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Evaluation of Greenhouse Gas Emissions along the Small-Holder Coffee Supply Chain in Kenya

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Abstract Coffee plays an important role in sustaining millions of livelihoods around the world. The production of Arabica coffee is greatly affected by the changing climate. Besides suffering from changing climate, coffee is also a contributor to climate change as a result of greenhouse gases emitted throughout the supply chain. The coffee sector is therefore interested in climate-friendly coffee production methods. Understanding greenhouse gas emissions from the coffee supply chains is important for evaluating options for climate change mitigation within the sector. In this study, data from 108 small scale farmers affiliated to three wet mills in Kenya was used to calculate the carbon footprint of coffee parchment, and identify emission hotspots within different farmer production levels. The results indicate that farmer production level had a highly significant negative impact on carbon footprint ($p<0.0001$). The carbon footprint decreased with increase in production level. The mean farm level carbon footprints for 1kg of fresh coffee cherries were 0.05 kg CO_2e, 0.24 kgCO_2e and 0.54 kgCO_2e for high, medium and low producers respectively. The main GHG emission hotspot at farm level across all the levels of production was the inputs of organic and inorganic nitrogen (94%). The mean carbon footprint at processing for 1kg coffee parchment was 2.6 kgCO_2e. At the wet mills the major emission hotspot was the processing wastewater (97%). Mitigation practices proposed therefore focused on the reduction of emissions from fertiliser use and wastewater treatment.

Keywords Carbon footprint, climate change, Cool Farm Tool, greenhouse gases

1. Introduction

Climate change threatens to become an environmental disaster for farmers in many tropical and subtropical regions [1]. The resultant decreased water availability, new or altered insect and pest pressure [2] and increased risks of extreme events threaten crop yields and farmer livelihoods. Many farmers continuously vary their annual crops, selecting them based on several criteria including sustenance, market dynamics, productivity, and cultural preferences [3]. In view of the short growth cycle of annual crops, in many cases substitutions can be made with a minimum costs thus farmers have the capacity to make changes that will likely outstrip the speed of climate change such as changing crop varieties, crop types and planting dates. According to [3], whilst attention needs to be paid to adapting annual cropping systems to future changes in climate, more urgent action is required to address these issues as they apply to high-value perennial cropping systems such as coffee, which have large impacts on national economies through their contribution to the countries' GDP and supporting millions of livelihoods [4], [5], [7].

Indeed, coffee is the most valuable tropical commodity traded by developing countries worldwide, second in value only to oil, as a source of foreign exchange [6]. In Kenya, coffee supports about 700,000 households representing approximately 4.2m or 10% of Kenyan population [8]. It accounts for about 6% of the total export earnings [9]. The total area under coffee in Kenya is estimated to be 109,800Ha, of which 85,200Ha (78%) is under smallholder production with the rest being under Estates [10]. The current annual production stands at 32,700, tonnes for small holders and 16,800 tonnes for Estates [10] with yield values of 383kg/ha and 680kg/ha for small holders and estates respectively. Thus, smallholder farmers form an important portion of the Kenyan coffee supply chain. Moreover, the low yield figures in the small holder farms indicate a need for improved management practices in these farms.

Kenya produces almost exclusively washed Arabica coffee [9] whose productivity is tightly linked to climate variability and thus strongly influenced by natural climate oscillations [11]. According to [12], the first signs that there is need for climate change mitigation in agricultural supply chains are visible. In the coffee sector this is evidenced by the decreased production reported in the last few years attributed to depressed performance of both the long and short rains [10]. Besides suffering from the effects of climate change, coffee production also contributes to greenhouse gas (GHG) emissions throughout its supply chain [4]. There is therefore an urgent need for approaches to coffee farming that not only help farmers adapt to a changing climate, but also minimize the contribution of coffee farming itself to climate change.

