Technical performance and carbon footprint of commercial dairy farms in South West Uganda

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The aim of the present study was to evaluate technical performance and carbon footprint of 101 dairy farms participating the dairy development project SNV TIDE in south western Uganda. Results showed that average 24-h milk yield per lactating cow was 7.1 ± 2.0 (SD) kg/cow/d, and estimated annual milk yield was 1626 ± 614 kg/cow/y. Average calving interval was 483 ± 64 days, mortality rate of adult cows was 3.2 ± 4.8 % per farm, and average culling rate of adult cows was 18 ± 15 % per farm. With regard to the carbon footprint of farms, estimated average greenhouse gas (GHG) emission intensity was 2.1 kg CO_2-eq per kg fat and protein correct milk and 13.6 kg CO_2-eq per kg live weight. Most important sources of GHG emissions were rumen enteric fermentation (83%), followed by manure (11%), and feed production (5%). GHG emission intensity was lower in specialized farms than in mixed crop-livestock farms; lower in farms with supplemental feeding besides grazing than in farms with grazing only; and in farms with crossbreds than in farms with HF as predominant breed. GHG emission intensity was highest in Ntungamo district (2.6 kg CO_2-eq/kg FPCM) and lowest in Kiruhura district (1.8 kg CO_2-eq/kg FPCM).

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Summary

Dairy production in Uganda is rapidly expanding as a result of a high and increasing market demand and strategic prioritization of dairy for agricultural development. While the increase in production contributes to improved nutrition and livelihoods of rural communities, it may also be accompanied with significant increases in greenhouse gas (GHG) emissions from the Ugandan dairy sector and may lead to increased deforestation. The aim of the present study was to estimate and compare technical performance and GHG emissions of dairy farms participating the dairy development project SNV TIDE in south western Uganda. To this end, longitudinal data were collected from 101 commercial dairy farms participating in the SNV TIDE project in the districts Kiruhura, Lyantonde, Ntungamo, Isingiro and Mbarara in south western Uganda. GHG emissions were estimated using life cycle assessment (LCA). Results of this study can contribute to development of effective GHG mitigation strategies for the Ugandan dairy sector.

Key results:

- Average milk yield was 7.1 ± 2.0 (SD) kg per lactating cow per day, 2129 ± 781 kg milk per lactation, and 1626 ± 614 kg milk per cow per year.
- Average 24-h milk yield was significantly higher in farms in Kiruhura (9.3 ± 2.1 kg/cow/d) than in other four districts (6.0 to 7.3 kg/cow/d (SD=0.7 to 2.4)).
- Average 24-h milk yield was significantly higher in:
    - female-owned farms than in male-owned farms;
    - farms feeding supplemental feed or fodder besides grazed grass than in farms with grazing-only (particularly farms feeding maize/Napier silage or maize bran);
    - farms with paddocks compared to other grazing systems (perimeter fence, mixed fencing, stall feeding, open grazing);
    - farms with Holstein Frisian (HF) than in farms with crossbreds as predominant breed.
- Average calving interval was 483 ± 64 days and tended to be shorter in farms feeding silage than in those not feeding silage;
- Mortality rate of adult cows was 3.2 ± 4.8 %, and average culling rate of adult cows 18 ± 15 % per farm;
- Mortality rate of young stock was 13.2 ± 13.8 %, and significantly higher in farms with Holstein Frisian (HF) than in farms with crossbreds as the predominant breed;
- GHG emission intensity was 2.1 kg CO_2-eq per kg fat and protein corrected milk (FPCM) and 13.6 kg CO_2-eq/kg live weight (LW);
- Most important sources of GHG emissions were rumen enteric fermentation (83%), followed by manure (11%), and feed production (5%);
- GHG emission intensity was lower in:
    - specialized farms than in mixed crop-livestock farms;
    - farms with supplemental feeding than in farms with grazing only;
    - farms with crossbreds than in farms with HF as predominant breed.
- Absolute GHG emissions per farm were highest in Kiruhura and Isingiro district, whereas GHG emission intensity was highest in Ntungamo district (2.6 kg CO_2-eq/kg FPCM) and lowest in Kiruhura district (1.8 kg CO_2-eq/kg FPCM).

Conclusions and recommendations:

- Feeding silage or maize bran, paddocking, and using Holstein Frisian breeds show potential to increase milk yield, and feeding silage can contribute to improved reproductive performance.
- Specialization and supplemental feeding show potential to reduce GHG emission intensity, but it should be noted that feeding of supplemental feed with a high carbon footprint can cause the opposite effect (i.e., increase emission intensity). The use of HF breeds also shows potential, but this requires a reduction of young stock mortality in HF herds.

- In future LCA studies, the role of improved pasture management for GHG mitigation should be further explored by including farm- or farm-type specific quality of pasture grass, and emissions related to land use change should be included.
- Our findings support the focus on improved feeding in the Ugandan Nationally Appropriate Mitigation Actions (NAMA), as improved feeding was shown to have simultaneous beneficial effects on GHG emission reduction, farm productivity and climate resilience.

1 Introduction

Greenhouse gas emissions (GHG) from African agriculture are rising rapidly due to an increasing food demand, intensification of agricultural production, and expanding agricultural lands. More than half of these emissions are caused by ruminants through enteric fermentation and from pasture, range and paddocks (Tongwane and Moeletsi, 2018). At the same time, livestock remain an important source of livelihood for rural communities, providing food, income, employment, and other non-monetized products and services (e.g., savings, insurance, dung and traction) (Otte and Knips, 2005).

Dairy production systems are responsible for about 30% of the total GHG emissions from the global livestock sector (Gerber *et al.*, 2013). GHG emissions are emitted from the dairy value chains in the form of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), with sources being the animals (enteric fermentation), manure, feed production, land use change, and processing and transport of products. Dairy production systems in Sub-Saharan Africa show relatively high GHG emissions per unit of edible output compared to other global regions, mainly because of a low productivity of cattle as related to their multi-functionality and little specialization of production systems (Opio *et al.*, 2013; Weiler *et al.*, 2014).

In Uganda, dairy production is the most important livestock sub-sector, contributing about half of the total livestock GDP and supporting livelihoods of 1.2 million dairy farming households (FAO and New Zealand Agricultural Greenhouse Gas Research Centre, 2019). Dairy production in Uganda is rapidly expanding at an annual rate of about 8-10% mainly as a result of the high and increasing demand in the country and region, and by the government's strategic prioritization of dairy for accelerated agricultural development (Balikowa, 2011; MAAIF, 2017). The increase in production is realized through an expanding cattle population and improved productivity particularly in intensive farming systems (Creemers and Alvarez Aranguiz, 2019). Current GHG emissions from the Ugandan dairy sector are estimated at 19.1 million tons of CO_2-eq per year, with enteric methane dominating the emissions (FAO and New Zealand Agricultural Greenhouse Gas Research Centre, 2019). Enteric methane is the second largest source of GHG emissions from agriculture in Uganda after indirect N2O from managed soils (Ministry of Water and Environment, 2014). The growth in livestock numbers has been projected to increase methane emissions from the livestock sector by 4 times by 2030 (Uganda NDC, 2016).

Uganda's ambitions for climate action are laid down in the Uganda National Climate Change Policy (NCCP, 2015), Nationally Determined Contribution (NDC, 2016), and Nationally Appropriate Mitigation Actions (NAMA; MAAIF, 2017). For the agricultural sector the GHG reduction target is 10% below the 2014 levels by 2025, and 30% by 2040 (MAAIF and MWE, 2016). Targeted GHG mitigation strategies are low-cost solutions that should also contribute to food security and other development goals, and increase resilience to climate change. Proposed mitigation strategies for the dairy sector include: production of improved animal feed, production and supply of hay, milk collection and storage points, and manure management (biogas production) (NAMA, 2017). Recent modelling studies showed various effective mitigation options for the Ugandan dairy sector, including, e.g. improved forages, water harvesting, improved dairy breeds, and animal health interventions (FAO and New Zealand Agricultural Greenhouse Gas Research Centre, 2019; Kiggundu *et al.*, 2019).

The present study was part of The Inclusive Dairy Enterprise (TIDE) project[1] in south western Uganda. The TIDE project was aimed at increasing dairy farm productivity, food security and incomes, by supporting various interventions for dairy farmers such as water for production, fodder production, and fencing and paddocking. The objective of the present study was to evaluate effects of dairy

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[1] The TIDE project is implemented by SNV and funded by the Embassy of the Kingdom of The Netherlands (EKN) in Kampala, Uganda. https://snv.org/project/inclusive-dairy-enterprise-tide

farming practices and TIDE-supported interventions on technical performance and GHG emissions of dairy farms participating in the TIDE project.

