Journal of Cleaner Production 265 (2020) 121780

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Variation in the carbon footprint of milk production on smallholder dairy farms in central Kenya

Andreas Wilkes [a, *], Shimels Wassie [a], Charles Odhong' [a], Simon Fraval [b], Suzanne van Dijk [a]

[a] Unique Forestry and Land Use GmbH, Schnewlistraße 10, Freiburg, 79098, Germany
[b] International Livestock Research Institute, PO Box 30709, Nairobi, 00100, Kenya

ARTICLE INFO

Article history:
Received 13 November 2019
Received in revised form
15 April 2020
Accepted 16 April 2020
Available online 23 April 2020

Handling Editor: Prof. Jiri Jaromir Klemeš

Keywords:
Dairy cattle
Greenhouse gas
Carbon footprint
Feeding
Kenya

ABSTRACT

Milk production by smallholders in Africa has a high carbon footprint (CF) and is predicted to increase significantly in the coming decades. This study, based on data from a sample of 382 farms in central Kenya, is the first assessment of the CF of milk production in Sub-Saharan Africa based on a large dataset of actual farm management practices. The aims of the study were (1) to determine whether there are significant differences in the CF of farms with different feeding systems (i.e., zero-grazing, grazing and mixed systems), and (2) to identify factors associated with variability in CF between farms. This analysis is used to identify options for mitigating GHG emissions from Kenya's growing dairy production. Average CF ranged between 2.19 and 3.13 kg CO_2e/kg fat and protein corrected milk (FPCM), depending on the GWPs and allocation method used. Analysis based on variability in farm management showed that CF was similar between farms with zero-grazing and mixed feeding systems, and significantly higher on farms with grazing only feeding systems, but no difference was detected when input parameter uncertainty was considered. At individual cow level, variation in milk yields explained more than 70% of the variation in GHG intensity. At farm level, milk yield explained less than half of variation in CF. CF was correlated with feed characteristics, manure management practices and herd size and composition. In particular, the level of concentrate use was positively correlated with CF, and was the most important factor explaining variation in CF not attributable to variation in milk yield. Our findings suggest that promoting balanced feed rations and feeding concentrate according to cows' needs across the lactation cycle could provide opportunities to both increase milk production and reduce the CF of milk production on smallholder farms in central Kenya. Supporting smallholder farmers to implement these mitigation options will require interventions at several levels in feed supply chains in the dairy sector.

1. Introduction

Although Sub-Saharan Africa (SSA) produces only 3.5% of global milk output, it accounts for about 21% of the global herd of milking cows (FAO, 2020), indicating low milk yields per cow on the continent. The average intensity of greenhouse gas (GHG) emissions per unit of milk produced in SSA has been estimated to be three times higher than the global average (Opio et al., 2013). Demand for dairy products in SSA is projected to triple by 2050 (Herrero et al., 2014), suggesting that GHG emissions from the sector will increase significantly. Since the GHG intensity of milk production decreases as milk yield per cow increases, increasing productivity represents an important GHG mitigation strategy, especially in areas with low milk yields (Gerber et al., 2011). Previous assessments of the GHG intensity of milk production in SSA have used modelled or 'typical' farm data, or data from small samples of farms. To our knowledge, this study is the first to use actual data from a large sample of farms in SSA to estimate cradle to farm-gate GHG emissions in order to assess differences in the carbon footprint (CF) of milk production between different

* Corresponding author.
E-mail addresses: andreas.wilkes@unique-landuse.de (A. Wilkes), shimels.wassie@unique-landuse.de (S. Wassie), charles.odhong@unique-landuse.de (C. Odhong'), simonfraval@gmail.com (S. Fraval), suzanne.vandijk@unique-landuse.de (S. van Dijk).

https://doi.org/10.1016/j.jclepro.2020.121780
0959-6526/

production systems and to identify the key sources of variability in CF between farms.

Identifying GHG mitigation options in SSA's dairy sector has direct relevance for national and international climate change policies. With many SSA countries' GHG emission profiles dominated by agriculture, 40 out of 54 African countries have included the livestock sector in the scope of their Nationally Determined Contributions communicated to the United Nations Framework Convention on Climate Change under the Paris Agreement (Wilkes et al., 2017). However, few of these countries have elaborated specific policies or measures for reducing GHG emissions in the livestock sector. Kenya was selected for this study for two reasons. First, with a dairy cattle population of 4.6 million and annual milk production of 5 billion litres (State Department of Livestock, 2018), Kenya is the largest milk producer in Africa. Dairy cattle GHG emissions account for about 15% of Kenya's total GHG emissions (Government of Kenya, 2015). Modelling studies have projected an 85% increase in milk demand in Kenya between 2010 and 2050 (Enahoro et al., 2018), while the government's own dairy policy aims to increase milk production by 130% by 2030 (State Department of Livestock, 2013). This highlights the importance of pursuing GHG mitigation strategies, such as reductions in GHG intensity, that are compatible with producers' socio-economic needs. Second, compared to most African countries, Kenya has progressed further than many countries in elaborating measures to reduce GHG emissions from its dairy sector. Recognizing the challenge of meeting dairy product demand while reducing the sector's environmental footprint, the Government of Kenya has proposed a nationally appropriate mitigation action (NAMA), which aims to support smallholder dairy producers to increase dairy cattle productivity while reducing the CF of milk production (State Department of Livestock, 2017). A core component of the proposed NAMA involves strengthening extension services to smallholder farmers, with a focus on central Kenya and the Rift Valley, where the majority of milk is produced. The measures promoted may include both change in feeding system (e.g. adoption of stall-feeding) and change in management practices within feeding systems (e.g. adoption of improved breeds, better quality feed or improved animal management). The specific farm management practices to be promoted in the NAMA have not been determined, so this study contributes to knowledge of practice changes that can be promoted through Kenya's dairy NAMA. The analytical approach used may also be relevant in other countries that are similarly developing policies and measures to reduce the CF of the livestock sector while increasing productivity (Wilkes et al., 2017).

This study used a unique dataset covering 1284 individual animals on 382 farms in central Kenya to estimate the CF of milk production per farm. The data was analysed (1) to assess whether there are differences in the average CF of milk production in different feeding systems, and (2) to identify factors associated with variation in the CF between farms in order to identify options for mitigating GHG emissions from dairy production on smallholder farms in central Kenya. The rest of the paper is set out as follows. Section 2 reviews related work to explain the relevance of investigating differences in CF between feeding systems and farms for identifying GHG mitigation options. Section 3 explains the methods used to collect data from sampled farms, the carbon footprint methods implemented and the statistical analysis applied to the data, including uncertainty analysis. Section 4 describes the farms surveyed, sources of GHG emissions in milk production, the CF in different feeding systems (including uncertainty) and sources of variation in CF. Section 5 discusses the findings in relation to the existing literature, implications for GHG mitigation, and priorities for methodological improvements to reduce uncertainty. Section 6 summarizes the main conclusions. Supplementary information presents the specific data values and data sources used in quantification of the carbon footprint and the data values and sources used in the uncertainty assessment.

2. Literature review

There are three types of smallholder dairy production system in central Kenya defined by feeding system: zero-grazing (i.e. stall feeding only), grazing only, and mixed systems (referred to as 'semi-zero grazing' systems) (Bebe et al., 2003a). Zero-grazing farms are common in central Kenya because average farm size is small and more milk can be produced per unit of land than in grazing or semi-zero grazing systems (Bebe et al., 2003a). Zero-grazing systems are associated with adoption of improved breeds (i.e. *Bos taurus*) (Bebe et al., 2003b), which have higher yields than local (i.e. *Bos indicus*) breeds (Abeygunawardena and Dematawewa, 2004). However, improved breeds (e.g. Freisian, Ayrshire) typically have larger body size, which implies higher energy intake requirements and higher GHG emissions (Capper and Cady, 2012). Local breeds are preferred by some farmers with a grazing system because of their hardiness (Bebe et al., 2003b), but the lower energy digestiblity and protein content of natural pastures and other available forage limits milk yield and increases methane emissions (Archimède et al., 2011). Moreover, in all feeding systems, constraints on fodder availability and quality limit farmers' ability to realise the genetic potential of improved breeds, especially before and during lactation when nutritional requirements increase greatly (Butler, 2000). Various measures have been promoted to increase fodder availability and quality and to improve animal health and calf management (Bateki et al., accepted). However, the extent and intensity of their adoption, and their effects on the CF of milk production remain unclear. In the Kenyan context, therefore, both changes in feeding system and changes in management practices within feeding systems may be relevant to mitigation of GHG emissions from dairy production.

Previous studies of the GHG intensity of milk production in Africa have either been based on modelled farm characteristics (Opio et al., 2013; Brandt et al., 2018), assumed characteristics of 'typical' farms (FAO and NZAGRC, 2017a, 2017b), or actual data obtained from small samples of farms (Weiler et al., 2014; Udo et al., 2016; Woldegebriel et al., 2017). The limited available evidence on the effects of feeding system on the CF of milk is inconsistent. Studies based on assumed typical values of farm attributes in Kenya and Ethiopia have suggested significant differences in the CF of milk between feeding systems (FAO and NZAGRC, 2017a, 2017b). However, studies in those countries based on actual data from small samples of farms suggest that the CF may not vary significantly between systems (Udo et al., 2016; Woldegebriel et al., 2017). This inconsistency is also reflected in the international literature. For example, while some individual studies have found significant differences in the CF of milk production between systems (e.g. O'Brien et al., 2012), other studies and a global meta-analysis comparing grazing, confined and mixed dairy production systems highlighted the existence of greater variability in CF within systems than between systems (Lorenz et al., 2019). Therefore, analysis of data from a large sample of farms is necessary to identify the sources of variability in CF within feeding systems (Zehetemeier et al., 2014), and where variability reflects farm management decisions, they may indicate potential for farm management changes that reduce the CF of milk production (Henriksson et al., 2011). Analysis of uncertainty in input parameters should be applied to assess differences between feeding systems (Chen and Corson, 2014).

3. Materials and methods

3.1. Study area

We selected central Kenya as our study area because the region produces a large proportion of national milk supply and is targeted in the Kenyan dairy NAMA (State Department of Livestock, 2017). We implemented a survey in this region from January to February 2018, sampling dairy cattle keeping households in Embu, Kiambu, Kirinyaga, Meru, Murang'a, Nakuru, Nyandarua and Nyeri counties (Fig. 1). This region has two rain seasons (March to May, October to December). Average annual rainfall and temperature from 1991 to 2016 ranged between 910 and 1818 mm and 14.2–22.5 °C (Harris et al., 2014).

3.2. Sampling and data collection

A two-stage sampling procedure was followed. In the first stage, 43 points were randomly selected using a random-location selection script in ArcGIS after screening out urban and forest areas and water bodies and ensuring that only sites in non-contiguous wards were selected. A pre-survey visit was made to each point location to confirm the nearest village and obtain permission from the local government representative to conduct a household survey. In the second stage, in each village, ten households with dairy cows were sampled by randomly selecting transects across the village and sampling every fifth household along the transect until the desired samples were obtained (Staal et al., 2002). A pre-tested structured questionnaire was administered by trained enumerators to interview dairy farmers from 429 households. The questionnaire is presented in Wilkes et al. (2019). The questionnaire collected primary data on herd composition, milk yield of individual cows, feed rations and feeding practices, manure management, feed production and other farming practices. Heart girth measurements were taken of one animal of each sub-category present on each farm, which were converted to live weight estimates using a Box-Cox linear regression validated for East African dairy cattle (Goopy et al., 2018a).