Studies regarding GHG emission in coffee supply chains indicate that there is a knowledge gap with regards to the contribution of primary production on GHG emissions, and the most suitable climate change mitigation options for small holder farmers [4], [13] and [14]. In an attempt to fill this gap, the main purpose of this study was to determine the carbon footprint of a Kenyan small holder coffee production system. The study sought to identify 'hot spots' of GHG emissions in the small holder coffee supply chain, in order to determine where mitigation efforts should be focused, and to evaluate alternatives of mitigation efforts and their impact on the carbon footprint. To meet these objectives, the study focused on different stages of the primary coffee supply chain: at farm level, in the wet mills, and during the process of transportation to the dry mill.

2. Materials and Methods

2.1. Study Area

This study was conducted in Kiambu County (inset in Fig. 1) where a small holder farmer cooperative society was selected and its members used as respondents. The cooperative was selected due to its proximity to the research institution and willingness to provide the required data. For confidentiality purposes, the names of the cooperative, wet mills and respondents cannot be disclosed. The area lies at an altitude of between 1580m -1800m above sea level and falls under the upper midland zone 2 also known as the main coffee zone [15], [16]. This zone is characterised by a medium to long cropping season, intermediate rains and a medium to short cropping season allowing for sufficient production of coffee as well as legumes and fruit trees.

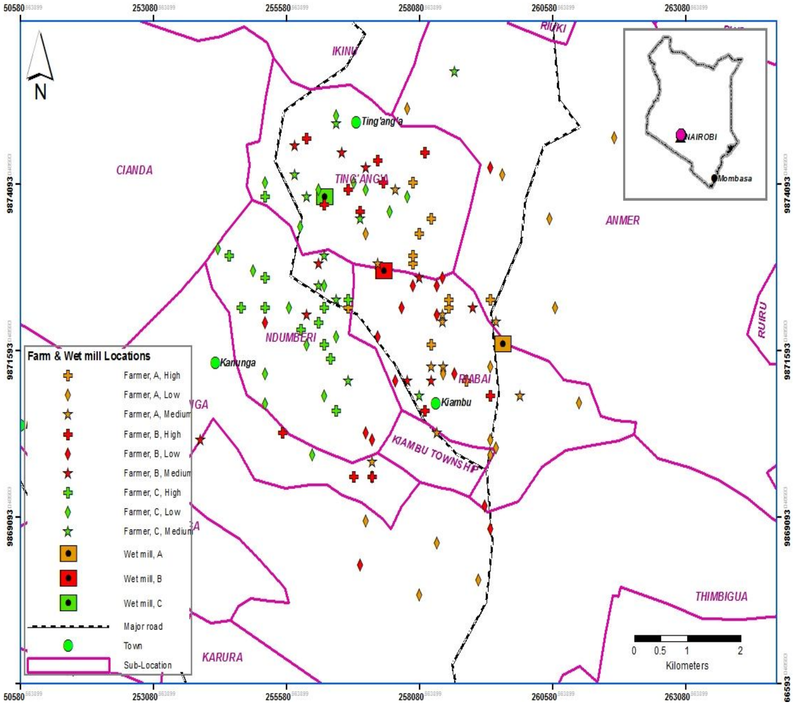

Fig. 1. Map showing distribution of the selected farmers and the coffee production areas

2.2. Farmer Sampling

The selected cooperative has 2600 members with 2127 of them active. The average number of trees and farm size per member is approximately 200 and 0.15 ha respectively with an average production of 3 kg cherry per tree. The population for this study was defined as all the active smallholder coffee farmers (i.e., 2127). A two-way stratified random sampling approach [17], [18] was used in determining a sample from the population, based on the wet mills that the farmers took their produce, and farmer production level. As a sampling frame, the complete list of all active coffee growers with their production levels was obtained from the society's main office. The production levels were based on yield per tree: high-level producers had yields ≥5kg per tree; medium-level between 3 and 4.9kg; and low producers

<3kg per tree. The final sample size was considered based on tables from [19]. Considering the time frame of the research the sample size was limited to 108 farmers i.e. 36 per wet mill. The proportions of the different farmer types in the population were determined to enable proper representation within the sample (Table 1)

Table 1: Sample sizes of the different strata

Wet Mill	High producers		Medium producers		Low producers	
	N	**n**	**N**	**n**	**N**	**n**
A	171	11	149	10	383	15
B	149	11	128	10	404	15
C	191	11	148	10	404	15

Where N and n represent the strata population and sample sizes respectively

2.3. Carbon Foot Print Boundary and Functional Unit

The study focused on emissions from coffee growing in the smallholder farms and initial processing at the wet mills (Fig. 2). Therefore only the emissions occurring within the operations of the cooperative society were taken into account.