2 Material and Methods

2.1 Study location

The study was implemented in 5 districts in south western Uganda that were part of the SNV TIDE project: Ntungamo, Mbarara, Kiruhura, Lyantonde, and Isingiro. Ntungamo and Mbarara districts belong to the Western Mid-Altitude Farmland Agro-Ecological Zone (AEZ; Figure 1), and Kiruhura, Lyantonde and Isingiro districts belong to the Southwest Rangeland AEZ. South western Uganda has a tropical climate with a bimodal rainfall pattern and moderate temperatures. Between 1991 and 2020 Mbarara received rainfall averaging between 950 and 1300 mm, and average temperature ranging between 15.8 and 28.4 degrees C (Uganda National Meteorological Authority, 2022 – unpublished data). During the study period in 2019, however, the dry period was less pronounced (see example of Mbarara in Figure 2).

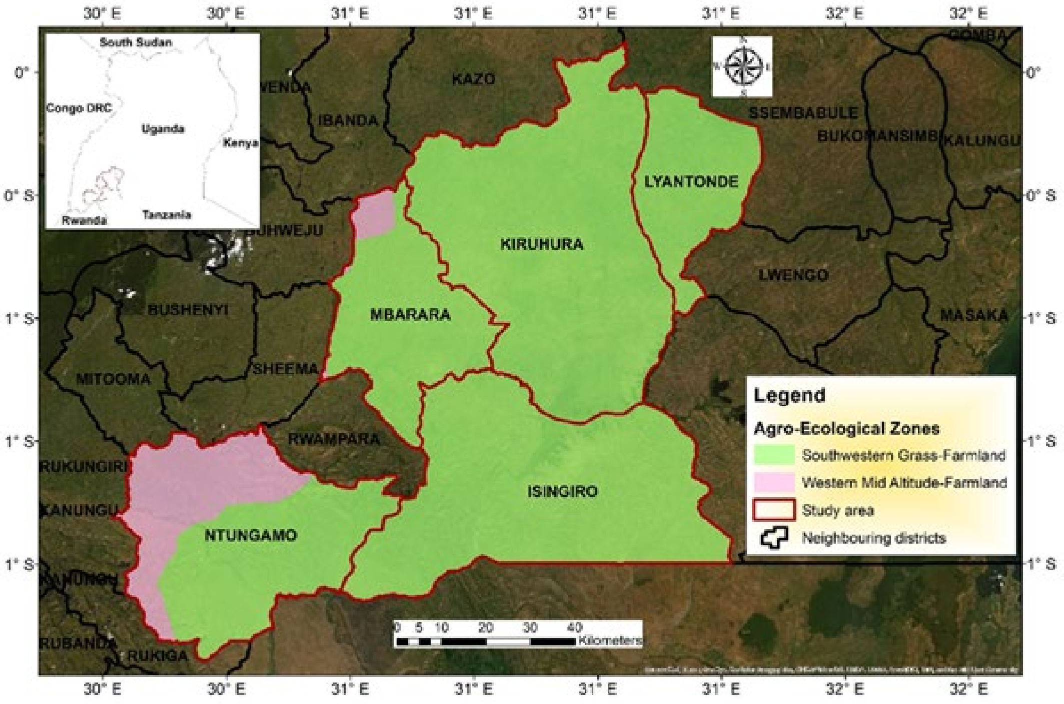

Figure 1 *Map of study location in south western Uganda with Agro-Ecological Zones.*

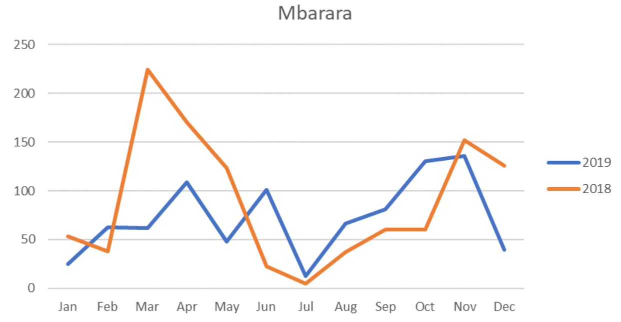

Figure 2 *Observed monthly rainfall (mm) in 2018 and 2019 in Mbarara (source: Mbarara meteorological station).*

Dairy production systems in the 5 districts can be described as follows:

- Ntungamo district: land is hilly with intermittent flat lands. This district is saddled by two ecological zones; 60% of the district is covered by Southwestern farmlands while the remaining 40% is covered by the pastoral rangelands. Main sources of livelihoods are dairy, matooke (variety of banana), coffee, beef cattle and goats. Maize planting for human and fodder production is gaining prominence. Landholdings are smaller than those of Kiruhura but larger than those of Sheema.
- Mbarara district: Main sources of livelihoods are dairy, matooke (variety of banana), coffee and beef (cattle, goats, and sheep). Maize planting for human and fodder production is gaining prominence. Landholdings are smaller than those of Kiruhura but larger than those of Sheema. Land is flat with few raised areas.
- Kiruhura district: Main source of livelihood is livestock (dairy, beef, goats) though crop farming (matooke, maize, beans) are gaining prominence, besides maize for fodder production. The area is a savannah type of vegetation with few trees. Land is flat with few hilly places. Landholdings are quite large (> 50 acres per household).
- Lyantonde district: this district is covered with one ecological zone; the pastoral rangelands. The main grazing system is open grazing, with more farms adopting fenced perimeter and fenced paddocks systems. Main sources of livelihoods are dairy, matooke (variety of banana), coffee, beef cattle and goats. Fodder production is gaining prominence. Landholdings are quite large with farer owning land in the range of 50 – 100 acres per farmer. Land is flat with intermittent hills.
- Isingiro district: Main sources of livelihood are dairy, beef and matooke. Main grazing systems are open grazing and fenced perimeter. Zero grazing has been introduced in the hilly areas. Landholdings are big for the commercial farmers but small for the subsistence farmers. Some areas are flat while others are hilly. This district is prone to drought conditions.

2.2 Farm selection

A stratified random sample of 116 dairy farms was drawn by SNV TIDE project staff members in early 2018, with 5 districts in Southwest Uganda as strata: Isingiro, Mbarara, Kiruhura, Lyantonde, and Ntungamo. From each district, a random sample was taken in a number proportional to the district population of dairy farms. The following criteria were used for farm selection:

- Participating in trainings at one of the Practical Dairy Training Farms in the SNV TIDE program;
- Minimum of 15 milking cows;
- Fenced and/or paddocked farms;
- Farmer is willing to participate in the exercise.

During the study, 15 farms dropped from participation, leaving 101 dairy farms in the final sample, located in Isingiro (17 farms), Mbarara (25 farms), Kiruhura (15 farms), Lyantonde (17 farms), and Ntungamo (27 farms). Participating farmers received a 2.000.000 UGX (about 550 USD at the time of reporting) cash voucher for TIDE products for every 2 months of participation in the study. Many different TIDE products were available and delivered via preselected private sector providers. Products were aimed at modernising the farm, to shift from subsistence to commercially-oriented dairy production. Examples are paddocking the farm, construction of a milk parlour, spray race, and subsidies on valley dam construction, among others.

2.3 Data collection

Data were collected from selected dairy farms between April 2018 and December 2019 by 10 local enumerators. Enumerators had a background in animal production (veterinarian or para-vet), and were trained by Wageningen Livestock Research and SNV TIDE project in a 5-day course (including field testing). Data collection was coordinated by TIDE, in collaboration with Wageningen Research (WR) and Mbarara University of Science and Technology (MUST).

The following methods of data collection were implemented:

1. TIDE farmer intake survey
2. Baseline survey
3. Bi-monthly farm visit (measurements & survey)
4. Smart phone application for herd recording (data entry by farmer)
5. Endline survey

The TIDE farmer intake survey (method nr. 1 listed above), the baseline survey (2), and the end-line survey (5) were aimed at collecting information about general characteristics of farms (specified in detail in Table 1). In addition, to capture seasonal dynamics of herd performance, herd management, and feed ration composition, bi-monthly farm visits (3) were carried out 7 times (V1,V2,…,V7) per farm, approximately every two months.

