of the farmers in the County (The Kenya Ministry of Agriculture, Livestock, and Fisheries (MoALF), 2016). The crop is grown under rain-fed systems. To enhance productivity, the smallholders practice different soil fertility management and climate change adaptation mechanisms, including the use of animal manure, inorganic fertilizer, integration of animal manure and inorganic fertilizer, and minimum tillage. However, most sorghum growing areas are affected by waterlogging, impeding farm operations, including ploughing, planting, weeding, and harvesting. Animal manure (cattle, sheep, goat, and poultry) is acquired from domestic livestock or nearby households but of low quality and quantity. Fertilizers are unaffordable for smallholder sorghum farmers, thus applied in small

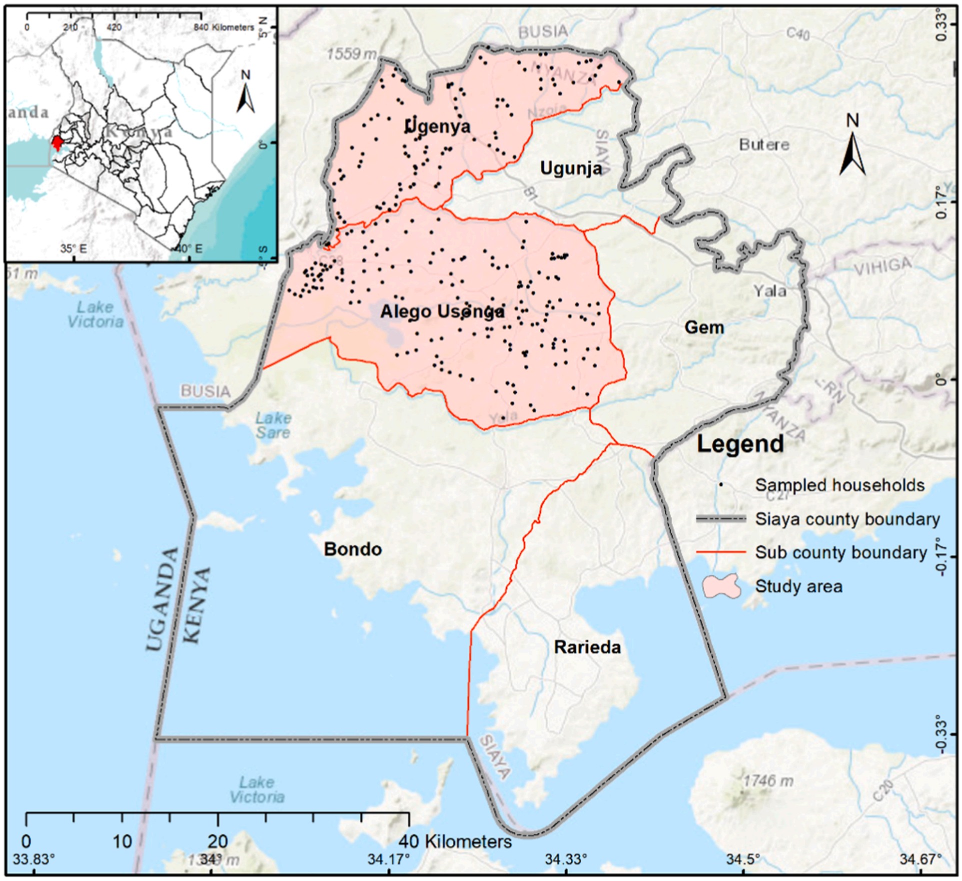

Fig. 1. Study area map.

quantities.

Data collection

We conducted a household survey of 300 farms from June to July 2020 using a comprehensive interview schedule to collect detailed information across sorghum farms. The interview schedule target respondents were the households' heads. Additionally, fieldwork observation and measurements of manure and yields were implemented to complement the survey. The smallholder farms were selected following the criteria: within Alego-Usonga and Ugenya sub-counties and implementing the sorghum cropping systems. The survey covered ten wards within the sub-counties. The data was used to construct farm typologies and estimate GHG emissions and removal.

The data collected included (i) farm description comprising of georeferenced coordinates, the sub-county, and ward, (ii) farmer gender, (iii) Farm factors comprising of land size (ha), seed rate (kg ha^{-1}), variety (1=improved)and tropical livestock unit (TLU units) (iv) soil fertility management practices such as application of animal manure, inorganic fertilizers, integration of animal manure and inorganic fertilizer, no inputs application, compost, land use change, cover crops, crop residue, and tillage practices, (v) inputs attributes such as quantity and type of manure and fertilizer applied, (vi) output including yields and price per kilo of sorghum. Each farm was georeferenced using the Global Positioning System.

Data analyses

Farm typology

Rain-fed smallholders farm are highly diverse due to variations in farmer, farm, and input characteristics. Thus, farm typology construction is used to group heterogeneous farms into homogeneous categories (Gil et al., 2019; Hammond et al., 2020). The farm typologies are valuable for enhancing smallholder farm innovations and policy implementation (Alvarez et al., 2018). The farm typologies are highly influenced by the factors included in the construction (Alvarez et al., 2014). Therefore, the research objectives guided the variables included in the farm typology construction (Pacini et al., 2014). Musafiri et al. (2020a) found that farm typologies could be pivotal in estimating GHG balance. We hypothesized that due to differences across farm typologies, GHG balance could significantly differ across them.

Farm typologies can be constructed using step by step comparison of farm functioning (Landais, 1998), expert knowledge (Pacini et al., 2014), participatory rankings (Kebede, 2007), and multivariate analysis (Alvarez et al., 2018; Musafiri et al., 2020a). The multivariate analysis allows for the statistical reduction of explanatory variables to homogeneous farm types. In this study, we performed multivariate analysis (principal components analysis (PCA) and hierarchical clustering (HC)) using R software as described by Alvarez et al. (2014) using the ade4 package (Mangin et al., 2012). The key variables included in the analysis were land size under sorghum (ha^{-1}), seed quantity planted (kg ha^{-1}), tropical livestock unit (TLU units), fertilizer amount applied during planting (kg ha^{-1}), fertilizer amount during top dressing (kg ha^{-1}), manure quantity (t ha^{-1}), sorghum yields (kg ha^{-1}) and sorghum income (Dollars ha^{-1}), (Table 1). Box plots were used to check for normal distribution. We log-transformed manure quantity, fertilizer amounts, yields, and revenue to achieve normal distribution.