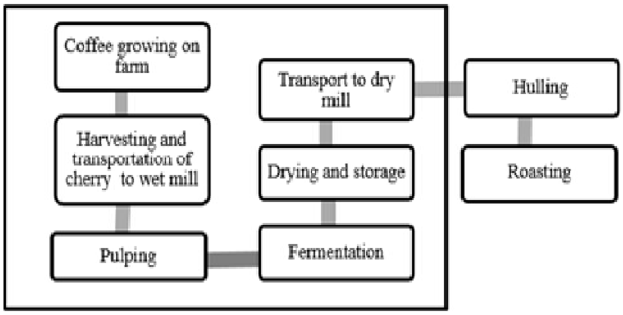

Fig. 2. Coffee processing stages and cut off level of footprint computation in this study

The three functional units used for this study were one kilogram coffee cherry, one acre of land and one kilogram of parchment. The first two units were used for footprints at farm level and the third for footprints from processing. The footprints were thus presented as kg CO_2e/kg coffee cherry, kg CO_2e/acre of land and kg CO_2e/ kg coffee parchment.

2.4. Selection of GHG Quantifying Tool

In order to select a suitable tool for greenhouse gas emission quantification, the following criteria were considered. Firstly, the tool had to be easy to use and could be applied within the time frame of the research project. It also needed to have the capability to take into account context specific variables such as soil and climate, and quantify not only GHG emissions arising from coffee production but also carbon stored in the coffee farms and the annual carbon sequestered. Further it had to be able to quantify emissions from primary processing especially from wastewater with reference to coffee. Finally it was required to present results in both kg CO_2e/ha and kg CO_2e/kg to enable the assessment of both the performance of farming systems in terms of land-use efficiency and efficiency per unit product. A comparison of GHG quantification tools and models such as the CALM calculator, EX-ACT carbon tool, CFF calculator, DNDC model and the Cool Farm Tool (CFT) was carried out based on the above criteria and recommendations by [20]. The Cool Farm Tool was the most suitable for the study. Moreover the CFT has already been modified to various tropical crops [21].

2.5. Data Acquisition for the Cool Farm Tool

An interviewer-administered questionnaire was used to collect data for the CFT. The questionnaire was based on a standard format designed by the Sustainable Food Lab to collect data for the CFT [22]. The questionnaire was pretested by administering to ten farmers to determine the clarity of the questions and the responses obtained from the farmers. Data collection at each individual farm started with a semi-structured interview with the farmer to compile data on farm management, fertilizer use, pesticide use, shading, coffee and shade tree densities, yields, processing methodologies and energy use. Alongside this, visual inspection of the coffee farms was done to verify information gathered in the interview. In addition, the geographical locations of the visited farms were obtained using a hand held GPS system (eTrex Vista, Garmin, Germany). Shade tree species and density were obtained from information from the farmer about the number of individual trees per species on the farm. Shade tree diameters at breast height (1.35m) were measured for the entire population per farm due to their low numbers. For coffee, 30 trees as suggested by [23] were measured per farm and these were selected randomly by moving in a zigzag direction within the farm. The diameters of the selected coffee trees were measured at 15cm from the ground level. The status of the litter layer whether decomposed or not was assessed. Sampling frames of $1m^2$ were located within different sections of the farms and undecomposed plant material and crop residues was collected from the understory sampling frames for analysis of dry weight [24]. The extent of pruning and weeding practices was also registered in the field i.e. whether heavy or light. Soil sampling frames were located randomly within the farms. Soil samples were collected from 0-15cm and 15-30cm depth using a shovel. Samples from the same depth taken in replicate sampling grids were combined directly in the field [24]. The composite sample was mixed thoroughly to obtain a representative sample of the whole farm. From each farm two samples were collected one for each depth. The collected soil samples were analyzed for organic carbon and pH.