A smart phone application (method nr. 4 above; 'E-lunda') was developed and implemented by the TIDE project in this project, in which participating farmers were asked to keep records of milk yields per cow. A large number of farmers, however, did not or irregularly register milk yields, making these data unsuitable for analysis. Therefore, from April 2019 onwards, recording of milk yields was done during the bi-monthly visits (method nr. 3; farm visits V4 to V7, i.e. approximately 8 months in total). Besides 24-h milk yields, hearth girth measurements were done in V4-V7, for estimation of live weights.

During the monitoring period (V3) it was found that enumerators did not register the number of animals (per age group) feeding from the offered feed/fodder in bi-monthly farm visits, which was required for estimation of the amount of feed/fodder intake per animal. From V4, the number of animals feeding from the feed/fodder was correctly registered. In the analysis, therefore, for V0-V3 the amount of feed/fodder per adult cow was estimated by dividing the amount of supplied feed/fodder by the total number of adult cows present in the herd (as registered in the herd count), whereas for V4-V7 the amount of feed/fodder per adult cow was estimated by dividing the amount of supplied feed/fodder by the number of cows and youngstock (factor 0.5) actually feeding from the offered feed/fodder.

The questionnaires for the baseline/endline and bi-monthly surveys, and the protocol for bi-monthly on-farm measurements were developed by Wageningen Livestock Research. The farmer intake questionnaire and herd recording app were developed by SNV TIDE project. Questions were in English, with translation to local language ('Runyankore') on the spot when needed. Answers to the questionnaires were administered on tablets. Data of on-farm measurements was written down on paper and entered in a Microsoft Excel database after each farm visit.

Table 1 *Data collection methods, monitoring period, type of data, and level.*

Method	Period	Frequency	Type of data collected	Level
Questionnaire (intake)	June 2016-Dec 2017	Baseline and annual review	Household demographics, cow breeds, milk sold per season, milk price per season, farm employees, farm assets, feed supplements, type of housing, grazing system, disease control measures, etc.	Farm
Questionnaire (baseline)	April-July 2018	Single occasion	Sources of income, herd management, feeding practices, grazing system, land area, land use and management, manure management, cost of farm inputs.	Farm
On-farm measurements	Sept 2018-Dec 2019	Bi-monthly (7 times)	Body condition score, heart girth, 24-h milk yields[1] (V4-V7 only)	Cow (sample of cows)

Method	Period	Frequency	Type of data collected	Level
			Herd count (heads per animal category), amounts[1] of feed and fodder fed other than grazed grass (V0-V7)	Farm
Questionnaire (bi-monthly)	Sept 2018-Oct 2019	Bi-monthly (6 times)[2]	Demographics (date of birth, age at first calving, lactations, calving dates), breed	Cow (sample of cows)
			Mortality, culling, diseases, purchases, sales and prices of animals/milk/feed, grazing practices, perceived availability and quality of pasture grass	Farm
Herd recording app	April 2018-Dec 2019	Daily or less frequent	Milk yield	Cow (all cows)
Questionnaire (endline)	Nov 2019-Jan 2020	Single occasion	Same as baseline (see above)	Farm

1 Using weighing scales
2 No results available for V7

Herd sample

In the bi-monthly farm visits, on-farm measurements were made for a pre-defined sample of cows. To this end, a random sample of mature (lactating and dry) cows was selected per participating farm, with the sample size depending on total herd size:

- Herd size <35 cows: all cows included in sample (hence, no selection)
- Herd size 36-40 cows: skip every 10th cow on the list
- Herd size 41-50 cows: skip every 5th cow on the list
- Herd size >50 cows: skip every 3rd cow on the list

Selected cows were ear tagged.

The aggregate number of cows in the study sample over the total study period was 3330 cows. At intake, the total number of cows in the study sample was 3132 cows (Table 2), with an average number of 31 cows per farm, ranging from 6 to 66 cows per farm. The number of 6 cows was lower than the minimum requirements for farm selection, due to changes in herd size in the period after selecting the farm (culling or relocation). Enumerators were instructed to add new primiparous cows to the sample in case cows left the sample, for example due to culling. However, although some cows were added to the sample, the total number of cows in the study sample declined from 3132 heads at the start (V0) to 2360 heads at the end of the monitoring period (V7; Table 2), whereas total herd size increased during the study period (see Results section 3.1). This was likely due to the lack of replacements at the farm and farmers not willing to include other cows in the study. The number of cows in the study sample decreased in all districts during the monitoring period (V0-V7), particularly in Kiruhura and Mbarara.

Table 2 *Planning of bi-monthly farm visits and number of cows included in the herd sample.*

Farm visit	Month/year	Total sample size (heads)
Baseline (V0)	April - July 2018	3132
V1	Sept - Nov 2018	3033
V2	Dec 2018 – Jan 2019	2980
V3	Jan - March 2019	2917
V4	Apr - June 2019	2723
V5	June - Aug 2019	2519
V6	Aug - Sept 2019	2416
V7	Nov - Dec 2019	2360

2.4 Data analysis

2.4.1 Calculation of herd parameters

To evaluate technical performance, herd parameters were calculated and compared to various farm characteristics and management practices. Some data were excluded from further analysis (thus not reported) due to expected low reliability:

- Age at first calving (AFC), as recalled by the farmer; AFC seemed low (varying from 24.7 to 31.3 months among districts) compared to other regional literature. For example, AFC was 37-38 and 31 months in studies in Uganda and Kenya, respectively (Nalubwama et al., 2016; Ojango and Pollot, 2001). For two enumerators, an AFC of "24 months" was reported for about half of the cows in the study sample, which was considered unlikely.
- Body condition scores (BCS) was scored on a five-point scale by enumerators for cows in the herd sample, but very little variation in BCS was found: 87% of cows obtained score 3, and there were no cows with score 1 ('very lean'). The lack of variation in BCS scores was possibly due to insufficient training of enumerators.
- Perinatal death rate (i.e., the percentage of pregnancies that end with a dead calf by abortion, still birth or death in the first 30 days after birth) as recalled by farmers seemed low compared to other literature. On average perinatal death was reported for 9.0% of the pregnancies, compared to, for example, 20% in Opio et al. (2013) for Sub Saharan Africa.

Furthermore, sensitivity to seasonal changes in weather (particularly drought periods) could not be analysed for milk yield because milk yields were recorded only in farm visits V4 to V7, and during the study period the dry period was less pronounced than other years. Therefore, with regard to sensitivity to seasonal changes in weather, only farmers' satisfaction about feed and water resources was evaluated. Farmers were asked in the bi-monthly questionnaire to score their satisfaction about feed and water resources on a 1 to 5 point scale, i.e. from "very dissatisfied" to "very satisfied".

Milk yield (cows in herd sample; V4-V7)

Average milk yield per lactating cow was evaluated per farm-visit day, as well as average milk yield per lactating cow across all four farm visits in which milk yield was recorded (V4-V7). In addition, to account for lactation stage and dry period, milk yield per lactation and milk yield per year were estimated. Because of limited milk yield data, these parameters were estimated by fitting a lactation curve to available milk yield records at the herd level.

Two types of lactation curves were explored: a linear equation (Equation 1) and a non-linear equation (Equation 2). Linear equations describe atypical lactation curves, i.e. lactation curves with an intercept and a slope, which is either decreasing, constant, or increasing. Non-linear equations are used to describe typical lactation curves, i.e. showing an increase in milk yield up to peak production, and subsequently a gradual decline until drying-off. In this study we chose the non-linear equation by Migose *et al.* (2020) after Jenkins and Ferrell ('J&K'; 1984), which is a modified Wood's equation, and requires only two parameters that were available in the data collected in the present study: milk yield and days in milk. The J&F equation, therefore, is suited to estimate milk production per lactation if limited lactation data are available (Migose et al., 2020). Cows with at least one milk yield record during the monitoring period (V4-V7) were included, i.e. 2510 cows out of the 3330 cows in the total study sample.

$$Y(t) = at + b \quad (\text{Equation 1})$$

$$Y(t) = t \times (m \times e^{kt})^{-1} \quad (\text{Equation 2})$$

where $Y(t)$ is daily milk production on the t^{th} week after calving (kg/day), t is the number of weeks after calving, and a, b, m and k are parameters that determine the slope, intercept, and curvature of the lactation curve.