The principal components (PCs) were selected based on Kaiser Mayer-Olkin (KMO), Alvarez et al., 2014; Musafiri et al., 2020a). The principal components with eigenvalues greater than one were retained. The sample size was greater than 250, so the KMO resulted in many PCs. Therefore, the PCs were selected if the cumulated percentage of

Table 1
Description of the study variables.

Variable description	Description	Units
Number of farms	Number of smallholders	count (%) hh
Farm typology description	Classification of the farm type	
Categorical variables *		
Site	Number of the smallholders who reside in Ugenya	count (%) hh
Gender	Number of male smallholders	count (%) hh
Control	Number of smallholders not practicing soil fertility management practices	count (%) hh
Manure	Number of smallholders who applied manure	count (%) hh
Fertilizer	Number of smallholders who applied fertilizer	count (%) hh
Fertilizer and Manure integration	Number of smallholders who integrated manure and fertilizer	count (%) hh
Minimum tillage	Number of smallholders who implemented minimum tillage	count (%) hh
Continuous variables		
Land size	Land size under sorghum production	ha
Seed quantity	The quantity of seeds planted	kg ha^{-1}
Tropical livestock unit	The units of livestock kept	TLU
Fertilizer planting	The quantity of fertilizer applied during planting	kg ha^{-1}
Fertilizer top dressing	The quantity of fertilizer applied during top dressing	kg ha^{-1}
Manure quantity	The quantity of manure applied	kg ha^{-1}
Yields	Sorghum grain harvested	kg ha^{-1}
Revenue	Income from sorghum sold	US$ ha^{-1}

* Only continuous variables were used in the multivariate analysis.

explained variability accounted for 60 % or more of the total variance (J. F. Hair et al., 2010). Therefore, critical PCs were selected if the cumulated percentage of explained variability accounted for 70 % or more of the total variance (Hair et al., 2010b). The resultant PCs were subjected to HC analysis similar to Kamau et al. (2018). The barplot (height = 40) and dendrogram suggested five categories ($k = 5$) (Fig. 2). We generated correlation circles for farm types visualization and interpretations (Fig. 3). We performed a one-way analysis of variance to assess whether there was a significant difference between the factors and the farm types (Table 2).

Greenhouse gas balance estimation

Previous studies have found that the CFT model had lower sensitivity (Clavreul et al., 2017) to input variables. Vervuurt et al. (2022) employed a similar analysis approach on cocoa cropping systems with a nitrogen application rate of 0- 250 kg N ha^{-1}, and the CFT model had low sensitivity. Given that the nitrogen application rate (0–89 kg N ha^{-1}) in our study was lower than 66–506 kg N ha^{-1} used by Clavreul et al. (2017) and 0- 250 kg N ha^{-1} by Vervuurt et al. (2022), the uncertainty in our study could be much lower.

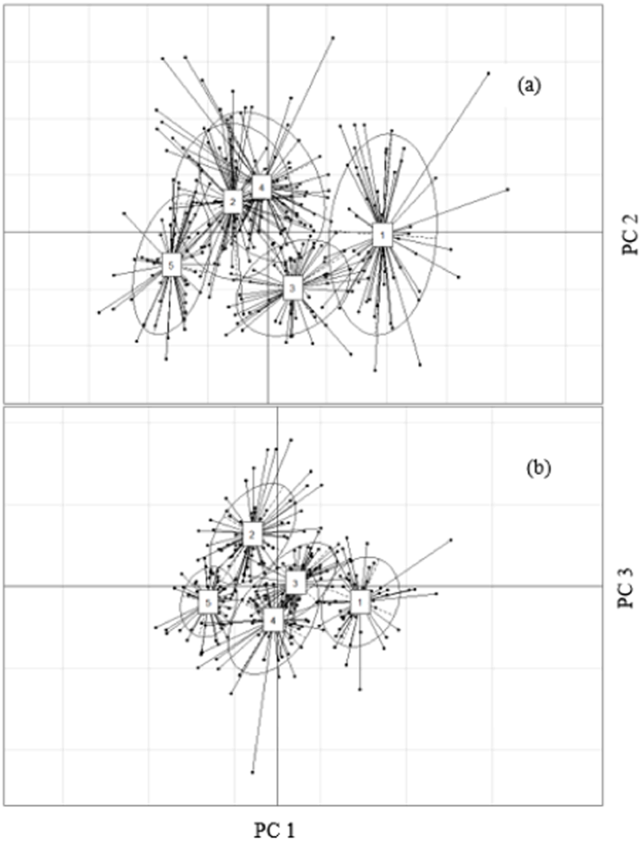

Fig. 3. Visualization of farm types by Principal Component analysis. The farm types are indicated in PC1-PC2 (a) and PC1-PC3 (b).

The GHG balance calculation requires a set system boundary (Alam et al., 2019; Chen et al., 2020b). The system boundary was set up to the farm gate. Therefore, emissions beyond the farm gate were not considered. The system boundary is used to assess the GHG balance based on sources and sinks. Fig. 4 highlights the GHG emissions sources and sinks considered in the study. The sink is the soil carbon sequestration, while the sources include CH_4, CO_2 and N_2O. The overall GHG balance is expressed as CO_2 eq. The CO_2 eq. is calculated using the global warming potential conversion factor of 265 for N_2O and 28 for CH_4 over a 100-year time horizon (IPCC, 2014).