After data entry and cleaning, 15 households were dropped due to data quality issues. Live weight for animals that had not been measured were interpolated using predictive mean matching in IBM SPSS Statistics v.1.0.0, as described in Wilkes et al. (2019). The analysis presented in this paper focuses on GHG emission intensity (kg CO_2e/kg FPCM), and a further 32 households that had dairy cattle but did not produce milk in the year prior to the survey were dropped from the analysis. GHG emissions were calculated for 1284 individual cattle and 382 farms using a Life Cycle Assessment (LCA) approach.

3.3. Carbon footprint methodology

The attributional LCA method was used to assess 'cradle to farm gate' GHG emissions over one year on each of the 382 farms surveyed, and the CF is expressed as kg CO_2e per kg FPCM (fat and protein corrected milk). Carbon dioxide equivalent (CO_2e) units were calculated by applying global warming potentials for carbon dioxide, methane and nitrous oxide from the Fourth and Fifth IPCC assessment reports (IPCC, 2007, 2013). Calculation of CF was implemented using a model programmed in Microsoft Excel.

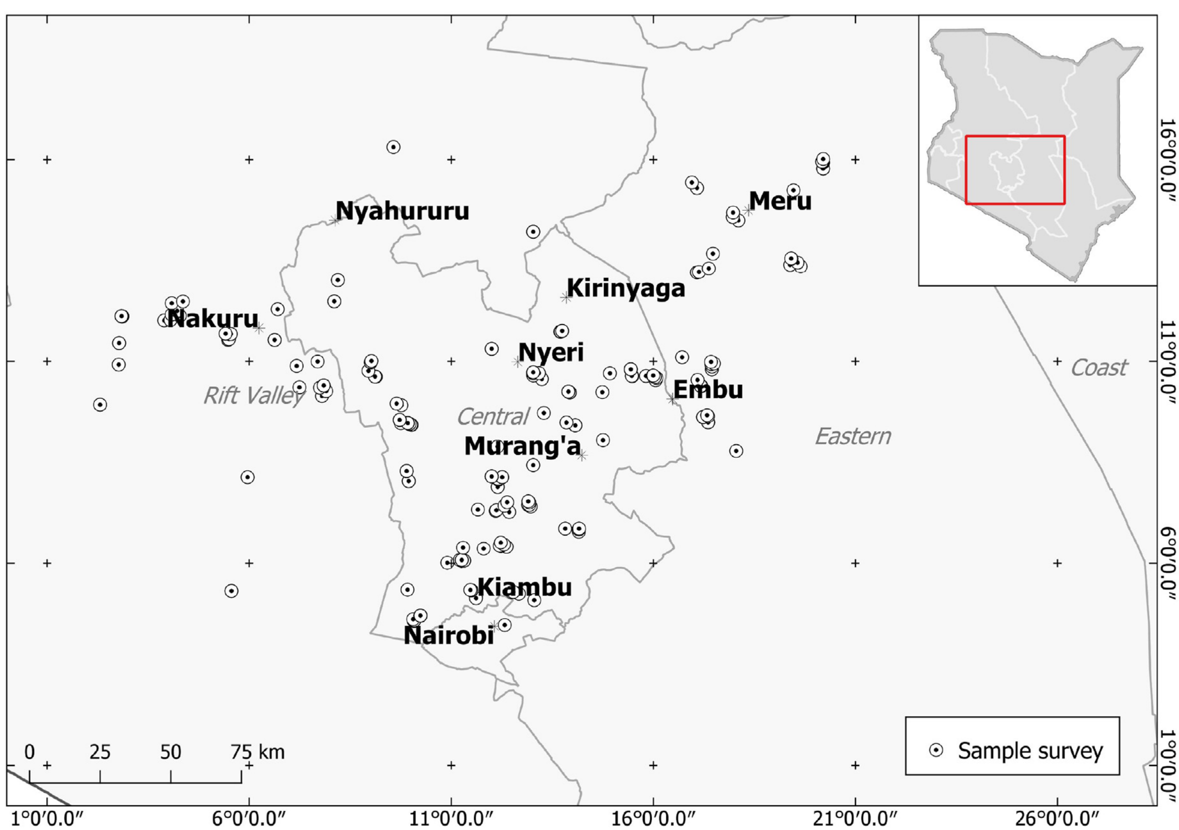

Fig. 1. Location of survey sites in central Kenya
Source: This study.

3.3.1. System boundary definition

The system boundary, determined following guidance in FAO (2016), was 'cradle to farm gate'. A schematic diagram of the system boundary is shown in Fig. 2. The system boundary included on-farm processes (i.e., feed production and processing, dairy cattle management and manure management) and off-farm processes (i.e., energy production, production and transport of imported feeds, and replacement animals kept off-farm). All major emissions of methane (CH_4), nitrous oxide (N_2O, direct and indirect) and carbon dioxide (CO_2) were accounted for. Consistent with guidance in FAO (2016), facilities and equipment with a lifetime greater than one year were excluded, but replacement animals kept off-farm were included. Replacement rates for male and female cattle were calculated for each farm following the method set out in FAO and ILRI (2016), and where insufficient replacement animals were kept on-farm, the average annual emissions from on- and off-farm processes were calculated for each replacement animal type (i.e., heifers, growing males) and attributed to each farm.

3.3.2. Functional unit and allocation

The functional unit used is kg CO_2e/kg FPCM, as recommended by FAO (2016). Milk yield (litres) was converted to kg using a standard density of 1.031 kg/L and corrected following equations described by (Opio et al., 2013) assuming 4.1% fat and 3.3% protein content based on small-scale surveys near Nairobi (Kabui, 2012) and in Nakuru (Kashongwe et al., 2017). Dairy farming plays multiple roles in smallholder farmers' livelihoods, providing nutrition (i.e., milk, meat) and income (e.g. from sale of animals and animal products), as well as other social and cultural services (Weiler et al., 2014). In our study, only two out of 382 dairy farms sold manure, so the products of dairy production considered included milk and live animals sold for meat. Emissions were attributed to milk production using three different allocation methods: economic allocation based on the prices of milk and live animals, mass allocation based on the protein content in milk and meat produced at the farm level, and no allocation where all GHG emissions were allocated to milk production at the farm level.

3.3.3. Inventory analysis

The questionnaire collected data on farm management activities in the year prior to the survey, including all animals present on the farm at the time of the survey and all animals that exited or entered the farm in the year prior to the survey. Thus, the GHG emissions estimated were representative for the 365 days prior to the date of each survey. Emissions were calculated for each individual animal and then summed for each farm. The data sources and values of default parameters used in calculating GHG emissions are given in the Supplementary Information Table S1.

3.3.3.1. Methane emissions from enteric fermentation. Enteric CH_4 emissions were estimated based on gross energy intake (GEI) calculated using the Tier 2 method and a CH_4 conversion factor of 6.5% (IPCC, 2006). To estimate the digestibility of feed, dry matter (DM) intake of each individual animal was predicted using equations 10.17−10.18 in IPCC (2006). The composition of DM intake was estimated based on farmer-reported estimates of the mass of each feedstuff fed with three adjustments as follows: 1) Assuming that farmer-reported mass of concentrate and supplements fed are more accurate than for roughage, when the total mass of farmer-reported feed intake exceeded predicted DM intake, a correction factor was applied to roughage so that total DM fed equalled DM requirement without changing the proportion of different roughage components reported by the farmer; 2) In semi-zero grazing or grazing systems, if reported feed intake volumes were less than predicted DM intake requirements, the difference was assumed to be derived from grazing on natural pasture; 3) Dry matter conversion coefficients and feed digestibility values were taken from published literature for Kenya (Goopy et al., 2018b; Ndung'u et al., 2018; Kirwa et al., 2015; Nyaata et al., 2000), East Africa (Laswai et al., 2013), the ILRI Sub-Saharan Africa Feed Database (https://feedsdatabase.ilri.org/) and Feedipedia (https://www.feedipedia.org/).

3.3.3.2. Emissions from feed production and transport. Feed emission factors (kg CO_2e kg DM^{-1}) were calculated from survey data for Napier grass (*Pennisetum purpureum*), other cultivated grasses (e.g. Rhodes grass [*Chloris gayana*], Kikuyu grass [*Pennisetum*

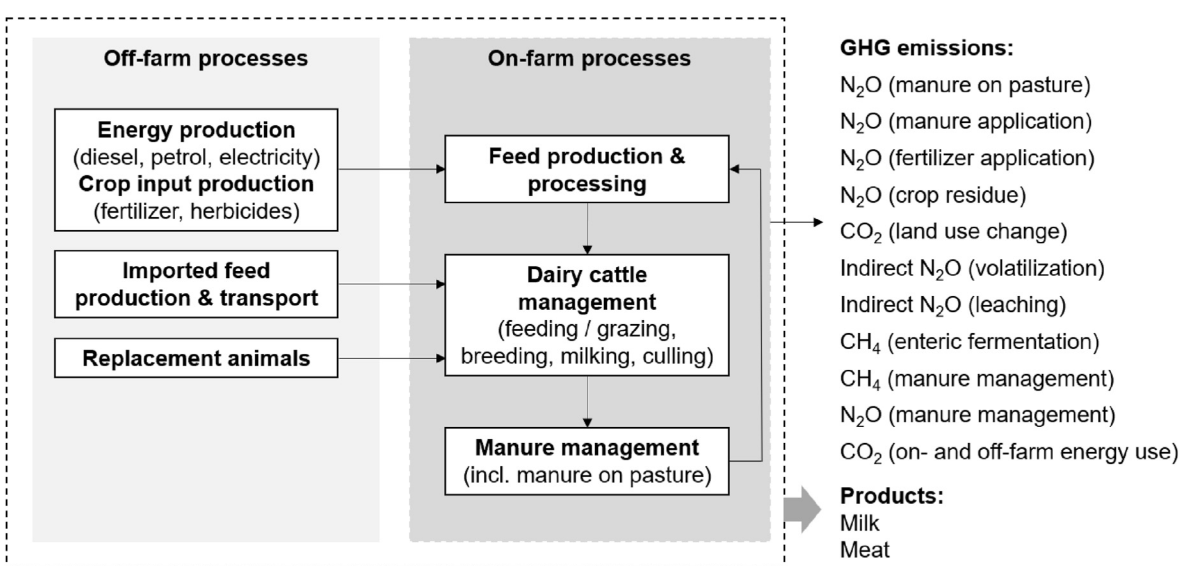

Fig. 2. Schematic diagram of the system boundary used to estimate cradle to farm gate emissions from milk production in this study.
Source: This study.

clandestinum], Star grass [*Cynodon dactylon*]), maize (*Zea mays*) and oats (*Avena sativa*), including: CO_2 emissions in fertilizer and herbicide production; CO_2 emissions from fuel use in transport of farm inputs, cultivation, irrigation and harvesting, feed transport to the farm and processing on-farm; CO_2 emissions from land use change; and N_2O emissions from manure and fertilizer application and crop residues. To avoid double-counting, direct and indirect N_2O emissions from deposit of urine and dung on pasture were accounted for in manure management and not attributed to feed production of natural pastures. An emission factor for wheat residue was calculated from (FAO and LEAP, 2015). For commercial concentrate and dairy meal mixed on farm, feed composition was estimated based on data from the National Farmers Information Service (www.nafis.go.ke) and (Kitalyi et al., n.d.) and emission factors for each ingredient were taken from FeedPrint (Vellinga et al., 2013). FeedPrint was also used to estimate emission factors for other feeds and supplements purchased off-farm. Our estimated emission factor for concentrate feed (1.13 $kgCO_2e\ kg\ DM^{-1}$) is lower than an estimate by Weiler et al. (2014) (i.e., 1.36 $kgCO_2e\ kg\ DM^{-1}$). FeedPrint is based on feeds available in the Netherlands. Dutch feed processors are likely to be more efficient that Kenyan feed processors and Kenya has a higher grid emission factor than the Netherlands. However, no other country-specific feed emission factors were available for use. Digestibility and emission factors used for the major feedstuffs identified in the survey are shown in Table 1.