The fit of the linear and the non-linear equation (i.e., how well the model fits the data) was compared based on the average RMSE of the two models. This comparison showed a better fit of the linear model compared to the J&F model for all herds (average RMSE=721 kg/lactation vs 1056 kg/lactation), which is in line with results of a study by Migose et al. (2020) in Kenyan herds. Therefore, the linear equation was used to estimate milk yield per lactation. Subsequently, the estimated milk yield per lactation was corrected for lactation length, which was estimated based on calving interval (CI) and the ratio of dry cows to lactating cows in the herd. During the milk recording period (V4-V7), the average ratio was 0.7 dry cow per lactating cow, ranging from 0.03 to 2.7 among herds. We assumed estimates of lactation lengths based on CI and the ratio of lactating cows to dry cows were more accurate than lactation lengths based on calving and dry-off dates (farmer-recall), since the estimated milk production per year showed a higher correlation with amount of milk sold from farms (R_s = 0.71 vs 0.57 when based on calving and dry-off dates). As a last step, average milk yield per lactation and registered calving interval (CI) was used to estimate the average annual milk yield per cow.

Reproduction parameters (cows in herd sample; V0-V7)
Reproduction parameters evaluated in this study were:

- Calving interval, i.e. the difference between last calving date (farmer recall) prior to the start of the study[2] and the first calving date recorded during the study. Cows with no or only 1 calving date were excluded, leaving 2450 cows for estimating calving intervals. Hence, calving interval is only based on cows that calved during the study period.
- Calving rate, i.e. the number of calves born relative to the number of exposed females in the herd sample in one year.

Demographics (cows in herd sample; V2-V7)
Demographic parameters evaluated in this study were:

- Mortality rate, i.e. the number of cows in the herd sample that died divided by the average number of cows present (i.e. cow-time at risk) in the herd sample in 1 year (V2-V7);
- Culling rate, i.e. the number of cows in the herd sample that exited the farm (for sales, slaughter, salvage or death; not for temporary transfer) divided by the average number of cows present (i.e. cow-time at risk) in the herd sample during 1 year (V2-V7);
- Percentage of cows transferred to another farm during the study period, divided by the average number of cows present in the herd sample in 1 year (V2-V7).

Changes in herd size were accounted for in these parameters by using cow-time at risk as denominator (based on bi-monthly counts), which is an acknowledged method for dealing with fluctuations in herd size (Fetrow et al., 2006)[3]. There is overlap between mortality rate and culling rate; culling rate is the sum of mortality rate and percentage of cows exiting the herd alive. In case the culled cow is replaced, the culling rate is the same as the replacement rate.

Availability and quality of feed and water
Parameters related to feed and water availability evaluated in this study are (for the total herd):

- Quantities of fodder and feed supplied to the herd, as measured by enumerators (V0-V7);
- Perception of the quantity and quality of pasture, fodder, feed and drinking water as perceived by farmers, per farm visit.

2.4.2 Statistical analysis

Descriptive statistics were carried out to describe general characteristics of farms in the baseline survey. Farms were then compared based on various farm and herd characteristics, management, and farm performance. Differences between categories were statistically tested using the Independent-Samples T Test (2 categories) or one-way ANOVA (>2 categories) for normally distributed continuous variables and the Pearson Chi-Square test for categorical variables. To evaluate differences between

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[2] The monitoring period was too short to record two calving dates (only 407 cows calved two times during the study). Data of the last calving date prior to the study was possibly less reliable because it was based on farmer recall.

[3] The mean cow inventory (i.e. the denominator), however, is recommended to be calculated at least on a monthly basis (Fetrow et al., 2006).

farm visits over time, repeated measures ANOVA was used. Statistical analyses were performed in IBM SPSS Statistics version 25.

2.4.3 Life Cycle Assessment

An attributional life cycle assessment (LCA) was carried out to estimate GHG emissions (CO_2, CH_4, and N_2O; jointly expressed as 'CO_2 equivalents') during all processes for the production of milk and live weight up to the dairy farm gate (i.e., 'cradle-to-farm gate'). This included production of farm inputs and on-farm processes, but excluded post-farm gate transport and processing of the milk (Figure 3). GHG emissions related to land use and land use change (LULUC) were not included in this LCA, because of its complexity (e.g., De Rosa, 2018; Hawkins *et al.*, 2021).

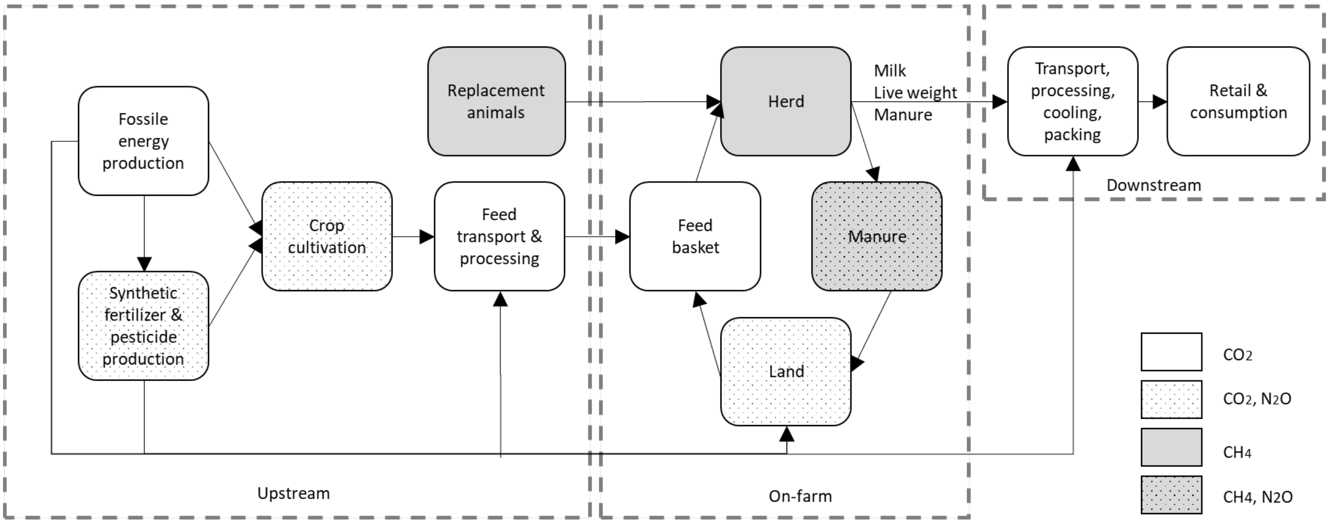

Figure 3 *Cradle-to-farm gate system boundaries for the life cycle assessment of dairy systems (downstream process not included in present study).*

2.4.3.1 Data inventory

Primary, farm-specific data (see description of data collection in section 2.4) were used for the following LCA input parameters: number of mature cows and bulls, milk yield per cow, death rates of young stock and adult cattle, replacement rate, calving rate, heart girth (for estimation of live weights), quantities of feed and fodder supplied, manure quantity per manure management system, amount and type of organic and synthetic fertilizer and pesticides applied on pasture and forage for cattle (on-farm), and mechanization level.

Herd size

Herd size was based on the total number of mature cows and bulls counted in farm visits (of the total herd, not only the sample), with numbers of young stock estimated based on farm-specific rate parameters of reproduction, culling, and mortality. Replacement rate was calculated based on the number of cows that departed from the herd sample (alive or dead) relative to the average number of cows present in the herd sample (i.e., culling rate). Calving rate was calculated based on the number of calves born from the herd sample relative to the number of exposed females in the herd sample in one year.

In case the number of cows culled per year exceeded the number of replacement heifers available on the farm, we assumed additional replacement heifers were purchased. In this case an emission factor related to the purchased replacement heifer was added to total farm emissions.

Milk yield and live weight output

Annual milk production per cow was estimated by fitting a lactation curve to available milk yield records (see paragraph 2.4.1). Milk yield was not corrected for calves suckling (calves were allowed to suckle on most farms). Live weights of cows were estimated based on heart girth measurements, using the following equation (Goopy et al., 2017):

$$LW = 73.599 - 2.291 * HG + 0.02362 * HG^2$$

where LW = live weight (kg) and HG = heart girth (cm).