The GHG balances comprised fertilizer production, background soil process, crop residue management, and carbon sequestration. This study

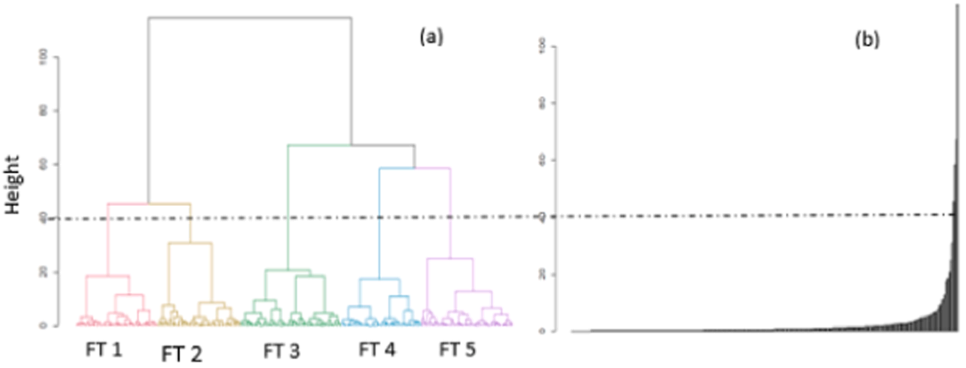

Fig. 2. Dendrogram (a) and bar plot (b) indicate the number of farm types resulting from multivariate analysis. The dotted horizontal line indicates the cut-off points that resulted in five farm types (FT 1–5). The vertical axis represents the distance or ’height’ between the farm types.

Table 2
Descriptive characteristics of the five farm types in Western Kenya.

Typology description/ Variables	FT 1	FT 2	FT 3	FT 4	FT 5	p-Value	Pooled
Number of farms	57 (19.0)	69 (23.0)	56 (18.7)	63 (21.0)	55 (18.3)		300
Categorical Variables							
Site	31(26.1)	14 (11.8)	28 (23.5)	29 (24.4)	17 (14.3)	0.000	119
Gender	26 (22.8)	29 (25.4)	12 (10.5)	28 (24.6)	19 (16.7)	0.044	114
Control	0 (0)	12 (23.5)	0 (0)	4 (7.8)	35 (68.6)	0.000	51
Manure	0 (0)	37 (82.2)	0 (0)	2 (4.4)	6 (13.3)	0.000	45
Fertilizer	45 (29.2)	0 (0)	50 (32.5)	47 (30.5)	12 (7.8)	0.000	154
Fertilizer and Manure integration	12 (24.0)	20 (40.0)	6 (12.0)	10 (20.0)	2 (4.0)	0.002	50
Minimum tillage	11 (19.0)	9 (15.5)	16 (27.6)	15 (25.9)	12 (7.1)	0.128	58
Continuous Variables							
Land size	0.22 ± 0.05b[g]	0.17 ± 0.01b	0.15 ± 0.02b	0.38 ± 0.05a	0.24 ± 0.02b	0.000	0.23 ± 0.02
Seed quantity	20.12 ± 1.63a	17.48 ± 1.08a	15.35 ± 1.08ab	11.38 ± 1.72b	11.62 ± 1.16b	0.000	15.23 ± 0.64
Tropical livestock unit	0.54 ± 0.05a	0.63 ± 0.04a	0.27 ± 0.04b	0.65 ± 0.04a	0.28 ± 0.04b	0.000	0.49 ± 0.02
Fertilizer planting	143.29 ± 16.28a	18.78 ± 4.46cd	68.76 ± 7.59b	37.86 ± 3.93bc	3.31 ± 1.03d	0.000	52.94 ± 4.59
Fertilizer top dressing	88.25 ± 10.91a	0.36 ± 0.36b	10.28 ± 3.33b	13.28 ± 3.78b	0.22 ± 0.15b	0.000	21.60 ± 2.97
Manure quantity	502.39 ± 161.08b	1918.53 ± 242.36a	195.84 ± 96.08b	110.44 ± 38.15c	90.87 ± 48.41c	0.000	613.13 ± 78.90
Yields	1565.62 ± 93.88a	1105.24 ± 55.14bc	1333.58 ± 85.27ab	1061.62 ± 63.50c	688.28 ± 33.77d	0.000	1149.73 ± 34.70
Revenue	702.48 ± 53.10a	434.46 ± 25.24b	531.97 ± 37.99b	440.29 ± 31.06b	269.70 ± 13.55c	0.000	474.60 ± 17.15

[g] Mean values with different letters across rows are significantly different at $P < 0.05$.
FT indicates the farm types
Values in parenthesis are the percentage
The ± showed the standard error of the mean
The soil fertility inputs, sorghum yields, and revenue are for one cropping season.

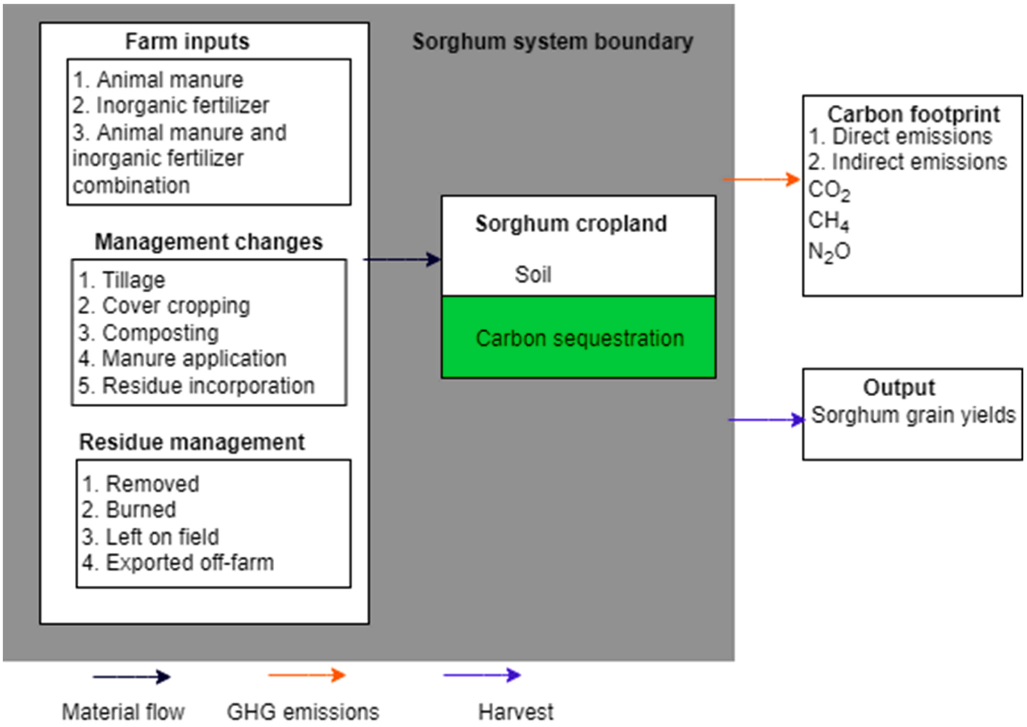

Fig. 4. Sorghum cropping system boundary.