At the three wet mills data was obtained from the society's records on the total amount of cherry received, amount and type of energy used, the amount of water used for cherry pulping and washing, the total amount of parchment produced, the dry mills where parchment was delivered, mode of transportation of the parchment and the distance to the dry mills. Data spanning three years was obtained for computation of average values as required by the Product Category Rules PCR for green coffee [25]. Wastewater samples were collected for analysis. The pH of the wastewater was measured using a standard pH electrode meter (Hanna HI 98129 pH ECD/TDS waterproof combo tester/meter, Hanna Instruments Inc. Woonsocket, Rhode Island, USA). Total suspended solids (TSS), Total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), electrical conductivity (EC) and other chemical constituents were estimated using the standard methods for examination of water and wastewater (APHA, 1998).

2.6. GHG Quantification and Data Analyses

Data obtained from each farm was fed to the Cool Farm Tool (version 2.0-beta 3) [26] for quantification of GHG emissions. The CFT calculates GHG emissions by using different models for each of the different emission sources. GHG emissions from the production and distribution of a range of fertilisers was taken from Ecoinvent database. Nitrous oxide (N_2O) emissions related to fertiliser application are estimated using the multivariate empirical model of [27]. This model utilises data on fertiliser type, rate, climate and soil characteristics. NO and NH_3 is calculated based on the model of FAO/IFA and converted into N_2O via the factor 0.01 as given by the Intergovernmental panel on Climate Change IPCC. Leaching is assumed to occur at a rate of 0.3*N applied for moist climates. Emissions from CO_2 from the soil resulting from Urea application and liming are accounted for using IPCC emission factors. CO_2 emissions from (or accumulation in) the soil depend on climate, soil characteristics, tillage practices, crop management practices such as residue incorporation based on [28]. The effect of manure and compost addition on soil carbon stocks are derived from data of [29]; about 0.04% change of soil organic matter concentration per tonne dry matter of manure or compost. The tool uses a figure of 20.5kg CO_2 equivalent per product application per hectare based on data from [30] for agrochemicals such as fungicides, herbicides and pesticides. Energy usage (petrol, diesel, electricity) for farm operations and primary processing were taken from ASABE technical standards [31]. Country specific grid electricity emissions were taken from GHG protocol's emission factors for cross sector tools. Table 2 shows how the CFT transforms input data from various sources into carbon dioxide equivalents.

Table 2: Data transformation by the CFT

Emission factor	**Input variables**	**CFT Output**
Fertiliser induced N_2O	Fertiliser type/ application rate per acre/ management practices	Kg CO_2e/acre, Kg CO_2e/kg product
Fertiliser production	Fertiliser type/ application rate, production technology	Kg CO_2e/acre, Kg CO_2e/kg product
Pesticide production	Number of applications	Kg CO_2e/acre, Kg CO_2e/kg product
Diesel use	Litres used	Kg CO_2e/acre, Kg CO_2e/kg product
Electricity use	Kwh	Kg CO_2e/acre, Kg CO_2e/kg product
Crop residue management	Kg/ management practice	Kg CO_2e/acre, Kg CO_2e/kg product
Wastewater production	Litres/ management practice	Kg CO_2e/acre, Kg CO_2e/kg product
Off farm transport	Km/weight/mode	Kg CO_2eq/acre, Kg CO_2eq/kg/ product
Carbon sequestration	Tree species/DBH shade trees/ D15 coffee trees/ number of trees cut down or planted, land use changes	Kg CO_2eq/acre, Kg CO_2eq/kg product

For each farm, the CFT provided total emission information per farm, unit area and kilogram of finished product. The value of GHG emissions was presented in kgCO_2e/acre and kg CO_2e/kg of coffee.