Feed intake

Intake of supplemented feed and forage was measured in bi-monthly farm visits. Pasture intake was not measured, but estimated based on gross energy (GE) requirements of animals, and GE in supplemented feed and forage. Farm-specific GE requirements of animals were estimated using the Tier 2 method described in IPCC (2006). To estimate intake from pasture grass, GE supplied via supplemented feed and forage (as measured in bi-monthly farm visits) was subtracted from total GE requirements. All supplemental feed fed to herds was assumed to be fed to the dairy cows, whereas bulls and young stock (including surplus animals) were assumed to be fed on pasture only. Average estimated DM intake from pasture was 91%, varying from 79% in Ntungamo to 99% in Lyantonde and Isingiro.

As forage species were not specified in bi-monthly measurements, the following assumptions were made about forage species (see nutritional values in Table 3):

- Grazed grass: Signal grass (Brachiaria spp) and Kikuyu grass (Pennisetum clandestinum), in equal proportions;
- Fresh cut grass: Elephant/Napier grass (Pennisetum purpureum), 6 weeks old;
- Hay: Rhodes grass (Chloris Gayana) and Guinea grass (Panicum maximum), in equal proportions;
- Haylage: Alfalfa (Medicago sativa);
- Grass silage: Elephant/Napier grass (Pennisetum purpureum), low CP;
- Whole maize silage (Zea mays);
- Crop residues: Banana peelings (Musa acuminata);
- Other green fodder (not specified): desmodium (Desmodium intortum) and Calliandra (Calliandra calothyrsus), in equal proportions.

Two types of feed ingredients were ignored in the LCA: fresh grain (fed in 2 farms) was ignored because of low prevalence, and dairy meal (fed in 4 farms) was ignored because of low prevalence and no information could be obtained about its composition, nutritional values, and production processes (kept confidential by manufacturers).

Prices and transport distances of purchased feeds were supposed to be obtained from bi-monthly interviews, but enumerators failed to do so. Therefore, prices and transport distances were estimated by local experts of SNV TIDE project.

Manure management

The fraction of animal excreta per manure management system (MMS) was based on farmers' estimates in the baseline survey. MMS included pasture/ range, liquid/ slurry, solid storage, composting, anaerobic digestion, exit livestock (burned for fuel, used for construction, to arable crops), and discharged manure (a description of these MMS can be found in IPCC, 2019). The share of manure excreted on pasture was assumed to be proportional to the time spent on pasture. The following assumptions were made about types of MMS (as related to IPCC emission factors; IPCC, 2019):

- for anaerobic digestion, anaerobic digester with 'high leakage, low quality technology, low quality gastight storage technology';
- for liquid storage, with natural crust, and a storage time of 6 months;
- for composting, passive windrow (infrequent mixing and turning).

Fertilization

Nitrogen (N) application rates on homegrown forage were calculated based on Tier 2 estimates of N excretion rates in manure, the share of manure applied on land, areas of agricultural land, and assumed N losses (IPCC, 2019). Amounts of synthetic fertilizer applied on forage and mechanization level were based on farmer responses (baseline survey).

Secondary data sources

Where primary data were not available from farms or were biased, secondary data (i.e. readily available data) were used from existing databases, expert opinion, or literature, including: fat and protein contents of milk (3.8% and 2.6%; Atusasiibwe et al., 2019); perinatal death rate (20%; Opio et al., 2013); age at first calving (37.8 months; Nalubwama et al., 2016); nutritional values of feed ingredients (Table 3); crop yields, fertilizer use and pesticide use of purchased feeds (Table 4); and data for field work emissions, feed processing emissions, and energy use of road transport (FeedPrint; Vellinga *et al.*, 2012).

Nutritional values of feed and forages were partly obtained from SNV Tropical Feed Library for Rumen8, but this library did not contain data about gross energy content and energy digestibility of feed and forages; therewith other databases were employed (see Table 3).

Table 3 *Assumed nutritional values of feed ingredients.*

	Dry matter content	**N content**	**Gross energy**	**Digestibility**
	(%)	(g/kg DM)	(MJ/kg DM)	(%)
Grazed grass				
Signal grass (Brachiaria decumbens)	25.5[a]	20.6[a]	18.1[d]	52.7[d]
Kikuyu grass	19.6[a]	34.1[a]	18.3[d]	66.0[d]
Fresh cut Napier (6 wk)	20.8[a]	22.4[a]	17.0[b]	67.0[b]
Rhodes grass, hay, standard	82.0[a]	12.8[a]	18.1[d]	55.6[d]
Haylage (Alfalfa)	44.4[c]	30.6[d]	18.2[d]	66.7[c]
Napier silage	22.7[b]	8.6[b]	17.4[d]	47.1[b]
Whole maize silage	26.2[a]	10.4[a]	19.0[d]	68.6[d]
Maize bran	88.7[a]	16.0[a]	18.5[d]	71.6[b]
Brewers spent grain (BSG)- wet	23.5[a]	42.1[a]	20.3[d]	81.8[d]
Other green fodder				
Desmodium intortum	23.2[a]	26.1[a]	17.2[b]	50.2[b]
Calliandra (mature)	28.7[a]	35.0[a]	19.5[b]	44.6[b]
Banana peelings	21.7[b]	10.4[b]	18.4[d]	50.5[b]

[a] SNV Tropical Feed Library for Rumen8
[b] Laswai et al., 2013
[c] Kononoff and Heinrichs, 2003; Gordon et al., 1961
[d] Feedipedia, accessed March 2021.

Table 4 *Assumed crop yields, fertilizer use, and pesticide use[1].*

	Gross yield	**Synthetic fertilizer (kg per ha/y)[f]**			**Animal manure**	**N fixation**	**Pesticides**
	(ton DM/ha)	N	P2O5	K2O	(kg N per ha/y)	(kg N per ha/y)	(kg/ha)
Grazed grass	8.5[c]	-	-	-	(farm specific)	-	(farm specific)
Fresh cut Napier	12.8[h]	-	-	-	(farm specific)	-	(farm specific)
Hay	10.0[c]	-	-	-	(farm specific)	-	(farm specific)
Alfalfa	8.0[e]	-	-	-	(farm specific)	177[g]	(farm specific)
Other green fodder	6.0[e]	-	-	-	(farm specific)	238[g]	(farm specific)
Maize (whole plant)	2.4[i]	1.6[a]	0.6[a]	1.8[a]	1.5[j]	-	-
Banana fruits	5.6[b]	-[b]	-[b]	-[b]	20[b]	-	-[b]

[1] We assumed no lime was used in any of the crops.
[a] Godfrey and Dickens, 2015 (assuming 3.2% of the acreage was fertilized)
[b] Expert opinion (pers. comm. H. den Braber (WUR), March 2021)
[c] Feedipedia
[e] Feedipedia & expert best guess (pers. comm. B. Wouters (WUR), March 2021)
[f] Only few farmers applied synthetic fertilizer on pasture (1 farm) or land for other forages (6 farms)
[g] Burity et al., 1989; Snijders et al., 2011
[h] Kabirizi et al., 2013
[i] Grain: expert opinion (pers. comm. W. Marinus (WUR), March 2021), above ground residue : IPCC (2019).
[j] Nkonya et al., 2005

2.4.3.2 GHG emission calculation

GHG emissions were estimated using the Global Livestock Environmental Assessment Model (GLEAM; MacLeod et al., 2017). In GLEAM, GHG emissions are calculated based on IPCC Guidelines (IPCC, 2019), based on an attributional LCA approach and using Tier 2 methods where data permit. The GLEAM model consists of five modules:

i) Herd module: characterizing herd structure, dynamics, and production. The herd model computes the number of young stock to maintain the adult stock, using rate parameters on reproduction, growth, and mortality, as well as live weight (LW) output.

ii) Manure module: specifying the proportion of manure in each manure management system. Results of this module are used as input to the system module (calculating emissions from manure management using the IPCC Tier 2 method (IPCC, 2006)) and the feed module (calculating emissions from manure applied to crops and grasses).

iii) Feed module: specifying the total herd feed ration and calculating CO_2, CH_4, and N_2O emissions arising during feed production, processing and transport. Emission sources include direct and indirect N_2O and CO_2 from crop cultivation and cultivation inputs (e.g., synthetic fertilizer), and CO_2 from energy use associated with field operations, crop processing and transport. CO_2 emissions arising from LULUC were not included. Total emissions per feed ingredient are allocated between the grain and its co-products using economic or digestible fraction allocation, depending on the type of feed ingredient (MacLeod et al., 2013). In addition, average digestible energy and N content of the feed ration as a whole are calculated, which are used in the System module to determine total DM intake per animal cohort.

iv) System module: calculating DM feed intake per animal cohort based on cattle energy requirements and the digestible energy and N content of the ration from the Feed module. N and P retention in animal products (milk and LW) and volatile solids are determined, and N and P excreted in dung and urine (IPCC, 2014). Emissions arising from enteric fermentation (CH_4), manure management ($CH_4$and N_2O), energy use in housing (CO_2), and the production, processing, and transport of feed (CO_2, CH_4, and N_2O) are calculated using Tier 2 approaches (IPCC, 2014). For enteric methane the emission factor is adjusted for ration digestibility [details can be found in MacLeod et al. (2017)]. For GWP characterization, factors of 1, 28, and 265 were used for CO_2, biogenic CH_4, and N_2O, respectively, to sum up emissions (IPCC AR5, 2014).

v) Allocation module: GHG emissions are allocated to milk and live weight, using biophysical relationship allocation (Thoma et al., 2013). In the present study, emissions were not allocated to other functions of cattle (non-edible outputs or services).