did not consider emissions from trees, electricity, farm machinery, or sorghum processing. Smallholder sorghum cropping systems mostly use animals for farm labor, such as land preparation. Our study did not include emissions from livestock systems as it could lead to an overestimation of GHG emissions. The key determinants of soil emissions from the background processes include soil pH, texture and soil organic matter, drainage, and climate (Hillier et al., 2011). The net GHG balance is expressed as CO_2 eq. A positive sign indicates a source, while a negative sign indicates a sink. The soil characteristic data such as pH (5.2), SOM (2.8 %), and texture (medium) were included in the model from the laboratory analysis. Manure and inorganic fertilizers' C and N concentrations from the laboratory analysis, and manufacturer-specific concentrations, respectively, were used.

We determined the environmental hotspots by calculating the GHG balance of smallholders' sorghum cropping system. The environmental hotspots were expressed as area-scaled emissions (kg CO_2 eq. ha^{-1}), yield-scale emissions (kg CO_2 eq. kg $sorghum^{-1}$), and monetary-scaled emissions (kg CO_2 eq. $US\$^{-1}$ generated). Smallholder sorghum farming in Western Kenya is mainly subsistence (ICRISAT, 2017; Okeyo et al., 2020). Most of the sorghum yields are consumed by the farmers without selling. However, the farmers reported the prevailing market prices which were used to calculate the market value of the produced sorghum. Therefore, we allocated the GHG balance to the market value of the sorghum grain yields produced. We performed heatmap analysis to identify the environmental hotspots using R software. We compared the environmental hotspots across different farm types using one-way analysis of variance (ANOVA) and mean separation using Tukey's Honestly Significant Difference (HSD) when $P < 0.05$ in R software.

Results

Farm typology

We identified five FT through PCA and HC (Figs. 2 and 3). The descriptive characteristics of each FT were as shown in Tables 2 and 3. Farm type 1 (FT1) comprises small farms (0.22 ha), sole fertilizers, and manure and fertilizer-integrating farming households. The FT1 also had a high resource endowment in terms of TLU (0.54 units). FT1 had a high fertilizer (143.29 kg ha^{-1}) and moderate manure (502.39 kg ha^{-1}) use intensity. The FT1 was categorized as fertilizer-intensive and moderate manure-intensity small farms. The FT2 comprised small farms (0.17 ha), sole manure and manure and fertilizer integrating farming households. The FT 2 had high manure (1918.53 kg ha^{-1}) and low fertilizer (18.78 kg ha^{-1}) use intensity. FT 2 had a high TLU (0.63 units) regarding resource endowment. Therefore, FT2 was grouped as manure-intensive and low fertilizer-intensity small farms.

Farm type three (FT3) comprised small farms (0.15 ha) with sole fertilizer and manure and fertilizer integrated farming households. The FT3 had moderate manure (195.84 kg ha^{-1}) and fertilizer (68.76 kg ha^{-1}) application rates. The farming households in FT3 had a low resource endowment (0.27 units of TLU). We classified the FT3 as moderate fertilizer and manure intensifying small farms. Contrary, farm type 4 (FT4) had large farms (0.38 ha) and predominantly mineral fertilizer users. The FT4 was characterized by low fertilizer (37.86 kg ha^{-1}) and manure (110.44 kg ha^{-1}) use intensity. Regarding resource endowment, FT4 had a high TLU of 0.65 units. We grouped the farm type as low fertilizer and manure intensity large farms.

Farm type five (FT5) was characterized by small farms (0.24 ha) with minimal utilization of soil fertility management technologies. FT5 had very low fertilizer (3.31 kg ha^{-1}) and low manure (90.87 kg ha^{-1}) application rates. Additionally, the FT had a low resource endowment of 0.28 TLU units. We grouped FT5 as no or minimal soil fertility replenishment on small farms. The distribution of farm types in the two sub-counties is represented in Fig. 5.

Table 3
Farm type distribution in Ugenya and Alego-Usonga sub-counties.

Pooled sample ($n = 300$)			Ugenya ($n = 119$)		Alego-Usonga ($n = 181$)	
Farm type description	Farm type	(%)	frequency	(%)	Frequency	(%)
Fertilizer-intensive & moderate manure-intensity small farms	1 ($n = 57$)	19.0	31	26.1	26	14.4
Manure intensive and low fertilizer-intensity small farms	2 ($n = 69$)	23.0	14	11.8	55	30.4
Moderate fertilizer and manure intensity small farms	3 ($n = 56$)	18.7	27	22.7	29	16.0
Low fertilizer and manure intensity large farms	4 ($n = 63$)	21.0	29	24.4	34	18.8
No or minimal soil fertility replenishment small farms	5 ($n = 55$)	18.3	18	15.1	37	20.4

Sorghum yields and revenue

The sorghum yields significantly ($p < 0.0001$) differed across the FTs. The average sorghum productivity was 1149.73 kg ha^{-1}. The sorghum yields ranged from 688.28 to 1565.62 kg ha^{-1} under FT5 and FT1, respectively (Table 2). The sorghum yields were lower in FT2, FT4, and FT5 and higher in FT1 and FT3. The FT1 had the highest sorghum yields, 2.27 times higher than FT5. The average revenue across the FTs was 474.60 US\$ ha^{-1} (Table 2). The sorghum revenues significantly ($p = 0.000$) differed across the FTs. FT5 had the lowest (269.70 US\$ ha^{-1}), while FT1 had the highest revenue (702.48 US\$ ha^{-1}). The sorghum revenues in FT2, FT3, and FT4 were statistically similar.

Farm GHG environmental hotspots

We presented the GHG environmental hotspots on a heat map to visually interpret GHG balance and yield-scaled emissions across farm types (Table 4). The heat map interpretation is based on color intensity. The darker colors suggested hotspots and hot moments at multiple scales. FT1 and FT2 had the darkest colors for both GHG balance and yield scaled emissions, thus highlighted as environmental GHG hotspots among smallholder sorghum cropping systems in Western Kenya. Fertilizer production and application were the main contributors to the GHG hotspots.