3.3.3.3. Emissions from manure management. Direct and indirect N_2O and CH_4 emissions from manure management were calculated for each animal using the IPCC Tier 2 method (IPCC, 2006). The fraction of manure managed in each manure management system used survey data from each farm. CH_4 conversion factors were selected considering average annual mean air temperature (°C) in each county (Harris et al., 2014). For manure management N_2O emissions, nitrogen excretion was estimated by subtracting nitrogen retention from nitrogen intake (IPCC, 2006). Nitrogen intake was estimated following the IPCC equations using crude protein content of each feedstuff taken from the same sources used for feed digestibility.

3.4. Data analysis

Previous studies in Kenya have identified associations between milk yield and feeding system (Bebe et al., 2003). Feeding systems in central Kenya include zero-grazing, semi-zero grazing and grazing systems. Allocation of each household to one of these feeding systems was done using survey data on feeding practices for cows and heifers in the wet and dry seasons. Thus, if no cows or heifers obtained feed through grazing in either season, the household was categorized as zero-grazing. If all cows and heifers were reported to graze every day in both seasons, the household was categorized as a grazing feeding system. If any cows or heifers obtained some feed through grazing but was stall-fed at other times, the farm was categorized as semi-zero grazing.

Descriptive statistics were calculated using Minitab 19.1.1.0 7. Mean comparisons were made using the Kurskall-Wallis non-parametric test for data not normally distributed and using one-way ANOVA for normally distributed data. Because CF and several input variables were not normally distributed, factors associated with variation in CF were analysed using power and logarithmic regression and Spearman rank correlations performed in IBM SPSS Statistics v.1.0.0. We also used stepwise multiple linear regression to identify factors associated with relative prediction error from regressions of milk yield against CF. Here, we calculated the relative prediction error as:

$$RE = (x_{obs} - x_{pred})/x_{pred}$$

For all statistical tests, significance was set at $P \leq 0.05$ unless otherwise noted in the text.

Sensitivity analysis was conducted by running the CF model using different allocation methods and GWPs. Uncertainty analysis was also conducted using Monte Carlo simulation implemented in Palisade @Risk software to quantify the uncertainty of CF estimates and to identify the model inputs that contributed most to uncertainty. Uncertainty analysis was applied to data from farms with the median CF in each feeding system and to the farm with the median CF among all 382 farms. Owing to lack of empirical data on variance in emission factors for individual feed types, uncertainty analysis was implemented on a simplified version of the LCA model in which an overall uncertainty range of ±25% of the mean was applied to feed emissions per farm as a single category. This uncertainty range was estimated on the basis of uncertainty analysis of whole dairy rations in Vellinga et al. (2013), with additional consideration for uncertainty in the applicability of emission factors in FEEDPRINT to the Kenyan context. All other GHG emission sources were modelled in detail as in the original CF model. The specific values for variance of each parameter, the probability density functions used and the references consulted are listed in Supplementary Information Table S2. Multiple regression

Table 1
Feed emission factors and feed digestibility for the main diet components used in this study.

Feed	Emission factor (kg CO_2e/kg DM)	Digestibility (%)		
		Fresh	Dry	Silage
Natural pasture	0.000	60.2	n.a.	n.a.
Napier grass	0.028	58.7	55.3	53.7
Rhodes grass	0.028	57.7	55.6	58.6
Kikuyu grass	0.028	66.0	56.0	56.15
Star grass	0.028	55.8	50.1	56.15
Maize thinnings	0.057	64.2	52.6	n.a.
Maize stover	0.038	64.2	52.6	69.4
Maize silage	0.060	n.a.	n.a.	69.4
Commercial concentrates	1.131	n.a.	64.6	n.a.
Home-made dairy meal	1.373	n.a.	71.4	n.a.
Wheat bran	0.849	n.a.	71.4	n.a.
Maize bran	1.295	n.a.	72.4	n.a.
Maize germ	1.110	n.a.	85.6	n.a.

n.a. indicates not applicable. Sources: Emission factors are from this study and Vellinga et al. (2013). Digestibility values are from Goopy et al. (2018b), Ndung'u et al. (2018), Kirwa et al. (2015), Nyaata et al. (2000), Laswai et al. (2013), the ILRI Sub-Saharan Africa Feed Database (https://feedsdatabase.ilri.org/) and Feedipedia (https://www.feedipedia.org/).

coefficients normalized by the standard deviation of the output were used to compare the relative contribution of input variables to uncertainty in the output variable (Basset-Mens et al., 2009). Thus, a regression coefficient of 0 indicates no relationship between an input variable and CF, while a value of 1 or -1 indicates that a 1 or -1 standard deviation change in the input variable will lead to a 1 or -1 standard deviation change in the CF.

4. Results

4.1. Characterization of dairy production systems

Of the 382 households surveyed, 64%, 25% and 11% of households used zero-grazing, semi-zero and grazing only feeding systems, respectively. The mean number of cattle per household was 3.36 ± 7.84. Average herd size in this study is much smaller than in CF studies in developed countries (e.g. Hagemann et al., 2011), but is typical of average herd size in developing countries (Hemme and Otte, 2010). Cows accounted for 54.5% of the total 1284 animals enumerated, which is similar to the percentage reported in other studies of smallholder farms in Africa (e.g. Reinecke and Casey, 2017; Udo et al., 2016) and Asia (e.g. Garg et al., 2016; Wang et al., 2016). Heifers, calves, and males more than one year old accounted for 18.2%, 19.6% and 7.7%, respectively. Herd structure was broadly similar across the different feeding systems (Table 2). Males were the most common type of animal sold, and the vast majority of sales were to meet planned household expenditures (data not shown).

Major feed resources consumed by dairy cattle included natural pasture, Napier grass, maize, commercial and homemade concentrate, and other feed resources (e.g. crop residues, industrial by-products). Cultivated protein supplements (e.g. *Calliandra* leaves) were fed to less than 5% of all animals. The use of feed resources differed between feeding systems (Table 3). Natural pasture contributed significant proportions of total diet consumed in both grazing only (44%) and semi-zero grazing (26%) dairy farms, but was only consumed by small numbers of male animals in zero-grazing farms. Maize (including maize thinnings, green and dry stover, and silage) and cultivated grasses accounted for 64.4% of total DM intake on zero-grazing farms, 47.2% on semi-zero grazing farms and 30.0% on grazing only farms (Table 3). Concentrates were either purchased commercially produced concentrates, or homemade concentrates made using purchased ingredients, and were fed on 93% of zero-grazing farms, 92% of semi-zero grazing farms and 86% of grazing farms (authors' survey). The average proportions of concentrates, supplement feeds (e.g. maize germ, maize bran, wheat bran) and mineral supplements in total diets were higher on zero-grazing and semi-zero grazing farms than on grazing farms (Table 3). The proportion of concentrates in this study were much lower than average rates in dairy LCA studies of confined and mixed grazing systems in other countries (Lorenz et al., 2019), but similar to proportions reported on smallholder farms in India (Garg et al., 2016). Feed digestibility averaged across all animal types followed the order zero grazing > semi-zero grazing > grazing. Overall, feed digestibility on the farms surveyed was much lower than typical values (i.e. 70%–77%) in dairy farming systems in developed countries (IPCC, 2019). About half of households feeding concentrate to cows reported feeding 2 kg or less per day, and only 43% of households reported varying concentrate feed levels during lactation (authors' survey), suggesting that concentrate feeding practices may constrain milk yields.

Manure management systems differed between farms with different feeding systems (Table 3). About two thirds of manure was managed in solid storage systems in both zero grazing and semi-zero grazing systems, compared to one third in grazing systems. Almost half of manure was deposited on pasture in grazing systems, compared to 12.4% in semi-zero grazing systems. Daily spread and composting were more common on zero-grazing farms than other farm types.

Average daily milk yield per cow (kg FPCM) was higher in zero-grazing farms than in semi-zero and grazing only farms, which had similar milk yields (Table 4). However, average milk yields per cow in all feeding systems were very low, and at 2450 kg FPCM cow^{-1} year^{-1} were about 28% lower than the lowest milk yield reported in a meta-analysis of 30 CF studies (Lorenz et al., 2019). In addition to differences in feed composition and feeding system, cows on zero-grazing farms on average had greater live weight than on other farms. All cows on zero-grazing farms were either Holstein-Friesian or Ayrshire and their crosses with local breeds, while 13% of cows on semi-zero or grazing farms were of other, typically smaller breeds with lower milk yields, such as Jersey, Guernsey and local breeds. After normalizing the data, total milk yield per farm averaged 3249 ± 2.26 kg FPCM per year, and varied considerably both between and within feeding systems, with 3467 ± 2.27 kg in zero-grazing farms, 3090 ± 2.17 kg in semi-zero grazing farms and 2570 ± 2.29 kg in grazing only farms. This variation in total milk yield per farm reflects variation in average yields per cow and variation in the numbers of productive cows per farm.

4.2. Sources of greenhouse gas emissions from dairy farms

Enteric fermentation (CH_4) was the primary source of GHG emissions, accounting for 55.5% of total GHG emissions, followed by GHG emissions from feed production and transport (31.6%) and CH_4 and N_2O emissions from manure management (12.6%). Emissions from replacement animals kept off-farm were a very small proportion (0.3%) of total emissions. Other CF studies also find that enteric fermentation is the largest source of GHG emissions, and several studies have also found that feed production is the second largest source (e.g. Wang et al. 2016; Garg et al., 2016; Morais et al., 2018). In the grazing system, manure management emissions were similar to feed emissions, as has also been reported in other grazing

Table 2
Herd structure on farms with different feeding systems in central Kenya.

Herd structure	Feeding system								
	Zero-grazing (N = 245)			Semi-zero grazing (N = 95)			Grazing only (N = 42)		
	Mean ± SD	Median	Range	Mean ± SD	Median	Range	Mean ± SD	Median	Range
Head per farm	3.3 ± 2.0	3	1–11	3.5 ± 2.6	3	1–14	3.3 ± 2.0	3	1–12
Cows	1.8 ± 1.1	1	1–9	1.9 ± 1.5	1	1–8	1.8 ± 1.2	1	1–7
Heifers	0.6 ± 0.8	0	0–4	0.7 ± 0.8	0.5	0–8	0.6 ± 0.9	0	0–3
Calves	0.7 ± 0.9	0	0–4	0.7 ± 0.9	0	0–5	0.5 ± 0.7	0	0–2
Adult males	0.1 ± 0.4	0	0–3	0.1 ± 0.4	0	0–2	0.2 ± 0.5	0	0–2

Source: Authors' survey

Table 3
Diet composition and feed digestibility (%, mean ± SD), percent of manure managed in different manure management systems and contribution of GHG emission sources for dairy farms with different feeding systems in central Kenya.