Data were analysed using a 2-way ANOVA where the Factors were Wet Mill and Production Level, while the response variable at farm level was emissions per kilo or acre of production. Interactions between the two factors were also investigated.

3. Results and Discussion

The small holder coffee farms were typically less than one hectare with the area under coffee ranging from 0.1 to 1.2 Ha (Table 3). The farms varied in management practices such as pruning, fertiliser use and shade and residue management. Most of the coffee trees had been planted in the 1960s and 1970s. The age of coffee trees ranged from 22 years to 55 years (mean: 52±1.2 years). The yield levels per acre ranged from 503-5590 kg for high producers, 508-1406 kg for medium producers and 267-1172 kg for low producers. The soils in the area had a pH ranging from 4.3 to 6.7 and organic carbon content ranging from 2.6 to 5.31

Table 3: Characteristics of the small holder farms

	High producers	Medium producers	Low producers
No. of farms	33	30	45
Area under coffee (acres)	0.75±0.3	0.71±0.2	0.68±0.3
No. of coffee trees per acre	716±12	481±11	451±15
Age of coffee trees (yrs)	52.63±3.1	52.16±2.5	52.36±2.4
No. of shade trees per acre	23±2	18±5	13±3
Fertiliser use (Kg N/ha)	176.71±27	90.23±38	71.56±26

3.1. GHG Emissions per Weight of Coffee Produced

The carbon foot prints at farm level ranged from -0.37 to 0.35 kg CO_2e per kg coffee cherry for high producers, -0.1 to 0.76 kg CO_2e for medium producers and 0.09 to 1.29 kg CO_2e for low producers. There was an increase in emissions for farmers from all the mills as the level of production decreased (Fig. 3). A negative carbon footprint indicated that a farm was sequestering more carbon than it was emitting. A 2-way ANOVA for emissions per kilogram cherry at each production level across the wet mills shows that there were no significant differences in emissions per kg cherry from farmers from the three levels of production across the three wet mills (P = 0.51). These results imply that there is homogeneity of farmers at each production level across the three wet mills. Further, the results also showed that there was a highly significant difference in emissions across the three production levels (P<0.0001) at individual wet mills. This implies that production level has a significant negative effect on the product carbon footprint of coffee. The product carbon footprints decreased with increase in production. There was however no interaction between farmer production level and wet mill (ANOVA, P=0.87).

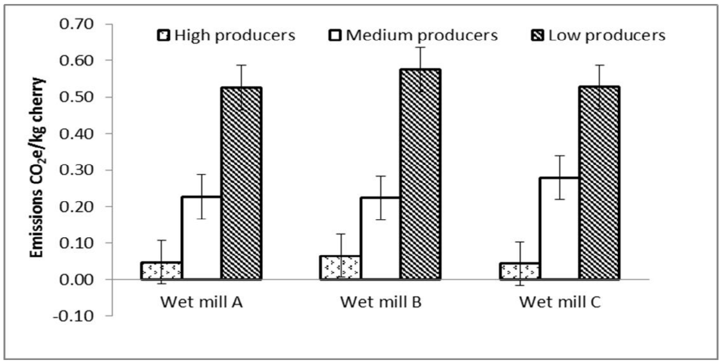

Fig. 3. Mean farm level footprints across the three production levels and wet mills

The variation of emissions with production level can be explained by the fact that in agricultural supply chains carbon footprint is measured per unit of product. According to [22], in the calculation of Product Carbon Footprints PCF all emissions arising from a production system are allocated to the amount of coffee produced which therefore has an impact on the final footprint: the higher the yields the lower the carbon footprint. These results are in agreement with [32] who concluded that product carbon footprints decrease with increase in production.