Differences in GHG balance were found across farm types ($p = 0.046$) for fertilizer production, ($p = 0.01$) for fertilizer application, $p < 0.0001$ for crop management, and $p = 0.023$ for carbon sequestration (Table 5). FT1 (1208.52 kg CO_2 eq. ha^{-}) and FT2 (1187.52 kg CO_2 eq. ha^{-}) had the highest GHG emissions from fertilizer production, while FT5 (86.23 kg CO_2 eq. ha^{-}) had the lowest. Both FT3 (416.15 kg CO_2 eq. ha^{-}) and FT4 (336.89 kg CO2 eq. ha^{-}) contributed the same amount to the GHG balance. FT2 (400.00 kg CO_2 eq. ha^{-1}) had the highest contribution regarding fertilizer application, while FT5 (288.77 kg CO_2 eq. ha^{-1}) had the lowest. From crop management, FT1 (81.70 kg CO_2 eq. ha^{-1}) had the highest, while FT5 (61.50 kg CO_2 eq. ha^{-1}) had the lowest contribution to GHG balance. Different management practices resulted in soil carbon sinks, with FT2 (− 2478.77 kg CO_2 eq. ha^{-1}) having the highest soil carbon sink while FT5 (− 577.07 kg CO_2 eq. ha^{-1}) had the lowest. The overall contribution of the different GHG sources was ranked as; crop management (7 %), fertilizer application (30 %), and fertilizer production (63 %), Fig. 6).

There were statistical differences in yield scaled emission across different farm types; $p = 0.015$ for fertilizer production, $p<0.0001$ for fertilizer application, $p < 0.0001$ for crop management, and $p = 0.027$ for carbon sequestration (Table 5). Considering fertilizer production, the average carbon footprint was 1.23 kg CO_2 eq. kg sorghum $^{-1}$. We observed the lowest CFT under FT5 (0.56 kg CO_2 eq. kg sorghum $^{-1}$) and the highest in FT2 (2.05 kg CO_2 eq. kg sorghum $^{-1}$). FT1 (0.31 kg CO_2 eq. kg sorghum $^{-1}$) had the lowest and FT5 and the highest (1.02 kg CO_2 eq. kg sorghum $^{-1}$) CFT resulting from fertilizer application. The average CFT from fertilizer application was 0.63 kg CO_2 eq. kg sorghum $^{-1}$. On average, crop management had a CFT of 0.11 kg CO_2 eq. kg sorghum $^{-1}$. The lowest CFT was recorded in FT1 0.07 kg CO_2 eq. kg sorghum $^{-1}$ and the highest in FT5 at 0.18 kg CO_2 eq. kg sorghum $^{-1}$. Regarding carbon sequestration, smallholder farms in Siaya sequestered −2.65 kg CO_2 eq. kg sorghum $^{-1}$. The lowest carbon sequestration was observed in FT3 −1.10 kg CO_2 eq. kg sorghum $^{-1}$ and the highest in FT2 −4.05 kg CO_2 eq. kg sorghum $^{-1}$. The overall contribution of different sources to CFT was in rank crop management (6 %), fertilizer application (32 %), and fertilizer production (62 %), Fig. 7).

Area, yield, and monetary scaled footprint

Smallholder sorghum farms in Siaya County were predominantly GHG sinks (Table 6). This implies that the GHG emissions were less than the carbon sequestration. The GHG balance varied ($p = 0.025$) across

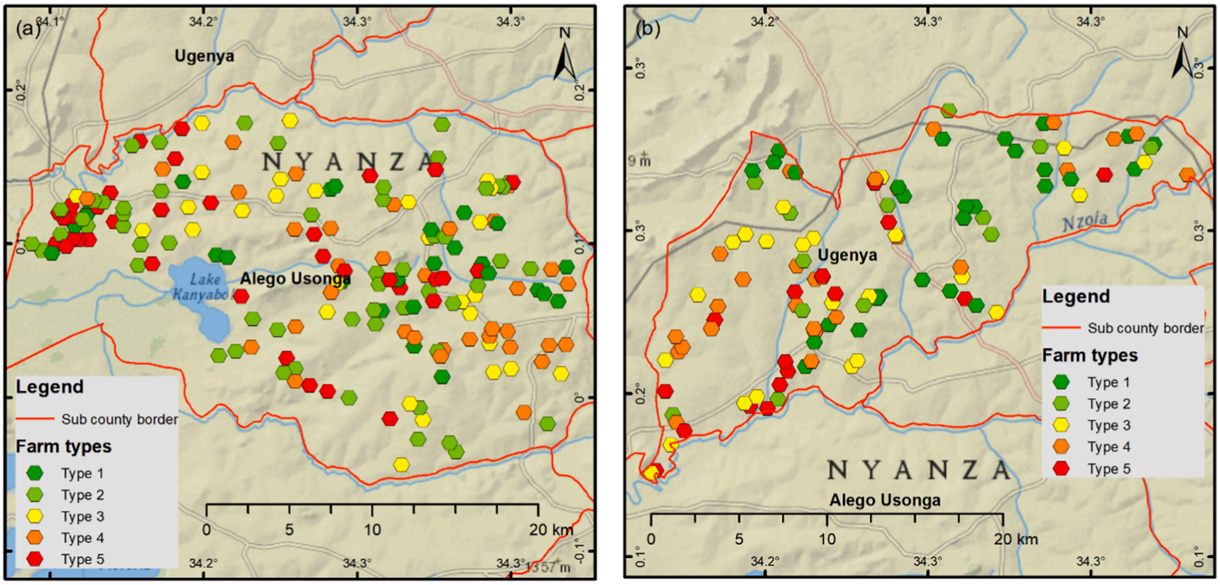

Fig. 5. Maps showing the spatial distribution of the five farm types in Western Kenya: a) Alego-Usonga and b) Ugenya.

Table 4
Heat map of environmental GHG hot moments and hotspots.