Variable	Feeding system		
	Zero-grazing N = 245	Semi-zero grazing N = 95	Grazing only N = 42
Feed type			
Grazing (natural pasture)[a]	0.36 ± 5.57	25.5 ± 32.5	43.6 ± 36.9
Napier grass	24.8 ± 22.1	13.6 ± 12.8	8.13 ± 9.80
Other grasses[b]	9.22 ± 18.2	5.86 ± 13.5	5.80 ± 13.1
Maize	30.4 ± 24.7	27.7 ± 23.5	16.1 ± 23.2
Protein supplement[c]	1.11 ± 6.28	0.51 ± 3.48	0.26 ± 1.67
Concentrates[d]	9.81 ± 10.4	7.47 ± 8.18	7.86 ± 8.70
Germ[e]	3.58 ± 7.57	3.29 ± 9.28	1.06 ± 4.26
Mineral blocks	5.09 ± 9.6	4.59 ± 8.21	3.68 ± 8.15
Other feed resources[f]	15.9 ± 19.5	11.5 ± 17.7	13.6 ± 22.2
Total	100	100	100
Feed digestibility (%)	60.05 ± 3.83	59.66 ± 3.67	58.88% ± 4.53
Manure management system (%)			
Deposited on pasture	0.9 ± 7.0	12.4 ± 24.9	46.8 ± 36.2
Solid storage	62.8 ± 43.9	66.0 ± 41.4	35.2 ± 36.7
Drylot	4.8 ± 16.6	2.7 ± 13.0	4.3 ± 17.0
Daily spread	11.8 ± 28.0	7.1 ± 23.0	8.3 ± 22.1
Composted	12.5 ± 30.0	7.6 ± 23.5	5.0 ± 17.8
Liquid storage	1.6 ± 9.8	2.3 ± 11.8	0.2 ± 1.5
Biogas	4.8 ± 17.65	1.8 ± 10.7	0.2 ± 1.5
Total	100	100	100
Contribution of GHG sources to total GHG emissions per farm per year (%)			
Enteric fermentation	57.03 ± 12.38[a]	60.27 ± 11.69 [ab]	62.96 ± 11.05 [b]
Manure management	11.71 ± 4.00[a]	14.28 ± 4.46 [b]	17.68 ± 4.88 [c]
Feed production and transport	31.32 ± 14.24[a]	25.45 ± 14.50 [ab]	19.36 ± 13.45 [b]
Replacement animals off-farm	0.00 ± 0.00 [a]	0.45 ± 1.62 [ab]	1.03 ± 1.91 [b]

Note: Different superscript letters in the same row indicate significant differences between feeding systems ($P \leq 0.05$).
[a] Natural pasture in the zero-grazing system is due to grazing by small numbers of male animals.
[b] Other grasses include Rhodes grass, Kikuyu grass and Star grass.
[c] Protein supplements include Lucerne, *Lucaenia*, *Desmodium* and *Calliandra*.
[d] Includes commercial and homemade concentrate.
[e] Wheat bran, maize bran and maize germ.
[f] E.g. oat residue, sweet potato vine, banana residues, weeds, etc.
Source: Authors' survey and this study.

systems (e.g. Gollnow et al., 2014). The main difference with some other studies (e.g. Henriksson et al. 2011; Morais et al., 2018) is that on-farm energy use was not a significant GHG source in central Kenya.

The structure of total GHG emissions varied between feeding systems (Table 3). Enteric CH_4 was the largest source of emissions in all three feeding systems, and was significantly higher in the grazing system than in the zero-grazing system ($P \leq 0.05$), which may be due to lower average feed digestibility in grazing farms compared to other farms (Table 3). The main feed resources in grazing feeding systems are typically lower quality in terms of crude protein and metabolizable energy concentration than in zero-grazing farms. This lower quality ration results in lower energy digestibility of diets in grazing feeding systems, which not only implies low feed dry matter intake and animal productivity (milk yield), but also high enteric CH_4 emissions (Archimède et al., 2011). The average enteric fermentation emission factors for dairy cows in different feeding systems are shown in Table 4.

The proportion of GHG emissions (CO_2, CH_4, N_2O) related to feed production and transport were significantly higher (31.3%) in zero-grazing dairy farms than in semi-zero grazing (25.5%) or grazing (19.4%) dairy farms ($P \leq 0.05$) (Table 3). The high GHG emission from feed production and transport with zero-grazing reflects the higher volumes of feed fed and greater dependence on off-farm

Table 4
Production characteristics and enteric methane emission factors (kg CH_4 cow^{-1} year^{-1}) of dairy cows in different feeding systems in central Kenya.

	All cows	Zero-grazing	Semi-zero grazing	Grazing only
	N = 700	N = 443	N = 182	N = 75
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Dry matter intake (kg/year)	3623 ± 857	3713 ± 877	3509 ± 778	3367 ± 845
Live weight (kg)	366 ± 63	372 ± 65.8	360 ± 57.7	351 ± 54.5
AFC (months)	27 ± 3.8	27 ± 4	28 ± 4	27 ± 4
Milk production				
kg FPCM/cow/day	6.7 ± 3.9	7.3 ± 4.1	5.7 ± 3.4	5.8 ± 3.5
kg FPCM/cow/year	2450 ± 1422	2657 ± 1483	2085 ± 1243	2110 ± 1222
Enteric EF (kg CH_4/cow/year)	78.1 ± 20.3	79.9 ± 20.8	74.4 ± 18.9	76.4 ± 18.9

AFC: age at first calving; FPCM: fat and protein corrected milk; EF: emission factor. *Source: This study.*

feed products. Positive correlations between concentrate feed and CF (Table 8) further suggest the importance of concentrate feed in driving feed GHG emissions. In this study, the lower proportion of total GHG emissions from feed production and transport on grazing-only farms reflects both the smaller proportion of DMI consumed in the form of cultivated grasses, crop residues and purchased supplements, as well as allocation of N_2O emissions from urine and dung deposited on pasture to manure management rather than feed production in the CF model used. Total emissions from manure management were higher in grazing-only (17.7%) than in semi-zero (14.3%) and zero-grazing (11.7%) dairy farms (Table 3). This is due to a greater proportion of excreta deposited on pasture in grazing systems, causing much greater direct and indirect N_2O emissions in grazing systems when estimated using the IPCC default emission factors (IPCC, 2006).

4.3. Carbon footprint of milk production

4.3.1. Carbon footprint, sensitivity and uncertainty analysis

The CF of milk production (kg CO_2e/kg FPCM) was calculated for each farm using different allocation methods and global warming potentials (GWPs) (Table 5). Using GWPs from IPCC (2007), with all emissions allocated to milk, average CF was 2.99 kg CO_2e/kg FPCM. When GHG emissions were allocated between milk and meat on the basis of their protein content, the CF of milk production was 2.45 kg CO_2e/kg FPCM, and on average 88% of total GHG emissions were allocated to milk. Using prices for crop products, milk and live animals current at the time of the survey, the mean CF with economic allocation was 2.19 kg CO_2e/kg FPCM. CF increased when GWPs from IPCC (2013) were used. This is because CH_4 is the largest source of GHGs from the farms surveyed, and the GWPs for CH_4 were 25 and 28 in the Fourth and Fifth Assessment Reports, respectively, while the GWP for N_2O decreased from 298 to 265. For comparability with existing literature, the remaining analysis uses the IPCC (2007) GWPs and CFs calculated using mass allocation. The average CF estimated in this study is higher than CFs analysed in a recent meta-analysis if studies in middle income and developed countries (Lorenz et al., 2019), but similar to estimates in India (Garg et al., 2016) and the global average for milk from dairy and non-dairy cows estimated by FAO (Opio et al., 2013).

Zehetmeier et al. (2014) distinguish between variability uncertainty, which is due to inherent variability in input parameters, and epistemic uncertainty due to data quality. The standard deviations of mean CFs reported in Table 5 indicate that the mean CF estimated in our study had a margin of error of about ±16% at a 95 percent confidence interval. This range of variability is significantly larger than the margin of error reported in dairy CF studies based on large samples of farms in Europe (e.g. O'Brien et al., 2012), North America (e.g., Jayasundara et al., 2019) and Oceania (Gollnow et al., 2014), which range between ±2.5% and ±4.0%. However, a study of smallholder farms in India showed a similar wide range of estimated CFs due to input variability (Garg et al., 2016). This is most likely because inter-household differences in adoption and efficient use of improved genetics, nutrition and animal health practices are greater on smallholder farms in developing countries than in more developed contexts (Mayberry et al., 2017).

Table 5
Carbon footprint (kg CO_2e/kg FPCM) of milk production on dairy farms in central Kenya (mean with s.d. in parentheses).

	IPCC (2007) GWPs	IPCC (2013) GWPs
100% allocated to milk	2.99 (2.32)	3.13 (2.39)
Protein mass allocation	2.45 (1.50)	2.56 (1.56)
Economic allocation	2.19 (1.43)	2.30 (1.50)

Source: This study.

Regarding data quality and measurement uncertainty, Monte Carlo simulation of the estimated CF for the median farm indicates an uncertainty of (+28.2%, −22.8%). The uncertainty range was lower for the median zero-grazing farm (+28.0%, −22.3%) than for the median semi-zero (+31.3%,-23.9%) and grazing (+46.6%,-33.0%) farms. These uncertainty ranges are larger than the ±11.5% estimated in a study of New Zealand dairy farms based on statistical data (Basset-Mens et al., 2009) and the range of uncertainties (±16.9% to ±21.0%) reported in a study of Irish dairy farms based on survey data (Casey and Holden, 2005). This reflects differences in assumptions applied in the uncertainty analysis as well as greater uncertainty associated with data collection methods used in this study. The main sources of uncertainty varied between feeding systems (Table 6). Milk yield, milk protein content and feed digestibility ranked in the top four sources of uncertainty in all three feeding systems. Feed emissions were the most influential source of uncertainty in the zero-grazing system, in which feed emissions account for a large proportion of total emissions (Table 3), but were not strongly correlated with uncertainty for the median farm in the other feeding systems. For the median grazing farm only, uncertainty was also influenced by uncertainty in crude protein content of the diet, the proportion of manure deposited on pasture and the emission factor for manure deposited on pasture, all of which are related to N_2O emissions from manure deposited on pasture.

4.3.2. Comparison between feeding systems

When estimated using mass allocation, the CF was similar between zero-grazing (2.2 kg CO_2e/kg FPCM) and semi-zero grazing (2.4 kg CO_2e/kg FPCM) systems, but CF in the zero-grazing system was significantly lower ($P < 0.05$) than in the grazing system (3.0 kg CO_2e/kg FPCM) (Table 7). This difference may be attributed to the higher feed efficiency in zero-grazing farms, implying that zero-grazing farms used less feed of higher quality to produce more milk compared to other farms. However, this finding is based on variability in farm characteristics alone. When uncertainty of the input parameters (Section 4.3.1) is considered, the 95% confidence intervals of the CF in zero-grazing and grazing farms overlap, suggesting that there are no significant differences between feeding systems. This is consistent with the conclusion of Chen and Corson (2014) who stressed the importance of considering input parameter uncertainty when comparing farm types.