3.2. GHG Emissions per Area of Land under Coffee Production

The GHG emissions per acre at farm level for individual farms ranged from -422 to 420 kg CO_2e/acre for high producers, 46 - 526 kg CO_2e/acre for medium producers and 166 - 742 kg CO_2e/acre for low producers. The results also reveal an increase in carbon footprints per acre with decreasing production levels from farmers across all the wet mills (Fig. 4). High production level farmers have the lowest footprints per acre of land with those from wet mill A storing more carbon than they are emitting hence a negative footprint.

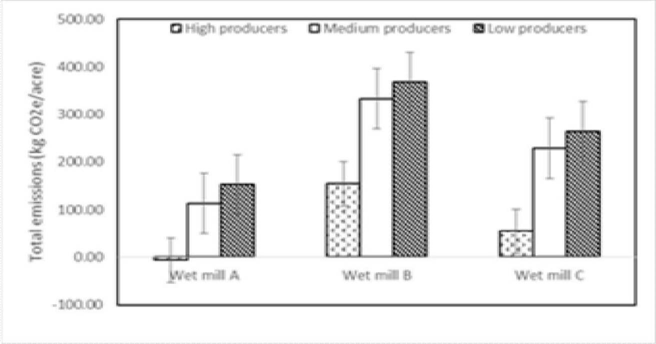

Fig. 4. Mean footprints per acre of land across the three production levels and wet mills

A 2-way ANOVA for emissions per acre across the three production levels showed that there were highly significant differences in emissions per acre across the three production levels (P=0.0006). Production level of the small holder farmers therefore had a significant effect on emissions per area of land as well. Moreover, the results indicate significant differences in emissions per acre across the three wet mills (P= 0.019) but no interactions between production and wet mill (P=0.9). High production farms are characterized by higher fertiliser use, heavier pruning regimes, better management practices and higher coffee and shade tree densities, as a result the amount of carbon sequestered in these ecosystems is much higher. This counters the apparently higher emissions from fertiliser use resulting in the lower per acre footprints recorded.

3.3. GHG Emissions Hotspots at the Farm Level

A breakdown of the various emission sources at farm level shows that the major source of emissions from the small holder coffee farms is the application of fertilisers (Fig. 5 and 6). Fertiliser production and nitrous oxide emissions account for 94 % of the total on-farm emissions, as contrasted with crop residues which account for 4%, pesticide use 1% and transport of cherry from the farm 1%. The results also show that the emissions per kilogram cherry from the different sources increase with a decreasing production levels (Fig. 5). This could be due to the fact that the computation of PCF is based on total cherry produced thus the footprints are inversely proportional to the amount of coffee cherry produced. However carbon stock changes per unit product increased with decreased productivity indicating a greater level of carbon storage per unit product for the low producers.

Emissions per acre of land from individual sources show that emissions from fertiliser use increase with increase in production while the carbon sequestered was highest for high producers followed by low producers and lowest for medium producers (Fig. 6). High production level farmers have the highest fertiliser emissions indicating a high reliance on inorganic fertilisers. Carbon stock changes were higher for these farms as well which may be attributed to the high pruning regimes, better farm management practices and a higher density of shade trees. Low producers had higher carbon stock change values as a result of intercropping coffee with crops such as beans, pumpkins thus more residue incorporated into the soil. This implies that intercropping has the potential of improving carbon storage in coffee farms. Intensifying production while maintaining the carbon storage potential of these farms would greatly improve the climate friendliness of the low producers [1].