Category	Sources of emissions	FT1	FT2	FT3	FT4	FT5
Product Footprint	Fertilizer Production					
(kg CO2 eq. ha^{-1})	Fertilizer application					
	Crop Management					
	Carbon sequestration					
Carbon Footprint	Fertilizer Production					
(kg CO2 eq. kg^{-1} yields)	Fertilizer application					
	Crop Management					
	Carbon sequestration					

Darker colors indicate higher emissions, FT is farm type.

farm types. The mean GHG balance across farm types was −205.54 kg CO_2 eq. ha^{-1}. The lowest GHG balance was observed in FT2 −818.76 kg CO_2 eq. ha^{-1} and the highest in FT1 at 174.29 kg CO_2 eq. ha^{-1}. FT1 had the highest GHG balance among the five FTs, which was 5.7 folds higher than FT2.

Differences in yield-scaled emissions (also known as CFT) were observed across farm types at $p = 0.018$ (Table 6). The smallholder sorghum farm resulted in a CFT of −0.64 kg CO_2 eq. kg sorghum $^{-1}$. The study showed the lowest CFT in FT2 − 1.29 kg CO_2 eq. kg sorghum $^{-1}$ and the highest in FT1 0.45 kg CO_2 eq. kg sorghum $^{-1}$. The findings showed that transition from FT2 to FT1 could have increased the yield-scaled emissions by 3.9 folds.

The Monetary footprint (MFT) significant ($p = 0.004$) varied across farm types. The smallholder sorghum farms had a mean of −0.53 kg CO_2 eq. US\$$^{-1}$ generated. The lowest MFT was observed in FT2 − 2.02 kg CO_2 eq. US\$$^{-1}$ and the highest in FT1 0.13 kg CO_2 eq. US\$$^{-1}$. Manure intensification did not increase CFT and MFT.

Discussion

Sorghum crop yields

The sorghum grain yields of 688 to 1566 kg ha^{-1} were lower than those reported in the literature, 300 to 4300 kg ha^{-1} under drier conditions of Kenya (Okeyo et al., 2020; Kimaru-Muchai et al., 2021; Tegemeo Institute, 2021). Our study found that the sorghum yields were much lower than the production potential of 2000 to 5000 kg ha^{-1}. The increased sorghum yields among the five farm types could be attributed to readily availability of nutrient from inorganic fertilizer and manure. Increased application as mineral fertilizer and animal manure leads to improved soil fertility (Macharia et al., 2020; Musafiri et al., 2020b), thus enhancing crop productivity. Additionally, the application of animal manure in the drylands of Western Kenya could have resulted in increased soil properties such as water content and organic carbon and reduced degradation, thus enhancing crop yields. The findings

Table 5
The GHG balance and yield-scaled emissions for different GHG sources and sinks.

Farm type description	The GHG balance (kg CO_2 eq. ha^{-1}) Fertilizer production	Fertilizer application	Crop Management	Carbon sequestration
FT1	1208.52a ± 360.32	313.78ab ± 10.20	81.7a ± 78	− 1429.71b ± 275.44
FT2	1187.52a ± 297.82	400.00a ± 47.46	72.5ab ± 2.46	− 2478.77c ± 277.69
FT3	416.15b ± 120.89	295.19b ± 2.51	72.29ab ± 2.28	− 832.00ab ± 120.69
FT4	336.89b ± 120.92	311.56ab ± 10.27	64.28bc ± 1.76	− 780.06ab ± 107.98
FT5	86.23c ± 44.51	288.77b ± 6.48	61.51c ± 2.06	− 577.07a ± 86.62
p-value	0.046	0.010	0.000	0.023
	The yield-scaled emissions (kg CO_2 eq. kg sorghum $^{-1}$)			
FT1	1.90a ± 0.42	0.31d ± 0.03	0.07c ± 0.01	−1.87b ± 0.15
FT2	2.05a ± 0.25	0.64c ± 0.10	0.09c ± 0.01	− 4.05d ± 0.16
FT3	0.71b ± 0.12	0.39d ± 0.04	0.08c ± 0.01	− 1.10a ± 0.06
FT4	0.77b ± 0.15	0.77b ± 0.12	0.13b ± 0.02	− 3.69c ± 0.52
FT5	0.56c ± 0.12	1.02a ± 0.20	0.18a ± 0.03	− 2.05b ± 0.18
p-value	0.015	0.000	0.000	0.027

[h] Mean values with different superscripts across columns are significantly different at $P < 0.05$.
FT indicates the farm types
The ± indicated the standard error of the mean.