4.3.3. Determinants of variation in GHG intensity and carbon footprint

Various factors affect GHG intensity at the individual animal level and CF at the farm level. Plotting kg FPCM per cow against GHG intensity (kgCO_2e/kg FPCM) shows that differences in GHG intensity among individual cows are explained largely by milk yield performance ($R^2 = 0.72$, Fig. 3). This is consistent with the findings of many studies of the relationship between GHG intensity and milk yield (Lorenz et al., 2019) and can be attributed to the 'dilution of maintenance' effect (VandeHaar and St-Pierre, 2006) whereby increases in milk yield result from cows using a smaller proportion of feed energy and protein intake for maintenance and a greater proportion for milk production. Fig. 3 also shows that this relationship is most strongly driven by the relationship between milk yield and the intensity of enteric fermentation ($R^2 = 0.84$). Manure management emissions, which are also related to GEI, have a moderate relationship with milk yield ($R^2 = 0.54$), while emissions embodied in feed have a weak relationship with milk yield at the individual cow level ($R^2 = 0.23$).

A Kruskall-Wallis test showed a statistically significant difference in GHG intensity per cow for large breeds (i.e. Holstein-Friesian and Ayrshire) compared to other breeds ($\chi^2 = 29.275$, $p < 0.001$). Feed efficiency (FE) had a significant non-linear

Table 6
Regression coefficients and rank orders of input variables influencing uncertainty of carbon footprint (CF) estimates for farms with median CF in different feeding systems in central Kenya.

Parameter	Zero-grazing		Semi-zero grazing		Grazing only	
	Regression coefficient	Rank order	Regression coefficient	Rank order	Regression coefficient	Rank order
Milk yield	0.48	2	0.43	1	0.59	1
Feed digestibility	0.16	4	0.24	3	0.48	2
Milk protein content	0.22	3	0.3	2	0.27	4
Live weight	–	–	0.14	5	0.32	3
Feed emissions	0.52	1	–	–	0.12	8
Y_m	–	–	0.12	7	0.21	6
Milk fat content	0.11	5	0.13	6	0.12	8
Cf	–	–	–	–	0.12	8
EF_3, pasture	n.s.	–	n.s.	–	0.24	5
CP%	n.s.	–	n.s.	–	0.15	7
MMS%, pasture	n.s.	–	n.s.	–	0.1	10

'n.s.' indicates regression coefficient not significant; '-' indicates regression coefficient <0.1 or rank order not calculated; Y_m is enteric fermentation methane yield (%); Cf is coefficient for maintenance used in calculating enteric fermentation; EF_3 is emission factor for N_2O emissions from urine and dung N deposited on pasture (kg N_2O—N (kg N input)$^{-1}$; CP% is crude protein content of the diet; MMS%, pasture is the proportion of manure deposited on pasture. *Source: This study.*

Table 7
Milk yield, dry matter (DM) intake and carbon footprint (CF) of milk produced per farm in different feeding systems in central Kenya (mean values with s.d. in parentheses).

Parameter	All farms N = 382	Zero-grazing N = 245	Semi-zero grazing N = 95	Grazing only N = 42	SD[a]	P-Value
FPCM (kg/year)[b]	3249 (2.3)	3467.4^{A}	3090.3^{B}	2570.4^{C}	2.24	0.04
Total DM intake (kg/year)[b]	7651 (1.8)	7762.5	7585.8	7413.1	1.91	0.86
CF (mass allocation)	2.4 (1.4)	2.2 (1.2)^{B}	2.4 (1.7)^{AB}	3.0 (2.0)^{A}		0.05
Feed efficiency[c]	0.47 (0.3)	0.50^{A}	0.43^{B}	0.40^{B}		0.01

[a] Pooled standard deviation.
[b] Data were log transformed for ANOVA test of means.
[c] Feed efficiency calculated as kg FPCM/kg DM intake. Different superscript letters within the same row indicate significant difference at P ≤ 0.05. *Source: This study*.

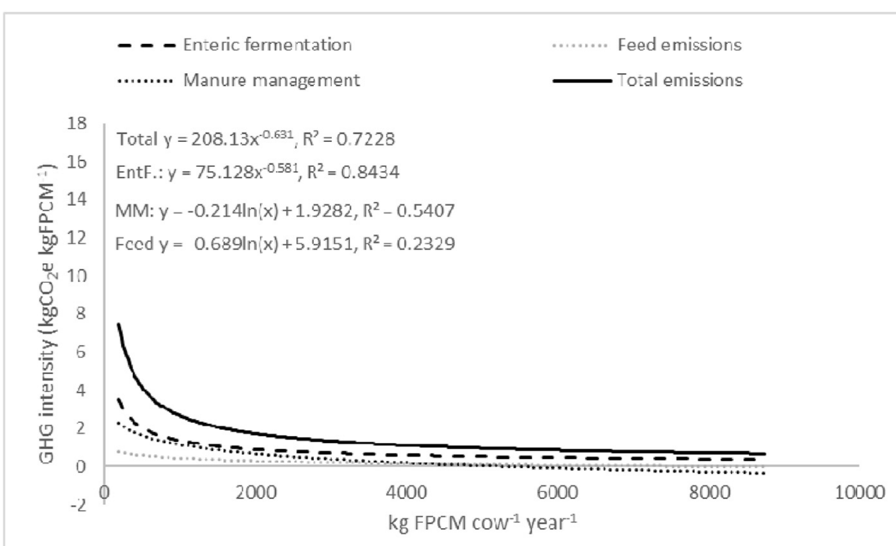

Fig. 3. Relationship between milk yield and GHG intensity of 700 dairy cows in central Kenya
Source: This study.

relationship with GHG intensity at the individual cow level (GHGI = $1.1006FE^{-0.742}$, R^2 = 0.79), such that GHG intensity fell below the average of 2.45 kg CO_2e/kg FPCM when FE exceeded 0.34 kg FPCM/kg DMI (Fig. 3). Because feed efficiency and GHG intensity were not normally distributed, associations with other variables were tested using Spearman rank correlations (Table 8). Among feed categories, there were significant negative correlations between FE and kg natural pasture and between FE and kg mineral supplement intake per day, and positive correlations between FE and kg concentrate intake per day. GHG intensity was significantly and negatively correlated with both kg Napier grass and kg total DM intake per day and positively correlated with DE, kg concentrate and kg mineral intake per day. The positive correlation between kg concentrate intake and GHG intensity is associated with low marginal returns to additional concentrate consumption: on most farms, FPCM yield increased by less than 1 kg FPCM per kg concentrate fed, while the emission factor for concentrate remained constant at 1.13 kg CO_2e per kg concentrate. Hence, the intensity of feed emissions ($kgCO_2e_{feed}$/kg FPCM) does not decline significantly if milk yield is increased beyond the average in the farms surveyed (Fig. 3).

At the farm level, variation in milk yield explains less than half of variation in CF ($R^2 = 0.48$, Fig. 4). The variation explained was largely due to enteric fermentation, as regressions of the intensity of manure management and feed emissions against milk yield were not significant (data not shown). At farm level, feed efficiency had a strong negative relationship with CF ($CF = 0.9639FE^{-1.125}$, $R^2 = 0.81$), as has also been found in other studies (e.g. Thoma et al., 2013). Spearman rank correlation between CF and feed characteristics showed a significant negative correlation with the proportion of roughage in total DMI per farm, and a positive correlation with kg concentrate per farm (Table 8). CF was positively correlated with the proportion of manure deposited on pasture, most likely reflecting both the greater proportion of roughage in diets of grazing animals and higher N_2O emissions from manure deposit on pasture. By contrast, CF was negatively correlated with the proportion of manure managed in solid storage. CF was also negatively correlated with the number of cows per farm and the proportion of cows in the herd, and positively correlated with numbers of heifers and adult male animals per farm. Numbers of calves per farm had no significant correlation with GHG intensity, since their contributions to total feed consumption and emissions were small. Thus, at farm level, GHG intensity of milk production is influenced by both feed characteristics and herd structure, with farms keeping a greater proportion of cows in the herd having lower GHG intensity, while farms maintaining males over one year old tend to have higher GHG intensity. This is similar to the findings of other studies, such Wang et al. (2016).

Milk yield explained less than half of the variability in CF at farm level (Fig. 4). Stepwise regression of farm characteristics against the relative prediction error at farm level suggests that model prediction error is most strongly related to kg concentrate fed per farm, herd size and herd structure (Table 9). Relative error was also related to the proportions of manure deposited on pasture and managed in solid storage. However, the explanatory power of manure management characteristics and some feed characteristics (e.g. proportion of roughage in DMI, DE) was small.

5. Discussion

5.1. CF of milk production and its uncertainty

Average CF of milk production estimated in this study (2.45 ± 1.50 kg CO_2e/kg FPCM) was within the range of estimates from other studies in Africa. FAO and NZAGRC (2017a) estimated 2.1 kg CO_2e/kg FPCM for intensive systems and 4.1 kg CO_2e/kg FPCM for semi-intensive systems in Kenya using the GLEAM model parameterized using data from expert judgement and a method that combines mass and economic allocation. Weiler et al. (2014) estimated a mean of 2.0 and range of 0.9–4.3 $kgCO_2e$/kg milk using economic allocation to milk and meat. Brandt et al. (2018) estimated 2.4 kg CO_2e/kg FPCM with no allocation. A study in Ethiopia using economic allocation estimated a range of 1.75–2.20 kg CO_2e/kg FPCM (Woldegebriel et al., 2017). Our estimate is much lower than the estimate by Opio et al. (2013), which included non-dairy milking cows, and higher than estimates for South Africa by Reinecke and Casey (2017) who modelled farms with much higher milk yields. The average CF estimated in this study is higher than all estimates included in a recent global meta-analysis of milk LCA studies in middle-income and developed countries (Lorenz et al., 2019), in which the maximum value was 2.15 kg CO_2e/kg FPCM. All the studies included in that meta-analysis had higher milk yields and higher feed efficiencies than the average in this study. Low milk yields and low feed efficiencies and feed digestibility were also associated with a CF of 2.3 kg CO_2e/kg FPCM in a study of smallholder dairy production in India (Garg et al., 2016). These comparisons suggest that feed quality and low milk yields are key drivers of higher CF in Kenya.

Table 5 confirmed that CF is sensitive to the method of allocation and the GWP conversion factors used, as has been found in other studies (Baldini et al., 2017). While none of the previous studies in Africa quantified input parameter uncertainty, this study estimated

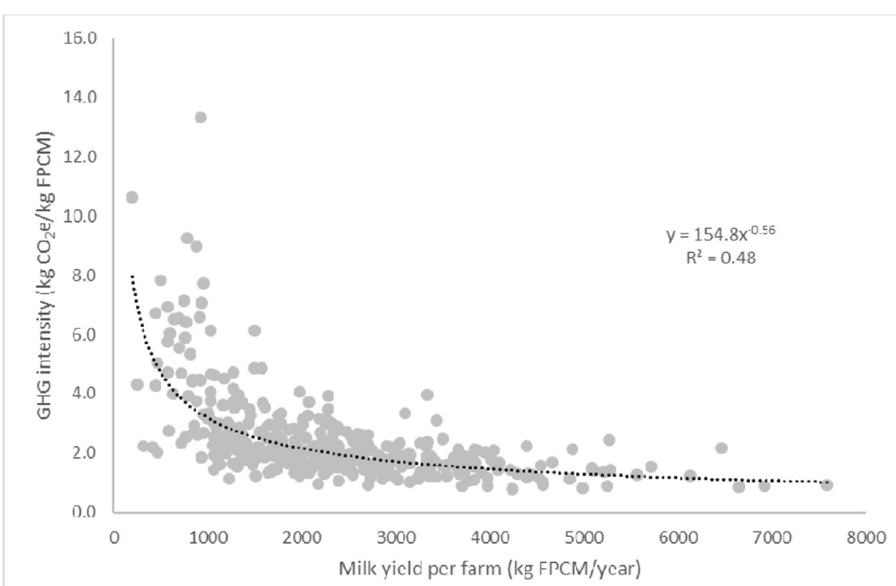

Fig. 4. Relationship between milk yield and GHG intensity of 382 dairy farms in central Kenya
Source: This study.