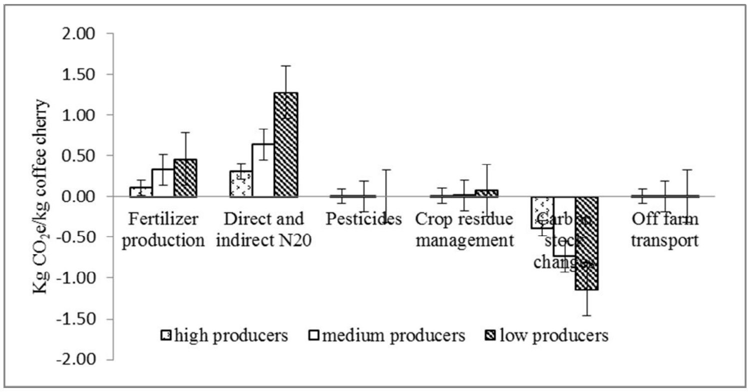

Fig. 5. Emissions per kilogram cherry from various sources at farm level

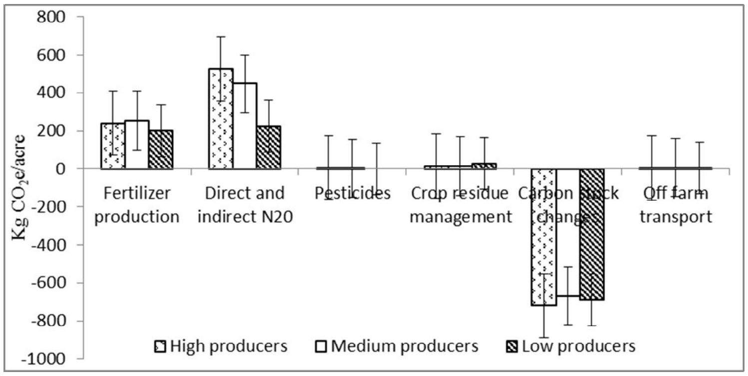

Fig. 6. Emissions per acre from various sources at farm level

From the results of Figures 5 and 6, it is evident that the use of footprints per acre of land is most suitable for comparison of the various farmer types in this study as the footprints per kg produce are biased towards productivity. The footprints per area of land bring to the foreground the effect of variations in management activities on farm level emissions. This is contrary to findings of [33] who argue that for comparison of products from different sources, the use of footprints per kg of product is much suitable.

3.4. GHG Emissions from Coffee Processing at wet Mills

The collected coffee processing wastewater from the three wet mills showed high BOD values (6000-10000mg/l) and low pH values (3.9-4.2) before treatment. The average amount of water used for pulping washing and fermentation was 5.39l/kg and 4.99l/kg per kg coffee cherry for wet mill B and C respectively. Data on water use from wet mill A was not available at the time of the study. In all the wet mills there was recirculation of the water. Processing level emissions are presented in Table 4. The results reveal that at processing level the major source of emissions is the generation of wastewater from pulping, fermentation and washing of coffee cherry. This accounts for 97% of the total processing emissions. Reference [34] also reported pulping and fermentation as the greatest sources of emissions from primary processing of coffee. Energy use at primary processing was mainly from the depulping machines and recirculation pumps, because drying of coffee at these wet mills is mainly by open sun.

Table 4: Emissions (kgCO_2e/kg coffee parchment) from various sources at processing level

Wet mill	Processing emission sources			
	Energy use	Wastewater	Transport	Total
A	0.150	-	0.036	0.186
B	0.014(0.5%)	2.57(98%)	0.036(1.5%)	2.62
C	0.019(0.8%)	2.34(97%)	0.036(2.2%)	2.40

3.5. Total Carbon Footprint

The study revealed an average footprint of 4kg CO_2e kg coffee parchment for the selected small holder coffee supply chain. This footprint is lower than the 5.81 kg CO_2e/kg reported using the CFT for coffee farms in Nicaragua [34]. This difference may be attributed to variations in production especially on coffee nutrition. Emissions from coffee processing contributed to more than half of the carbon footprint (Table 5). Thus for small holder coffee production in Kenya, the bulk of production emissions is at primary processing level. On the average of all systems, 63% of the total emissions was from fermentation and wastewater, 33% due to fertiliser production and application including background soil emissions, 4 % was from prunings and crop residues decomposing on the ground, and 1% was from pesticide application. These values are similar in trend to those reported by [1]

Table 5: Overall emissions from the entire small holder production chain

Wet mill	Emissions at farm level		Emissions at processing level
	kg CO_2e/kg coffee cherry	Kg CO_2e/kg coffee parchment	kg CO_2e/kg coffee parchment
A	0.33	1.65	-
B	0.28	1.40	2.62
C	0.30	1.50	2.40

3.6. Mitigation of Greenhouse Gas Emissions

The factors contributing the most to the mean product carbon footprint of primary coffee supply chain are the production and application of organic and synthetic fertilizers (29 to 36%), the generation and discharge of coffee processing wastewater (30 to 38%) and soil carbon storage (-30 to -35%) (Table 6 and Fig. 7). Mitigation should focus on minimizing emissions from these major sources and maximizing carbon sequestration.