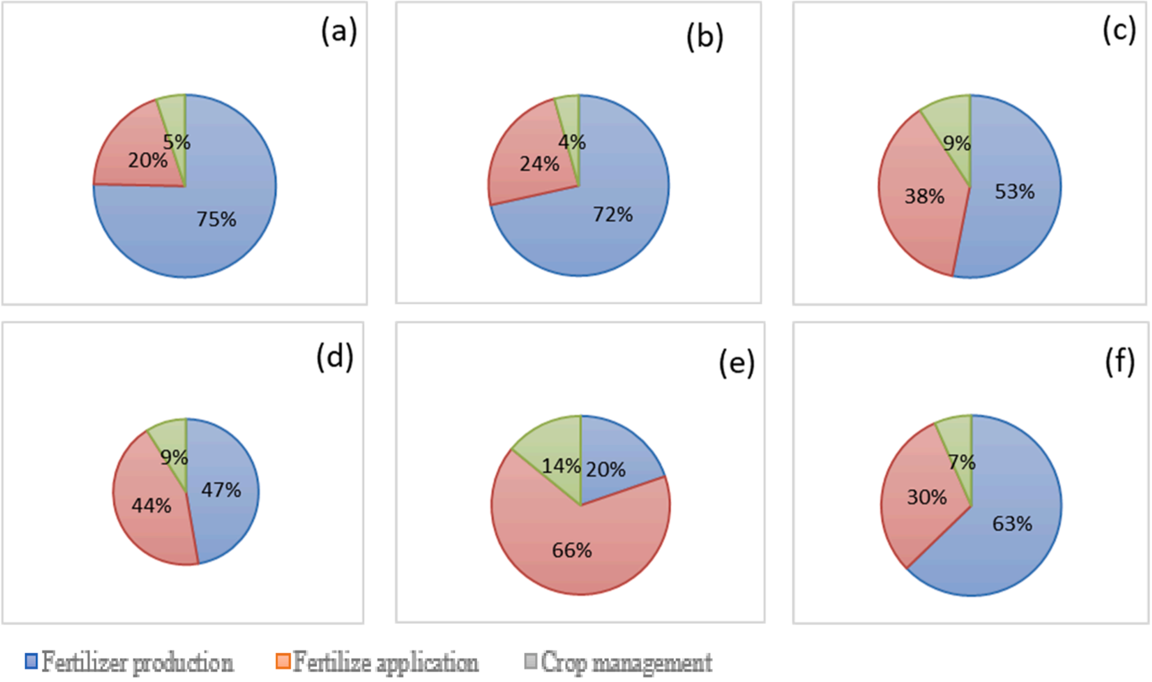

Fig. 6. The contribution of different farm activities on GHG balance across the farm types (FT 1–5) and the overall. a) farm type 1, b) farm type 2, c) farm type 3, d) farm type 4, e) farm type 5, and f) overall.

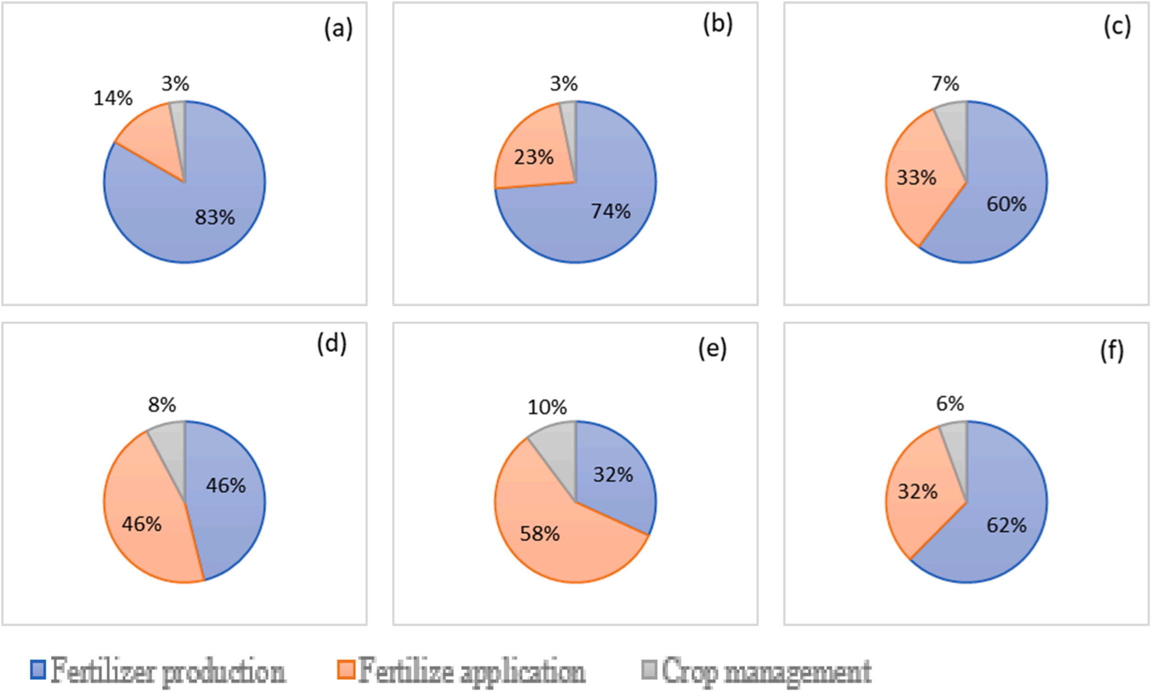

Fig. 7. The contribution of different sources to yield-scaled emissions, the farm types (FT 1–5), and the overall. a) farm type 1, b) farm type 2, c) farm type 3, d) farm type 4, e) farm type 5 and f) overall.

suggested that applying external nutrient-replenishing inputs such as animal manure and soil fertility could improve sorghum yields. However, the application rates by smallholders are below the recommended application rates of 60 kg N ha^{-1}1 season^{-1} (Fertilizer Use Recommendation Project (FURP), 1987). Therefore, soil fertility management practices promotion is essential for enhanced application rates.

Carbon sequestration in sorghum cropping systems

The observed carbon sequestration of − 577 to − 2478 kg CO_2 eq. ha^{-1} falls within the range documented by previous studies; − 1530 and − 3830 kg C ha^{-1} in Western Kenya (Karanja, 2020), −1300 to −2300 kg C ha^{-1} in the Central highland of Kenya (Ortiz-Gonzalo et al., 2017), and − 700 to − 1150 kg C ha^{-1} in Brazil (Corbeels et al., 2006). Considering the farm type, we found that the highest amount of carbon

Table 6
The area, yield, and monetary scaled footprint across different farm types in Siaya County.

Farm type	Area-scaled footprint (kg CO_2 eq. ha^{-1})	Yield-scaled footprint (kg CO_2 eq. kg sorghum $^{-1}$)	Monetary-scaled footprint (kg CO_2 eq. US$$^{-1}$ generated)
FT1	174.29a ± 62.79	0.45a ± 0.24	0.13a ± 0.04
FT2	− 818.76d ± 57.64	− 1.29d ± 0.19	− 2.02d ± 0.20
FT3	− 49.00b ± 25.18	− 0.07b ± 0.07	− 0.01b ± 0.01
FT4	− 67.34b ± 16.79	− 1.86e ± 0.49	− 0.01b ± 0.01
FT5	− 147.88c ± 20.86	− 0.30c ± 0.19	− 0.46c ± 0.07
p-value	0.025	0.018	0.004

[i] Mean values with different letters across columns are significantly different at $p < 0.05$.
FT indicates the farm types
The ± showed the standard error of the mean.

(2478 kg CO2 eq. ha^{-1}) was stored in FT2, while the lowest amount of carbon was stored in FT5. Notably, FT2 had the highest manure application rates (1919 kg ha^{-1}), and FT 5 was the lowest (91 kg ha^{-1}). Therefore, the highest and lowest carbon sequestration observed in FT2 and FT5 could be endorsed to the differences in the manure application rates. Manure application increases carbon sequestration (Huang et al., 2022). Our findings agreed with Ortiz-Gonzalo et al. (2017), who found that high manure application rates increased C sequestration. Manure contains a significant amount of C, which constitutes the soil organic matter, thus enhancing carbon sequestration (Miller et al., 2016).