Table 8
Spearman rank correlations between feed efficiency (FE, kg FPCM/kg DMI), carbon footprint per farm (CF, $kgCO_2e$/kg FPCM) and individual cow and farm variables.

		Feed efficiency	CF
Per cow			
kg intake per day	Natural pasture	-.125**	-.005
	Napier grass	.065	-.134**
	Other grass	.052	-.290
	Maize	.061	-.027
	Protein feeds	.033	-.040
	Concentrates	.108**	.127**
	Germ	.41	.063
	Mineral supplement	-.078*	.155*
	Other feed stuff	.044	.031
	DMI	.057	-.090*
	DE (%)	-.056	.122**
Per farm			
Feed variables	Proportion of roughage in total DMI	-.117*	-.147**
	Proportion of pasture in total DMI	-.138**	.080
	DE	.025	.022
	kg concentrate per farm	.090	.152**
	DMI per farm per day	-.015	.069
MMS			
	Proportion of manure deposited on pasture	-.143**	.124*
	Proportion of manure managed in solid storage	.182**	-.121*
Herd variables	Total cattle numbers	-.096	.138**
	Number of cows	.221**	-.180**
	Number of heifers	-.221**	.232**
	Number of calves	-.018	.037
	Number of adult males	-.253**	.276**
	Proportion of cows in total cattle	.424**	-.426**

MMS indicates manure management system variables. *indicates significance at $p \leq 0.05$, ** at $p \leq 0.01$, 2-tailed test. *Source: This study.*

Table 9
Stepwise regression of farm characteristics against relative error of prediction of the relationship between milk yield per farm and GHG intensity.

Term	Coefficient	SE of coefficient	P-value	VIF	R^2 adj.
Constant	1.218	0.375	0.001		
kg concentrate per farm	0.03289	0.00409	0.000	3.77	53.15%
Number of cows per farm	0.1911	0.0181	0.000	2.24	60.01%
Proportion of cows in the herd	−0.6158	0.0818	0.000	1.67	70.73%
Number of adult males per farm	0.2605	0.039	0.000	1.12	73.59%
Number of heifers per farm	0.0925	0.0233	0.000	1.56	74.51%
Proportion of dung and urine deposited on pasture	0.001686	0.000615	0.006	1.04	74.83%
Proportion of roughage in DMI	−0.533	0.161	0.001	2.79	75.17%
DE	−0.0118	0.00502	0.019	1.61	75.44%
Proportion of manure managed in liquid storage systems	0.0027	0.00124	0.031	1.12	75.68%

Source: This study.

the uncertainty of the point estimate of median CF to be (+28.2%, −22.8%). This high uncertainty range has three implications. First, consideration of input parameter uncertainty limits our ability to compare point estimates between production systems and between studies (Chen and Corson, 2014). Second, point estimates are less informative than the distribution around the mean and its association with variability in farm management practices, which may indicate opportunities for reduction in GHG intensity (Thoma et al., 2013). Third, the high uncertainty estimated in this study highlights the need for improvements in data collection methods to better estimate the CF of milk production in data poor contexts, such as central Kenya.

5.2. Mitigation of GHG emissions in milk production

Gerber et al. (2011) suggested that the non-linear, negative relationship between milk yield per farm and GHG intensity indicates that increasing productivity at farm level is one potential mitigation strategy. Our study found that this relationship is strong at the individual cow level, but weaker at the farm level, where milk yield explained just under half of the variability in GHG intensity (Fig. 4). Thus, the level of analysis (e.g., animal or farm level) matters for analysis of GHG mitigation options (Van Middelaar et al., 2013). At farm level, the intensity per kg FPCM of enteric fermentation emissions has a strong negative relationship with increasing milk yield, but the decrease in the intensity of manure management emissions and emissions embodied in feed at the individual animal level (Fig. 3) was not found at the farm level (Fig. 4) in our study. This points to the relevance of enteric fermentation as an entry point for identifying mitigation options in central Kenya. This is similar to the findings of many LCA studies conducted with more intensive dairy production systems (e.g. Gollnow et al., 2014), but differs from production systems where practices such as liquid storage of manure mean that manure management is a hotspot of GHG emissions (e.g. Guest et al., 2017).

Feed efficiency, defined as kg FPCM per kg DM intake, is a critical indicator affecting CF of milk production (Henriksson et al., 2011). The numerator, kg FPCM, is part of the functional unit used to measure CF, while the denominator, kg DM intake, is related to feed which accounted for just about 29% of total emissions in this study, and both indicators are related to enteric fermentation which accounted for about 59% of total emissions. CF at farm level was strongly related to feed efficiency in this study, and feed efficiency was negatively correlated with the proportion of natural pasture and other roughage feedstuffs in the diet (Table 8). Most farmers surveyed feed limited amounts of concentrates to supplement the limited energy and protein supply from pasture or roughage (Table 3). However, in this study, although the use of concentrates was positively correlated with feed efficiency at individual cow level, there was no correlation at the farm level. Surveys in Kenya have consistently found that dairy farmers tend to feed a fixed amount of concentrate per cow per day (generally 2 kg) (e.g., Biwott et al., 1998). Despite changes in nutritional needs during lactation, the majority of farmers do not vary concentrate feed levels with the lactation stage of cows (Richards et al., 2015). As a consequence, forage:concentrate ratios are high (Kashongwe et al., 2017), and nutrition is often insufficient to support optimal lactation (Richards et al., 2015). Supplementing dairy cows prior to parturition (Muraya et al., 2018), and increasing DM and protein intake in early lactation (Richards et al., 2016) can significantly increase milk production. Because use of concentrate at individual cow and farm levels were positively associated with GHG intensity (Table 8), and explained more than half of the deviation from predicted milk yields (Table 9), our findings suggest that promoting balanced feed rations and feeding concentrates according to cows' needs throughout the lactation cycle could provide important opportunities to both increase milk production and reduce the CF of milk production. Improving the efficiency of concentrate use may be particularly relevant to households where milk yields per cow are below 2450 kg FPCM, because above this level feed emission intensity tends to decrease only weakly (Fig. 3). Since concentrate feeding is prevalent in all three feeding systems, this mitigation option has widespread relevance on dairy farms in central Kenya.

A nationwide program in India providing farmers with technical advice on feed ration balancing demonstrated significant reductions in the GHG intensity of milk production at the individual cow level over three years (Garg et al., 2018), which may provide a useful example of how large-scale adoption of improved feeding practices could be promoted in Kenya. In that program, average concentrate consumption levels reduced due to better nutritional advice, which also led to a reduction in emissions from feed production and transport. In the Kenyan context, additional measures would be needed to ensure the quality of concentrate feeds (Lukuyu et al., 2009) and strengthen smallholders' access to financial to purchase feedstuffs (Odhong' et al., 2019), including by reviewing the 16% VAT on concentrate feed (Njagi et al., 2013). This illustrates that in developing regions, initiatives to promote technical measures to mitigate GHG emissions in dairy production will need to address the multiple constraints in the dairy sector (FAO, 2013).

Analysis of variability in farm data also suggested to the potential relevance of other GHG mitigation options. Since non-productive cattle raised and sold by smallholder farmers are an important source of income (Section 4.1), farmers have little incentive to mitigate GHG emissions through adjustments in herd structure. Large reductions in manure management emissions may only be possible with change in feeding system, which is related to factors such as population density and market access (Staal et al., 2002) that change slowly with socio-economic development. In Section 4.3.3, we reported a significant difference in GHG intensity between large and smaller breeds. In this study, the majority of cows were larger breed, but breed improvement may be a relevant mitigation option elsewhere in SSA (Mwanga et al., 2019).

5.3. Reducing uncertainty

Reducing the high level of uncertainty in input parameters should be a priority for future research. Monte Carlo simulation of uncertainty in input parameter values found that milk yield, milk protein content and feed digestibility were important sources of uncertainty in all three feeding systems, and feed emissions were the most influential in the zero-grazing system. Validation of farmer recall of milk yields against measurements in Mali showed that farmer recall estimates can correspond well (Zezza et al., 2016), but estimation errors of up to 30% have been reported, depending on the data collection method used (Migose et al., 2020). Similarly, there is some evidence that farmers overestimate volumes of concentrate fed (Richards et al., 2015). The accuracy of farmer-reported volumes of feedstuffs used, and errors in conversion of feed volumes to kg DM have not been systematically researched. Validation studies are needed that compare the accuracy of alternative survey methods with direct measurements or other 'gold standard' methods to quantify the relatively accuracy of alternative methods and identify cost-effective survey methods (Fraval et al., 2019). The only large-scale dataset on milk protein content in central Kenya does not distinguish between cows on commercial and smallholder farms (Kosgey et al., 2011). Since variation in feed composition is associated with changes in milk yield, milk protein and methane emissions (Aguerre et al., 2011), this indicates a data gap remaining to be filled.

Secondary data was used to characterize feedstuffs and for the source of many feed emission factors. While data used for feed characterization was largely from Kenyan studies, feed GHG emissions were calculated using several values from a database prepared for the Netherlands (Vellinga et al., 2013). The use of international data and global default values increases uncertainty. Given the importance of feed emissions in zero-grazing farms in central Kenya, improving the availability of feed emission factors through carbon footprint studies of common feedstuffs using more representative data should be a future research priority.

6. Conclusions

This study identified various management factors at individual cow and farm level that are associated with the CF of milk production on smallholder farms in central Kenya. The study area has been targeted by a NAMA designed by the government of Kenya, so the results are therefore useful for identifying GHG mitigation options in this initiative, and in other similar production systems in East Africa.

Average CF ranged between 2.19 and 3.13 $kgCO_2e/kgFPCM$, depending on the GWPs and allocation method used. High uncertainty of point estimates highlights that improvements in the accuracy of data collection methods should be a future research priority. Comparison of farm types based on variability in farm management data suggested that CF was similar between zero-grazing and semi-zero grazing farms and significantly higher on farms with grazing only feeding systems, but no difference was detected when input parameter uncertainty was considered. The level of concentrate use was positively correlated with CF, and was the most important factor explaining variation in CF not attributable to variation in milk yield. Promoting balanced feed rations and feeding concentrate according to cows' needs across the lactation cycle could provide opportunities to both increase milk production and reduce the CF of milk production in central Kenya. Supporting smallholder farmers to implement these mitigation options will require interventions at several levels in feed supply chains in the dairy sector.