Table 6: Contribution of various sources to the overall footprint

Wet mill	Fertiliser production & use	Crop residue management	Carbon stock changes	Wastewater
A	4.45	0.11	-2.95	2.46
B	5.55	0.25	-4.45	2.57
C	5.3	0.15	-3.95	2.34

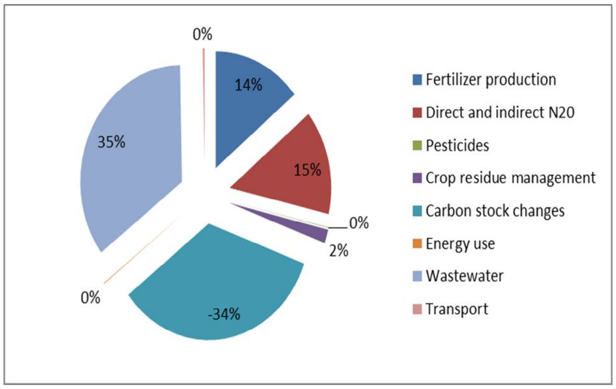

Fig. 7. Contribution of various sources to the overall footprint

Various practices have been proposed for their use in mitigation climate change on coffee farms (Table 7). The suitability of these practices is dependent on financial capability of the small holder farmers. Incorporation of more shade trees would reduce vulnerability of farmers to climate change by providing substitute products to coffee in the case of fruit trees [34]. Leguminous shade species would provide a long term reduction in fertiliser use as a result of nitrogen fixing. Efficient use of fertilisers is also an important component of climate friendly coffee production.

The results of this study reveal that majority of the farmers have fertiliser application rates below the recommended standards [35], which does not lead to higher yields but does raise the footprint. Fertilisers may also be wasted on these farms whose productivity is already limited by other factors such as the age and state of the coffee plants. A shift to efficient use of organic fertilisers would give positive reduction on fertiliser emissions. A possible solution to reduce emissions from wet processing could be to use one of several available fermentation methods that drastically reduce the amounts of waste water produced [36]. Low cost eco-technologies such as constructed wetlands can be employed to reduce methane emissions coffee processing wastewater.

Table 7: Suggested mitigation practices for small holder coffee farmers

Practices	Carbon footprint reduction potential	Carbon sequestration potential	Financial feasibility
Soil conservation	Low	-	Inexpensive
Incorporating more shade trees	-	Medium	Inexpensive
Optimal use of organic fertiliser	High	-	Inexpensive
Wastewater treatment	High	-	Expensive

4. Conclusions

The purpose of this study was to evaluate sources of GHG emissions in selected coffee farms with different levels of production. The major emission sources in the smallholder supply chain were wastewater from pulping and fermentation (63%), fertiliser production and use (33%) and finally management of crop residues (4%). Direct and indirect soil N_2O emissions from fertilisers are the major determinant in overall GHG emissions in coffee cultivation and therefore fertiliser management is a crucial management practice in terms of reducing GHG emissions at farm level. The study found that farms with a high level of production per unit area have lower carbon footprints compared to those with a lower production per unit area. The use of better management practices in coffee cultivation can substantially reduce GHG emissions as these practices have a lower reliance on manufactured fertilisers. GHG mitigation options in the coffee supply chain include: balanced fertiliser application or a reduction in fertiliser application as synthetic fertiliser application does not necessarily result in increased yield, residue management which aides in carbon sequestration in the soil, and better wastewater treatment process before release to the environment.

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