GHG balance and hotspots

The sorghum cropping systems in Western Kenya were mostly net sinks of soil GHGs. The magnitude of GHG emissions and removal among the smallholder sorghum cropping systems was influenced by the level of soil fertility management intensification. The smallholder sorghum farms with higher fertilizer rates produced higher area-scaled emissions than manure application rates. The GHG balance ranged from − 818.76 kg CO_2 eq. ha^{-1} under FT2 (high manure application rates) to 174.29 kg CO_2 eq. ha^{-1} under FT1 (high fertilizer application rates). The findings suggested that high manure application increased soil carbon sequestration, thus reducing the overall amount of GHG balance. Our GHG balance was lower than Ortiz Gonzalo et al. (2017) (4.5 to 12.5 t CO_2 eq ha^{-1} yr^{-1}) in the Central Highlands of Kenya, though they included trees and livestock. Further, our findings were lower than 4 and 6.5 t CO2 eq ha^{-1} yr^{-1} reported by Seebauer (2014); in Western Kenya, they included household energy consumption. Our low GHG balance observation in sorghum cropping systems of Western Kenya could thus be attributed to the failure to include GHG removal by trees and enteric fermentation from livestock. The GHG balance was lower than 1946 kg CO2 eq./ha to 6211 kg CO2 eq./ha reported under the potato cropping system in Zimbabwe (Svubure et al., 2018). Additionally, the findings on GHG balances were lower than the field measurements reported in Kenya (Ortiz-Gonzalo et al., 2018; Macharia et al., 2020; Musafiri et al., 2020b). However, the field measurements did not consider carbon removal through soil sequestration. Considering soil carbon sequestration, Githongo et al. (2022) found GHG balances that ranged from − 14,700 to 3390 kg CO_2 eq ha^{-1} yr^{-1}. The findings indicated that the smallholders' sorghum cropping systems acted as GHG sinks. Thus, they could significantly contribute to climate change mitigation and adaptation. However, it is noteworthy that the diversity of variables included in the CFT GHG estimation methodology limits comparing the study findings with those reported in experimental studies.

The smallholder sorghum cropping system integrates different management components (Musafiri et al., 2022c). The management components contribute differently toward the GHG balance. Our study revealed that the primary GHG emission hotspots were fertilizer production, fertilizer application (background soil emissions), and crop management. The influence of specific components varied across the farm types. Fertilizer production dominated the GHG balance in FT1, FT2, and FT5, while in FT3 and FT4, its contribution was relatively low. The indirect and direct emissions significantly contributed to the GHG balance in FT3 and FT4. The increased contribution of fertilizer production in FT3 and FT4 could be attributed to the low fertilizer application rates. The finding corroborated with Ortiz-Gonzalo et al. (2017), who reported that direct and indirect emissions significantly contributed to GHG balance. Seebauer (2014) demonstrated that the dissimilarities in GHG balances could be attributed to different system boundaries of the tools, mainly by highlighting which sources/ sinks were included in the calculations.

Carbon and monetary footprint

The results showed that farm-scale estimation of GHG emissions and sinks varied across farm typologies. The estimation showed that specific farm activities significantly contribute to the CHG emissions and removal (Figs. 6 and 7). The CFT range of − 0.64 to −1.29 kg CO_2 eq. kg sorghum $^{-1}$ in our study was lower than the amounts reported in the literature. For instance, according to SGS North America (2015), the sorghum CFT ranged 0.05 kg CO2e to 0.74 kg CO2e per kg of sorghum, with an average of 0.25 kg CO_2 eq. kg sorghum $^{-1}$. The low CFT in Western Kenya could be attributed to the low application of organic and inorganic amendments (Marenya and Barrett, 2009). The low application of soil amendments such as inorganic and organic fertilizers could lead to reduced GHG emissions, thus reducing area-scaled carbon footprint. Similar to our findings, Ortiz-Gonzalo et al. (2017) reported low area-scaled CFT in the central highlands of Kenya and that was attributed the low application rates of mineral fertilizer applied.

It is important to highlight the influence of farm types on monetary footprint. The highest monetary footprint in FT1 and the lowest in FT2 are consistent with the GHG balance and carbon footprint findings (Table 6). The findings suggested that moderate animal manure and fertilizer application results in climate-smart farming. Judicious integration of organic and inorganic inputs increases productivity (Mairura et al., 2023), and total production are used in allocating monetary value (Ortiz-Gonzalo et al., 2017). Smallholder farms with low area-scaled CFT are assumed to have a high product and monetary footprint (kg CO2 eq per kg produced or USD) (Seebauer, 2014). This may be attributed to increased production from readily available N (Richard et al., 2016).

Conclusion

Smallholder sorghum cropping systems showed lower CFT than other cropping systems in Kenya and SSA. This was mainly due to the low use of external inputs in Western Kenya sorghum farms. In our study, sorghum cropping systems were estimated to be net sinks of GHG emissions. The Carbon footprint varied significantly across the five farm types. The primary GHG emissions hotspots were fertilizer production and application in moderate to high fertilizer manure use intensity. Integrating animal manure and inorganic fertilizer resulted in increased yields. Smallholder farmers in Western Kenya have already implemented the integration of animal manure and inorganic fertilizer for increased soil organic carbon and fertility for enhanced crop productivity. Therefore, the smallholders are contributing to the sink of GHG emissions. The study underscored the low contribution of smallholder sorghum cropping systems in western Kenya to the mitigation of GHG emissions through integrated soil fertility management.

Limitation of the study

We set the system boundary in this study at the farm level. Therefore, emissions beyond the farm gate were not considered in the study. This study focused on GHG emissions from fertilizer production, background soil emissions, crop management, and carbon sequestration. Animals are central in providing labor and manure used in the sorghum cropping systems. However, livestock emissions were not included in the model similar to Svubure et al. (2018) as it could lead to cofound the emissions. The study did not consider GHG removal by trees under the sorghum cropping systems.

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 is contained within the article

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