Funding

The survey and analysis reported in this paper were implemented as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from CGIAR Fund Donors and through bilateral funding agreements. For details please visit https://ccafs.cgiar.org/donors. The survey was also supported by additional financing from the Food and Agriculture Organization of the UN. The views expressed in this article cannot be taken to reflect the official opinions of any of these organizations.

Author contributions

Andreas Wilkes: Conceptualization, Methodology, Software, Data curation, Formal analysis,

Writing – Review & Editing; Shimels Wassie: Formal analysis, Writing- Original draft

preparation. Charles Odhong': Methodology, Investigation, Data curation. Simon Fraval:

Methodology, Writing – Review & Editing. Suzanne van Dijk: Resources, Project

administration

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Authors AW, SW, CO and SvD are employed by UNIQUE forestry and land use GmbH, a consulting company.

Acknowledgements

This research was implemented in partnership with the World Agroforestry Centre, the State Department of Livestock and Kenya Dairy Board. The authors gratefully acknowledge most useful advice provided by Carolyn Opio (FAO), and support from Robin Mbae (SDL) and Mildred Kosgei (KDB). We thank the team of enumerators who collected the data, all the farmers who gave their valuable time to respond to the questionnaire, and the anonymous reviewers who provided useful suggestions for improving this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.121780.

References

Abeygunawardena, H., Dematawewa, C.M.B., 2004. Pre-pubertal and postpartum anestrus in tropical Zebu cattle. Anim. Reprod. Sci. 82, 373–387.

Aguerre, M.J., Wattiaux, M.A., Powell, J.M., Broderick, G.A., Arndt, C., 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. J. Dairy Sci. 94 (6), 3081–3093. https://doi.org/10.3168/jds.2010-4011.

Archimède, H., Eugène, M., Magdeleine, C.M., Boval, M., Martin, C., Morgavi, D.P., Lecomte, P., Doreau, M., 2011. Comparison of methane production between C3 and C4 grasses and legumes. J. Anim. Feed Sci. 166, 59–64. https://doi.org/10.1016/j.anifeedsci.2011.04.003.

Baldini, C., Gardoni, D., Guarino, M., 2017. A critical review of the recent evolution of Life Cycle Assessment applied to milk production. J. Clean. Prod. 140, 421–435. https://doi.org/10.1016/j.jclepro.2016.06.078.

Basset-Mens, C., Kelliher, F.M., Ledgard, S., Cox, N., 2009. Uncertainty of global warming potential for milk production on a New Zealand farm and implications for decision making. Int. J. Life Cycle Assess. 14 (7), 630–638. https://doi.org/10.1007/s11367-009-0108-2.

Bateki, C.A., van Dijk, S., Wilkes, A., Dickhoefer, U., White, R., accepted. Meta-analysis of on-farm management strategies that increase milk yields of dairy cattle on smallholder farms in East Africa. Animal.

Bebe, B.O., Udo, H.M., Rowlands, G.J., Thorpe, W., 2003. Smallholder dairy systems in the Kenya highlands: breed preferences and breeding practices. Livest. Prod. Sci. 82 (2–3), 117–127. https://doi.org/10.1016/S0301-6226(03)00029-0.

Bebe, B.O., Udo, H.M.J., Rowlands, G.J., Thorpe, W., 2003a. Smallholder dairy systems in the Kenya highlands: cattle population dynamics under increasing intensification. Livest. Prod. Sci. 82 (2–3), 211–221. https://doi.org/10.1016/S0301-6226(03)00013-7.

Biwott, K.J., Kaitho, R., Gachuiri, C.K., Wahome, R.G., Tanner, J., 1998. Effects of levels of concentrate supplementation on milk production and body weights of lactating dairy cows. https://cgspace.cgiar.org/handle/10568/1584.

Brandt, P., Herold, M., Rufino, M.C., 2018. The contribution of sectoral climate change mitigation options to national targets: a quantitative assessment of dairy production in Kenya. Environ. Res. Lett. 13 (3), 034016 https://doi.org/10.1088/1748-9326/aaac84.

Butler, W.R., 2000. Nutritional interactions with reproductive performance in dairy cattle. Anim. Reprod. Sci. 60, 449–457. https://doi.org/10.1016/S0378-4320(00)00076-2.

Capper, J.L., Cady, R.A., 2012. A comparison of the environmental impact of Jersey compared with Holstein milk for cheese production. J. Dairy Sci. 95 (1), 165–176. https://doi.org/10.3168/jds.2011-4360.

Casey, J.W., Holden, N.M., 2005. Analysis of greenhouse gas emissions from the average Irish milk production system. Agr. Syst. 86 (1), 97–114. https://doi.org/10.1016/j.agsy.2004.09.006.

Chen, X., Corson, M.S., 2014. Influence of emission-factor uncertainty and farm-characteristic variability in LCA estimates of environmental impacts of French dairy farms. J. Clean. Prod. 81, 150–157. https://doi.org/10.1016/j.jclepro.2014.06.046.

Enahoro, D., Lannerstad, M., Pfeifer, C., Dominguez-Salas, P., 2018. Contributions of livestock-derived foods to nutrient supply under changing demand in low-and middle-income countries. Glob. Food Secur. 19, 1–10. https://doi.org/10.1016/j.gfs.2018.08.002.

Food and Agriculture Organization of the UN [FAO], 2013. Climate Smart Agriculture Sourcebook. FAO, Rome.

Food and Agriculture Organization of the UN [FAO], 2016. Environmental Performance of Large Ruminant Supply Chains: Guidelines for Assessment. Livestock Environmental Assessment and Performance Partnership. FAO, Rome, Italy.

Food and Agriculture Organization of the UN [FAO], 2020. FAOSTAT. http://www.fao.org/faostat/en/. (Accessed 2 February 2020).

Food and Agriculture Organization of the UN and International Livestock Research Institute [FAO and ILRI], 2016. Smallholder Dairy Methodology: Methodology for GHG Emission Reductions from Smallholder Dairy Production Systems. FAO, Rome.

Food and Agriculture Organization of the UN and Livestock Environmental Assessment Partnership [FAO and LEAP], 2015. Global database of GHG emissions related to feed crops. http://www.fao.org/partnerships/leap/database/ghg-crops/en/.

Food and Agriculture Organization of the UN and New Zealand Agricultural Greenhouse Gas Research Centre [FAO and NZAGRC], 2017a. Options for Low Emission Development in the Kenya Dairy Sector: Reducing Enteric Methane for Food Security and Livelihoods. FAO, Rome.

Food and Agriculture Organization of the UN and New Zealand Agricultural Greenhouse Gas Research Centre [FAO and NZAGRC], 2017b. Options for Low Emission Development in the Ethiopian Dairy Cattle Sector: Reducing Enteric Methane for Food Security and Livelihoods. FAO, Rome.

Fraval, S., Hammond, J., Wichern, J., Oosting, S.J., De Boer, I.J., Teufel, N., Lannerstad, M., Waha, K., Pagella, T., Rosenstock, T.S., Giller, K.E., 2019. Making the most of imperfect data: a critical evaluation of standard information collected in farm household surveys. Exp. Agric. 55 (2), 230–250. https://doi.org/10.1017/S0014479718000388.

Garg, M.R., Phondba, B.T., Sherasia, P.L., Makkar, H.P., 2016. Carbon footprint of milk production under smallholder dairying in Anand district of Western India: a cradle-to-farm gate life cycle assessment. Anim. Prod. Sci. 56 (3), 423–436. https://doi.org/10.1071/AN15464.

Garg, M.R., Sherasia, P.L., Phondba, B.T., Makkar, H.P., 2018. Greenhouse gas emission intensity based on lifetime milk production of dairy animals, as affected by ration-balancing program. Anim. Prod. Sci. 58 (6), 1027–1042. https://doi.org/10.1071/AN15586.

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139 (1–2), 100–108. https://doi.org/10.1016/j.livsci.2011.03.012.

Gollnow, S., Lundie, S., Moore, A.D., McLaren, J., van Buuren, N., Stahle, P., Christie, K., Thylmann, D., Rehl, T., 2014. Carbon footprint of milk production from dairy cows in Australia. Int. Dairy J. 37 (1), 31–38. https://doi.org/10.1016/j.idairyj.2014.02.005.

Goopy, J.P., Pelster, D.E., Onyango, A., Marshall, K., Lukuyu, M., 2018a. Simple and robust algorithms to estimate liveweight in African smallholder cattle. Anim. Prod. Sci. 58 (9), 1758–1765. https://doi.org/10.1071/AN16577.

Goopy, J.P., Onyango, A.A., Dickhoefer, U., Butterbach-Bahl, K., 2018b. A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa–Results for Nyando, Western Kenya. Agr. Syst. 161, 72–80. https://doi.org/10.1016/j.agsy.2017.12.004.

Government of Kenya, 2015. Kenya Second National Communication to the United Nations Framework Convention on Climate Change. National Environment

Management Authority, Nairobi. https://unfccc.int/resource/docs/natc/kennc2.pdf.

Guest, G., Smith, W., Grant, B., VanderZaag, A., Desjardins, R., McConkey, B., 2017. A comparative life cycle assessment highlighting the trade-offs of a liquid manure separator-composter in a Canadian dairy farm system. J. Clean. Prod. 143, 824–835. https://doi.org/10.1016/j.jclepro.2016.12.041.

Hagemann, M., Hemme, T., Ndambi, A., Alqaisi, O., Sultana, M.N., 2011. Benchmarking of greenhouse gas emissions of bovine milk production systems for 38 countries. Anim. Feed Sci. Technol. 166, 46–58. https://doi.org/10.1016/j.anifeedsci.2011.04.002.

Harris, I.P.D.J., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset. Int. J. Climatol. 34 (3), 623–642. https://doi.org/10.1002/joc.3711.

Hemme, T., Otte, J., 2010. Status and Prospects of Smallholder Milk Production: A Global Perspective. FAO, Rome.

Henriksson, M., Flysjö, A., Cederberg, C., Swensson, C., 2011. Variation in carbon footprint of milk due to management differences between Swedish dairy farms. Animal 5 (9), 1474–1484. https://doi.org/10.1017/S1751731111000437.

Herrero, M., Havlik, P., McIntire, J., Palazzo, A., Valin, H., 2014. African Livestock Futures: Realizing the Potential of Livestock for Food Security, Poverty Reduction and the Environment in Sub-saharan Africa. Office of the Special Representative of the UN Secretary General for Food Security and Nutrition and the United Nations System Influenza Coordination (UNSIC), Geneva, Switzerland.

Intergovernmental Panel on Climate Change [IPCC], 2006. Guidelines for National Greenhouse Gas Inventories. IGES, Kanagawa, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm.

Intergovernmental Panel on Climate Change [IPCC], 2007. Climate change 2007. The physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K., pp. 20–91

Intergovernmental Panel on Climate Change [IPCC], 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, m., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, U.K., pp. 33–109

Intergovernmental Panel on Climate Change [IPCC], 2019. 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Jayasundara, S., Worden, D., Weersink, A., Wright, T., VanderZaag, A., Gordon, R., Wagner-Riddle, C., 2019. Improving farm profitability also reduces the carbon footprint of milk production in intensive dairy production systems. J. Clean. Prod. 229, 1018–1028. https://doi.org/10.1016/j.jclepro.2019.04.013.

Kabui, K., 2012. Assessment of Milk Quality and the Potential of a Quality Based Payment System in Small Holder Farms in Limuru and Eldoret, Kenya. MVPH thesis. University of Nairobi.