Salient features of the GLEAM model are described in MacLeod et al. (2017) and De Vries et al. (2019).

3 Results and discussion

3.1 Farm characteristics and practices

Herd size

Average herd size of farms in the study consisted of 36 adult cows (23 lactating cows, 13 dry cows; Std. Deviation specified in Table 6), 36 heads of young stock, and 5 bulls (male cattle > 1 year; V0-V7). Herd sizes in Isingiro tended to be larger than in Ntungamo (though this difference was not significant; $P<0.1$; Table 6). Average herd size increased during the study period from 71 to 85 heads of cattle, mainly due to an increase in the number of young stock, and to a lesser extent, an increase in number of adult cows. The number of young stock increased mainly in Ntungamo, Mbarara and Isingiro, while the number of adult cows increased mainly in Lyantonde and Ntungamo (Figure 4).

Herd sizes decreased after V3-V4 in Mbarara and Kiruhura, partly due to temporary transfers of cattle from farms to other locations. Temporary transfer of cows occurred during V4-V7 on 40.6% of the farms, mainly in Kiruhura (93.3% of farms) and Mbarara (92.0%), and on fewer farms in Lyantonde (11.8%) and Ntungamo (7.4%). In Isingiro none of the farms transferred cows. On average 7% (SD 11%) of cows per farm (i.e., about 2-3 cows) were transferred during V4-V7, ranging from 0 to 49% per farm. Transfer of cows occurred significantly more often in specialized farms than in mixed crop livestock farms (61.5% vs. 33.3%; $P<0.05$), and more often in farms with paddocks compared to other grazing systems (55.1% vs. 26.9%; $P<0.05$), but the latter result was likely confounded with districts (Kiruhura and Mbarara had more farms with paddocks).

Adult herd size was significantly larger in farms with relatively much land for grass and fodder production (Spearman rho=0.57; $P<0.01$). Adult herd size was smaller in farms that provided supplemental feed or fodder than in farms with grazing only ($P<0.05$; Table 6).

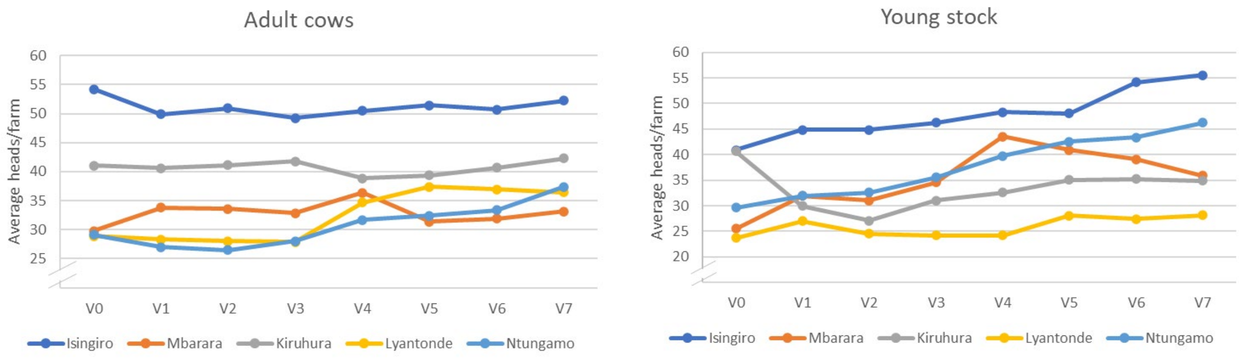

Figure 4 *Changes in herd size (n heads) per district during the study period (farm visits V0-V7).*

Land use

Average land area used for pasture or production of other fodders was 164 acres, of which 155 acres of pasture and 9 acres of other fodder. Land area was significantly larger in Kiruhura than in Lyantonde, Mbarara, and Ntungamo ($P<0.005$); and significantly larger in Isingiro than in Ntungamo ($P<0.05$; Table 6). Land size of farms providing supplemental feed or fodder was smaller than in farms with grazing only ($P<0.001$; Table 6). Only 2 farms indicated milking cows were partly grazed on communal grazing grounds (besides private area), and only during one farm visit.

Besides dairy farming, cash crops were produced on 74% of the farms, ('mixed crop-livestock farms'). In Isingiro and Ntungamo mixed farms were more common (94% and 96% of farms) than in Kiruhura, Lyantonde, and Mbarara (52-65%; $P<0.005$). Mixed farming was more common among male owned farms than among female owned farms (81% vs. 50%, P<0.05), and farms with rainwater harvesting were more often mixed farms than farms without rainwater harvesting (80% vs 60%; P<0.05).

Field inputs and field work

Milking cows were grazing on all dairy farms, with an average grazing time of 18 h per 24 h. Average grazing time was highest in Kiruhura (20 h), and lowest in Lyantonde (16h). Besides manure excretion on pasture, most of the farms (80%) collected manure excreted during milking and feeding, and applied this manure on arable crops and fodder crops (48%), or on pasture (31%).

Synthetic fertilizer use was low: only few dairy farms applied synthetic fertilizer on pasture (1 farm) or other fodder (6 farms; DAP, NPK, urea or other). Three dairy farms indicated that they applied synthetic fertilizer on food crops. Pesticides were used on pasture in 3 dairy farms, and on fodder and food crops in 13 and 20 dairy farms, respectively (out of 101 farms).

Twenty dairy farms used mechanization on pasture, particularly for ploughing (20 farms; 1 farm used mechanization for harvesting). Twenty-four dairy farms used mechanization on fodder crops, particularly for ploughing/seed bed preparation (24 farms; 4 farms used mechanization for harvesting, 1 farm used mechanization for fertilization/spraying). Farms did not use mechanization for manure application. Farms do not use cattle for draft power (pers. comm. Paul Kimbugwe (SNV); May 2021).

Grazing system

At the start of the monitoring period (V0), almost half of the farms used paddocks as grazing system (49%), whereas other farms used perimeter fencing (18%) or a combination of paddocks and perimeter fencing (20%). Other farms had open grazing/free range without paddocks (5%), stall feeding with limited grazing (1%), or a combination of different systems (4%). Use of paddocks as grazing system was significantly higher in Kiruhura than in Lyantonde and Ntungamo (P<0.05). Also, the use of paddocks was significantly higher among female owned farms than among male owned farms (72% vs. 46%, P<0.05), and among farms feeding supplemental feed and fodder compared to grazing only (57% vs 35%, P<0.05).

Supplemental feeding

Between V1-V7 more than 60% of farms fed supplemental feed and fodder besides grazed grass, whereas on nearly 40% of farms cows were grazed only. Supplemental feeding was done significantly more often in Mbarara (88% of farms) than in Isingiro, Kiruhura and Lyantonde (35-47%; P<0.005), and significantly more often in Ntungamo than in Lyantonde (Table 6). Also, supplemental feeding was practiced more often in farms that used paddocks compared to other grazing systems (71% vs 50%, P<0.05).

In terms of fresh supply, average supplemental feed supply was highest in Mbarara and Ntungamo (8.7 and 6.0 kg fresh/cow/d), intermediate in Kiruhura (3.2), and lowest in Isingiro and Lyantonde (1.2 and 0.7; Table 6; note that DM intake may be different). Offered feed supplements mainly consisted of cut grass and maize silage, but with large differences among districts:

- Mbarara: various types of feed and fodders, incl. cut grass, maize silage, crop residues, Napier silage, BSG, hay, and maize bran;
- Ntungamo: many types of feed and fodders, including all feed and fodder in Table 5 (mainly cut grass, maize silage and maize bran);
- Kiruhura: mainly maize silage, cut grass and maize bran;
- Isingiro: mainly maize silage, and few farms feeding maize bran;
- Lyantonde: few farms providing supplemental feed.