Kashongwe, O.B., Bebe, B.O., Matofari, J.W., Huelsebusch, C.G., 2017. Effects of feeding practices on milk yield and composition in peri-urban and rural smallholder dairy cow and pastoral camel herds in Kenya. Trop. Anim. Health Prod. 49 (5), 909–914. https://doi.org/10.1007/s11250-017-1270-3.

Kirwa, E.C., Njoroge, K., Chemining'wa, G., Mnene, W.N., 2015. Nutritive composition of Eragrostis superba Peyr and Cenchrus ciliaris L. collections from the ASALs of Kenya. Livest. Res. Rural Dev. 27. Article #144. Retrieved October 18, 2019, from. http://www.lrrd.org/lrrd27/8/kirw27144.html.

n.d Kitalyi, A., Lukuyu, B., Kirui, J., Kabirizi, J.. Mixing and feeding homemade dairy concentrates. EADD leaflet No. 6. https://cgspace.cgiar.org/bitstream/handle/10568/12522/MixingDairyConcentrates.pdf?sequence=2&isAllowed=y.

Kosgey, I.S., Mbuku, S.M., Okeyo, A.M., Amimo, J., Philipsson, J., Ojango, J.M., 2011. Institutional and organizational frameworks for dairy and beef cattle recording in Kenya: a review and opportunities for improvement. Anim. Genet. Res. 48, 1–11. http://doi:10.1017/S2078633610001220.

Laswai, G.H., Mgheni, D.M., Mtenga, L.A., Ndikumana, J., Zziwa, E. (Eds.), 2013. Chemical Composition and Nutritional Values of Feed Resources for Ruminants: Eastern and Central Africa (ECA) Feedstuff Table for Ruminants. ASARECA, Entebbe.

Lorenz, H., Reinsch, T., Hess, S., Taube, F., 2019. Is low-input dairy farming more climate friendly? A meta-analysis of the carbon footprints of different production systems. J. Clean. Prod. 211, 161–170. https://doi.org/10.1016/j.jclepro.2018.11.113.

Lukuyu, B.A., Kitalyi, A., Franzel, S., Duncan, A.J., Baltenweck, I., 2009. Constraints and options to enhancing production of high quality feeds in dairy production in Kenya, Uganda and Rwanda. In: ICRAF Working Paper No. 95. ICRAF, Nairobi, Kenya.

Mayberry, D., Ash, A., Prestwidge, D., Godde, C.M., Henderson, B., Duncan, A., Blummel, M., Reddy, Y.R., Herrero, M., 2017. Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India. Agr. Syst. 155, 43–51. https://doi.org/10.1016/j.agsy.2017.04.007.

Migose, S.A., van der Linden, A., Bebe, B.O., de Boer, I.J.M., Oosting, S.J., 2020. Accuracy of estimates of milk production per lactation from limited test-day and recall data collected at smallholder dairy farms. Livest. Sci. 232, 103911. https://doi.org/10.1016/j.livsci.2019.103911.

Morais, T.G., Teixeira, R.F., Rodrigues, N.R., Domingos, T., 2018. Carbon footprint of milk from pasture-based dairy farms in Azores, Portugal. Sustainability 10 (10), 3658. https://doi.org/10.3390/su10103658.

Muraya, J., VanLeeuwen, J.A., Gitau, G.K., Wichtel, J.J., Makau, D.N., Crane, M.B., McKenna, S.L.B., Tsuma, V.T., 2018. Cross-sectional study of productive and reproductive traits of dairy cattle in smallholder farms in Meru, Kenya. Livest. Res. Rural Dev. 30. Article #171. Retrieved October 18, 2019, from. http://www.lrrd.org/lrrd30/10/jmura30171.html.

Mwanga, G., Mujibi, F.D.N., Yonah, Z.O., Chagunda, M.G.G., 2019. Multi-country investigation of factors influencing breeding decisions by smallholder dairy farmers in sub-Saharan Africa. Trop. Anim. Health Prod. 51 (2), 395–409. https://doi.org/10.1007/s11250-018-1703-7.

Ndung'u, P.W., Bebe, B.O., Ondiek, J.O., Butterbach-Bahl, K., Merbold, L., Goopy, J.P., 2018. Improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: livestock systems of Nandi County, Kenya. Anim. Prod. Sci. 1136–1146. https://doi.org/10.1071/AN17809.

Njagi, T., Kamau, M., Gitau, R., Onyango, K., Kinyumu, N., Mathenge, M., 2013. Implications of Implementation of the VAT Act 2013 on Animal Feeds. Poliy Brief No. 10. Tegemeo Institute of Agricultural Policy and Development, Nairobi, Kenya.

Nyaata, O.Z., Dorward, P.T., Keatinge, J.D.H., O'Neill, M.K., 2000. Availability and use of dry season feed resources on smallholder dairy farms in central Kenya. Agrofor. Syst. 50 (3), 315–331. https://doi.org/10.1023/A:1006447915074.

O'Brien, D., Shalloo, L., Patton, J., Buckley, F., Grainger, C., Wallace, M., 2012. Evaluation of the effect of accounting method, IPCC v. LCA, on grass-based and confinement dairy systems' greenhouse gas emissions. Animal 6 (9), 1512–1527. https://doi.org/10.1017/S1751731112000316.

Odhong', C., Wilkes, A., van Dijk, S., Ndonga, S., Sing'ora, B., Kenyanito, L., 2019. Financing large-scale mitigation by smallholder farmers: what roles for public climate finance? Front. Sustain. Food Syst. 3, 3 https://doi.org/10.3389/fsufs.2019.00003, 3–3.

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B., Steinfeld, H., 2013. Greenhouse Gas Emissions from Ruminant Supply Chains: A Global Life Cycle Assessment. FAO, Rome.

Reinecke, R., Casey, N.H., 2017. A whole farm model for quantifying total greenhouse gas emissions on South African dairy farms. S. Afr. J. Anim. Sci. 47 (6), 883–894. https://doi.org/10.4314/sajas.v47i6.16.

Richards, S., VanLeeuwen, J., Shepelo, G., Gitau, G.K., Kamunde, C., Uehlinger, F., Wichtel, J., 2015. Associations of farm management practices with annual milk sales on smallholder dairy farms in Kenya. Vet. World 8 (1), 88. https://doi.org/10.14202/vetworld.2015.88-96.

Richards, S., VanLeeuwen, J.A., Shepelo, G., Gitau, G.K., Wichtel, J., Kamunde, C., Uehlinger, F., 2016. Randomized controlled trial on impacts of dairy meal feeding interventions on early lactation milk production in smallholder dairy farms of Central Kenya. Prev. Vet. Med. 125, 46–53. https://doi.org/10.1016/j.prevetmed.2016.01.006.

State Department of Livestock [SDL], 2013. The National Dairy Development Policy. State Department of Livestock, Nairobi, Kenya.

State Department of Livestock [SDL], 2017. Kenya's dairy nationally appropriate mitigation action (NAMA) concept note. http://www.kilimo.go.ke/wp-content/uploads/2018/03/NAMA-Kenya-Dairy-NAMA-GCF-concept-NoteJanuary-2017-1.pdf.

State Department of Livestock [SDL], 2018. Livestock Statistics 2017. State Department of Livestock, Nairobi, Kenya.

Staal, S.J., Baltenweck, I., Waithaka, M.M., DeWolff, T., Njoroge, L., 2002. Location and uptake: integrated household and GIS analysis of technology adoption and land use, with application to smallholder dairy farms in Kenya. Agric. Econ. 27 (3), 295–315. https://doi.org/10.1111/j.1574-0862.2002.tb00122.x.

Thoma, G., Popp, J., Shonnard, D., Nutter, D., Matlock, M., Ulrich, R., Kellogg, W., Kim, D.S., Neiderman, Z., Kemper, N., Adom, F., 2013. Regional analysis of greenhouse gas emissions from USA dairy farms: a cradle to farm-gate assessment of the American dairy industry circa 2008. Int. Dairy J. 31, S29–S40. https://doi.org/10.1016/j.idairyj.2012.09.010.

Udo, H., Weiler, V., Modupeore, O., Viets, T., Oosting, S., 2016. Intensification to reduce the carbon footprint of smallholder milk production: fact or fiction? Outlook Agric. 45 (1), 33–38. https://doi.org/10.5367/oa.2016.0229.

Van Middelaar, C.E., Berentsen, P.B.M., Dijkstra, J., De Boer, I.J.M., 2013. Evaluation of a feeding strategy to reduce greenhouse gas emissions from dairy farming: the level of analysis matters. Agr, Syst. 121, 9–22. https://doi.org/10.1016/j.agsy.2013.05.009.

VandeHaar, M.J., St-Pierre, N., 2006. Major advances in nutrition: relevance to the sustainability of the dairy industry. J. Dairy Sci. 89 (4), 1280–1291. https://doi.org/10.3168/jds.S0022-0302(06)72196-8.

Vellinga, T., Blonk, H., Marinussen, M., van Zeist, W.J., de Boer, I.J.M., Starmans, D., 2013. Methodology Used in Feedprint: A Tool Quantifying Greenhouse Gas Emissions of Feed Production and Utilization. Wageningen UR Livestock Research.

Wang, X., Kristensen, T., Mogensen, L., Knudsen, M.T., Wang, X., 2016. Greenhouse gas emissions and land use from confinement dairy farms in the Guanzhong plain of China–using a life cycle assessment approach. J. Clean. Prod. 113, 577–586. https://doi.org/10.1016/j.jclepro.2015.11.099.

Weiler, V., Udo, H.M., Viets, T., Crane, T.A., De Boer, I.J., 2014. Handling multifunctionality of livestock in a life cycle assessment: the case of smallholder dairying in Kenya. Curr. Opin. Env. Sust. 8, 29–38. https://doi.org/10.1016/j.cosust.2014.07.009.

Wilkes, A., Reisinger, A., Wollenberg, E., van Dijk, S., 2017. Measurement, reporting and verification of livestock GHG emissions by developing countries in the

UNFCCC: current practices and opportunities for improvement. In: CCAFS Report No. 17. CCAFS, Wageningen, The Netherlands.
Wilkes, A., Odhong, C., van Dijk, S., Fraval, S., Wassie, S.E., 2019. Methods and guidance to support MRV of livestock emissions: methods for data collection, analysis and summary results from a pilot baseline survey for the Kenya dairy NAMA. In: CCAFS Working Paper No. 285. CCCAFS, Wageningen, The Netherlands.
Woldegebriel, D., Udo, H., Viets, T., van der Harst, E., Potting, J., 2017. Environmental impact of milk production across an intensification gradient in Ethiopia. Livest. Sci. 206, 28–36. https://doi.org/10.1016/j.livsci.2017.10.005.
Zehetmeier, M., Gandorfer, M., Hoffmann, H., Müller, U.K., De Boer, I.J.M., Heißenhuber, A., 2014. The impact of uncertainties on predicted greenhouse gas emissions of dairy cow production systems. J. Clean. Prod. 73, 116–124. https://doi.org/10.1016/j.jclepro.2013.09.054.
Zezza, A., Federighi, G., Kalilou, A.A., Hiernaux, P., 2016. Milking the data: measuring milk off-take in extensive livestock systems. Experimental evidence from Niger. Food Pol. 59, 174–186. https://doi.org/10.1016/j.foodpol.2016.01.005.