Table 5 *Average feed supply (kg fresh/cow/d)[1] and number of farms feeding the feed ingredients per district (V1-V7).*

	All farms (101 farms)		**Isingiro (17 farms)**		**Kiruhura (15 farms)**		**Lyantonde (17 farms)**		**Mbarara (25 farms)**		**Ntungamo (27 farms)**	
	kg/cow	n	kg/cow	n	kg/cow	n	kg/cow	n	kg/cow	n	kg/cow	n
Cut grass	1.19	32	0.04	1	0.68	5	-	-	1.30	9	2.87	15
Maize silage	1.15	25	0.79	6	1.66	4	0.19	1	1.89	7	1.04	8
Crop residues	0.55	7	-	-	-	-	-	-	1.35	5	0.80	2
Napier silage	0.49	9	0.04	1	0.05	1	0.26	1	1.71	5	0.05	1
Brewers spent grain	0.38	17	0.00	1			0.19	1	1.37	12	0.04	3
Hay	0.36	12	0.11	1	0.14	1	-	-	0.85	8	0.41	2
Maize bran	0.23	27	0.17	3	0.17	6	0.03	1	0.25	7	0.40	10
Haylage	0.10	6	-	-	0.50	1	-	-	-	-	0.08	5
Other fodder	0.04	5	-	-	-	-	-	-	-	-	0.14	5
Dairy meal	0.04	4	-	-	-	-	-	-	-	-	0.16	4
Fresh grain	0.01	2	-	-	0.01	1	-	-	-	-	0.03	1
Total intake	*4.54*		*1.15*		*3.21*		*0.67*		*8.72*		*6.02*	

[1] Average of all farms, hence including farms not feeding the feed ingredient.

On the farms feeding supplemental feed and fodder (i.e. 60% of farms), average dry matter (DM) supply was 2.0 kg DM/cow/d during V1-V7. DM supply was lowest on farms in Lyantonde and Isingiro (0.5 and 1.0 kg DM/cow/d), and highest in Ntungamo, Kiruhura and Mbarara (1.8, 2.4 and 3.0 kg DM/cow/d). Average DM supply varied over farm visits, with the highest average supply in V4 and V5 (i.e. April-Aug 2019; Figure 5), likely due to the dry season. In V4 and V5, mainly the supply of maize silage, fresh cut grass, and crop residues per cow increased (Figure 6). It should be noted that DM supply was registered differently in V1-V3 and V4-V7: in V1-V3 the amount of feed/fodder per cow was estimated based on the total number of cows present in the herd (as registered in the herd count), whereas in V4-V7 the amount of feed/fodder per animal was estimated based on the number of cows and youngstock actually feeding from the offered feed/fodder (see explanation in Methods section). This has influenced estimates of DM supply and should be taken into account when interpreting results in Figure 5 and 6.

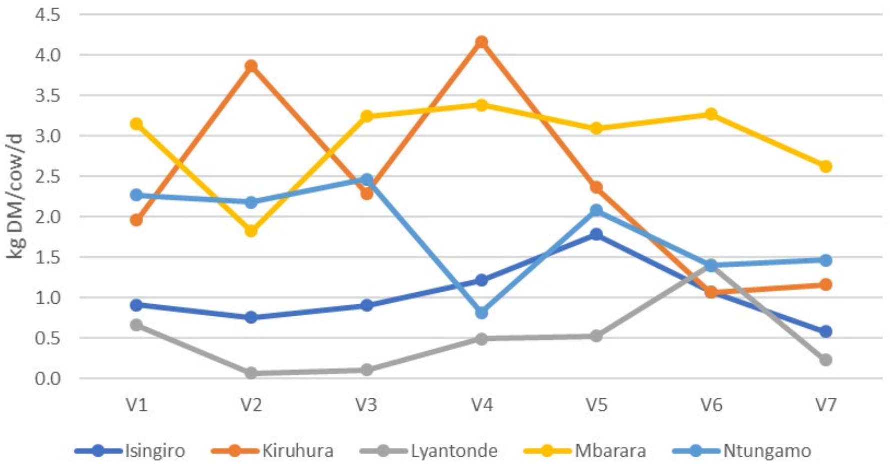

Figure 5 *Average feed supply (total kg DM/cow/d) over time (farm visits V1-V7; N=61 farms).*

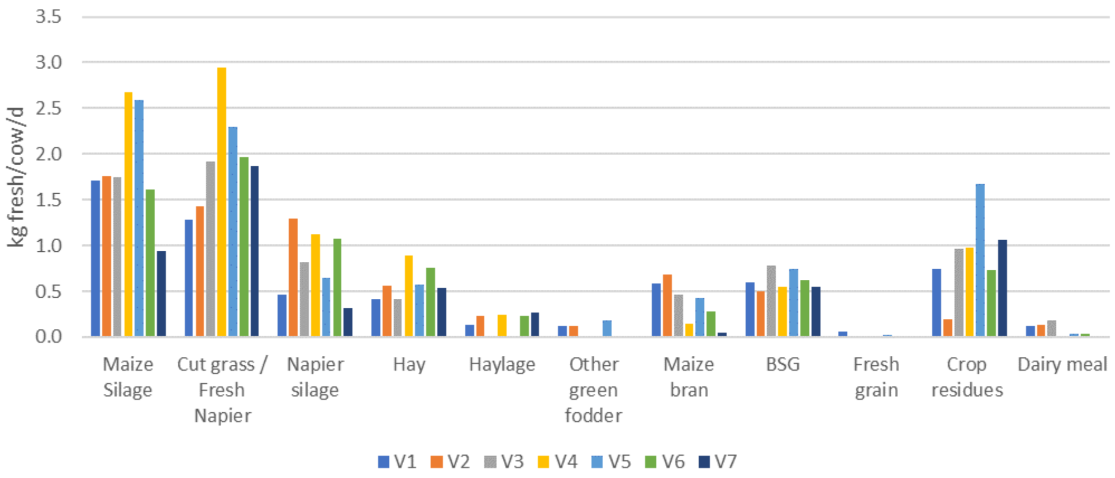

Figure 6 Average supply per feed ingredient (kg fresh/cow/d) during farm visits V1-V7 (N=61 farms).

Other farm management practices
Of all 3330 cows in the sample, enumerators classified 87.0% as crossbred, 11.8% as Holstein Frisian (HF), 0.5% as Jersey, 0.2% as local breed, 0.03% as Ayrshire, and 0.5% as 'other'. In interviews, farmers indicated that breeds present on farms were HF, Jersey, Ayshire, Ankole Long horned Sanga, Brown Swiss, Guernsey, East African Shorthorn zebu, and 'other'. For further analysis, farms were classified based on the classification of breeds in herd samples: as "HF" when >50% of the cows in the herd were HF (10.9% of farms), and as "crossbred" when >50% were crossbred (89.1%). Farms classified as HF were only present in Isingiro, Mbarara, and Ntungamo (Table 6).

More than 70% of farms used rainwater harvesting, particularly in Kiruhura. Significantly more farms used rainwater harvesting in Kiruhura than in Lyantonde (nearly all farms vs. less than half of the farms; P<0.05). Rainwater harvesting was done more often in farms using paddocks than in other grazing systems (84% vs 58%; P<0.05), and more often in mixed farms than in specialized dairy farms (76% vs 54%; P<0.05).

Table 6 *Farm characteristics, practices, and herd performance (average, standard deviation), and statistical associations*[1].

	District						**System**		**Owner gender**[2]		**Feeding**		**Breed (>50%)**		**Grazing system**		**Rainwater harvesting**	
	All farms	Isingiro	Kiruhura	Lyantonde	Mbarara	Ntungamo	Mixed	Spec.	Male	Female	Grazing only	Suppl. feed	Cross	HF	Paddock	Other	Yes	No
	N=101	N=17	N=15	N=17	N=25	N=27	N=75	N=26	N=79	N=18	N=40	N=61	N=90	N=11	N=49	N=52	N=71	N=30
Herd size (n adult cows)[3]	36.8 (23.4)	50.7 (35.4)	40.7 (19.4)	32.8 (14.8)	33.3 (26.1)	30.8 (11.8)	35.8 (22.6)	38.9 (25.3)	34.6 (17.6)	37.9 (27.8)	43.1 (28.7)^{a}	32.3 (17.8)^{b}	36.6 (24.0)	36.2 (16.2)	37.4 (21.4)	35.8 (25.0)	36.7 (20.0)	36.2 (29.7)
Land for fodder production (acres)	165.9 (232.9)	277.2 (174.2)^{ab}	378.7 (460.0)^{b}	105.0 (95.9)^{a}	98.7 (113.7)^{a}	71.6 (67.8)^{c}	167.8 (254.1)	153.6 (148.2)	157.3 (239.3)	170.1 (168.9)	270.2 (324.6)^{a}	94.6 (89.2)^{b}	171.7 (242.7)	102.5 (66.6)	203.2 (293.4)	127.4 (143.7)	189.6 (255.7)^{a}	103.8 (143.8)^{b}
Milk yield V4-V7 (kg/cow/d)	7.1 (2.0)	7.2 (2.4)^{a}	9.3 (2.1)^{b}	6.0 (0.7)^{a}	7.3 (2.1)^{a}	6.4 (1.1)^{a}	7.0 (1.7)	7.6 (2.6)	6.9 (1.7)^{a}	7.8 (2.2)^{b}	6.4 (1.8)^{a}	7.6 (2.0)^{b}	6.9 (1.8)^{a}	8.9 (2.6)^{b}	7.6 (1.9)^{a}	6.7 (2.0)^{b}	7.1 (2.0)	7.3 (2.0)
Calving interval (d)	482.9 (63.8)	452.6 (25.6)^{a}	442.5 (17.4)^{a}	514.8 (62.9)^{b}	490.2 (72.7)^{ab}	496.3 (72.3)^{ab}	483.1 (66.8)	481.1 (54.5)	480.7 (65.7)	479.2 (49.7)	482.5 (57.6)	482.6 (67.7)	479.6 (63.2)	506.9 (64.3)	480.3 (69.0)	484.7 (58.6)	478.2 (59.7)	492.8 (71.9)
Calving rate (%)	66.4 (13.5)	63.2 (14.5)	74.0 (8.2)	66.2 (14.9)	64.2 (13.1)	66.2 (14.1)	67.3 (14.5)	63.6 (10.0)	66.3 (13.7)	68.3 (13.3)	66.8 (13.0)	66.0 (14.0)	66.6 (13.8)	64.0 (11.7)	67.3 (13.6)	65.5 (13.6)	65.9 (13.2)	67.5 (14.6)
Culling rate (%)	17.6 (14.5)	15.2 (15.9)^{a}	30.0 (12.8)^{b}	13.9 (10.1)^{a}	18.6 (15.0)^{ab}	13.5 (13.3)^{a}	17.6 (14.8)	17.6 (13.8)	18.4 (14.9)	15.6 (13.0)	19.7 (14.1)	16.3 (14.7)	17.5 (14.3)	18.7 (16.6)	18.4 (14.3)	16.9 (14.8)	17.9 (14.4)	17.1 (14.9)
Mortality cows (% of farms)																		
Zero mortality	53.0	52.9^{a}	6.7^{b}	82.4^{a}	64.0^{a}	50.0^{a}	57.7	51.4	53.8	50.0	46.2	57.4	52.8	54.5	51.0	54.9	51.4	56.7
>0-5%	23.0	23.5^{ab}	53.3^{b}	5.9^{a}	20.0^{ab}	19.2^{ab}	23.1	23.0	24.4	16.7	20.5	24.6	24.7	9.1	24.5	21.6	25.7	16.7
>5%	24.0	23.5^{a}	40.0^{a}	11.8^{a}	16.0^{a}	30.8^{a}	19.2	25.7	21.8	33.3	33.3	18.0	22.5	36.4	23.5	23.5	22.9	26.7
Mortality young stock (% of young stock)	13.2 (13.8)	8.6 (10.7)^{ab}	13.2 (10.2)^{ab}	6.6 (5.8)^{a}	14.0 (11.9)^{ab}	19.4 (19.4)^{b}	14.0 (14.4)	10.9 (12.2)	13.9 (14.1)	9.9 (12.1)	15.0 (14.1)	12.0 (13.6)	12.1 (12.6)^{a}	21.9 (20.0)^{b}	11.7 (10.7)	14.4 (16.0)	12.6 (12.9)	13.9 (15.1)
Transferring cows (% of farms)	40.6	0.0^{a}	93.3^{b}	11.8^{a}	92.0^{b}	7.4^{a}	33.3^{a}	61.5^{b}	55.6	38.0	32.5	45.9	42.2	27.3	55.1^{a}	26.9^{b}	45.1	30.0
Practices[4] (% of farms)																		
Cash crop production	74.3	94.1^{a}	60.0^{b}	64.7^{b}	52.0^{b}	96.3^{a}	-	-	81.0^{a}	50.0^{b}	82.5	68.9	73.3	81.8	71.4	76.9	80.3^{a}	60.0^{b}
Supplemental feeding	60.4	47.1^{ab}	46.7^{ab}	35.3^{b}	88.0^{c}	66.7^{ac}	56.0	73.1	59.5	66.7	-	-	58.9	72.7	71.4^{a}	50.0^{b}	62.0	56.7
Breed HF	10.9	17.6	0	0	16.0	14.8	12.0	7.7	10.1	11.1	7.5	13.1	-	-	10.2	11.5	9.9	13.3
Paddocks	48.5	41.2^{ab}	86.7^{b}	23.5^{a}	60.0^{ab}	37.0^{a}	46.7	53.8	45.6^{a}	72.2^{b}	35.0^{a}	57.4^{b}	48.9	45.5	-	-	26.7^{a}	57.7^{b}
Rainwater harvesting	70.3	76.5^{ab}	93.3^{b}	47.1^{a}	64.0^{ab}	74.1^{ab}	76.0^{a}	53.8^{b}	72.2	77.8	67.5	72.1	71.1	63.6	83.7^{a}	57.7^{b}	-	-

[1] Averages of columns' categories with a different letter in superscript are significantly different ($P<0.05$).
[2] Data about gender of owner missing in 4 farms.
[3] Including dry cows and lactating cows, excluding young stock and bulls.
[4] Practices at the start of the monitoring period (V0; practices may have changed during the study)

3.2 Herd performance

Milk yield
Average 24-h milk yield per lactating cow of farm visits V4-V7 (4 test days) was 7.1 kg/cow/d, with 7.4 kg/cow/d in V4, 7.3 kg/cow/d in V5, 6.9 kg/cow/d in V6, and 7.0 kg/cow/d in V7. Average milk yield was lowest in Lyantonde and Ntungamo (6.0 and 6.4 kg/cow/d, resp.), intermediate in Isingiro and Mbarara (7.2 and 7.3, resp.) and highest in Kiruhura (9.3). Milk yield increased during the study period in Kiruhura, and decreased or remained stable in other districts between V4 and V7 (April-Dec 2019; Figure 7).

Average estimated milk yield per lactation was 2129 kg/cow (SD 781 kg), and average estimated milk yield per year 1626 kg/cow/y (SD 614 kg; based on test-day milk yields, calving intervals, and lactation lengths). The average milk yield per year is lower than the milk yield per lactation, because of the long dry period. Average estimated lactation length was 43.7 weeks (SD 11.5 wk; estimated based on ratio of lactating cows to dry cows and calving intervals).

The average 24-h milk yield found in our study is higher than average milk yields reported for dairy farms in this region in Uganda (e.g. 1.4 kg/cow/d in Western Uganda according to Balikowa (2011)). This was due to the fact that farms in our study were larger and more intensive farms. For example, farms in our study milked mainly exotic breeds and crossbreds, whereas these breeds constitute only 12% of the dairy herd in the western region. The average milk yield of exotic and crossbreds is about 2-3 times higher than that of indigenous breeds (Balikowa, 2011; Kabunga *et al.*, 2017). Milk yields found in our study were comparable to milk yields found for more intensive farms in other Ugandan studies. For example, Garcia *et al.* (2008) reported 8.0-8.2 kg/cow/d and 2400-2500 kg/cow/lactation for medium and large scale intensive farms in Mukono district, and Kiggundu *et al.* (2019) reported 1589 kg/cow/y for semi-intensive systems in Uganda’s central cattle corridor.

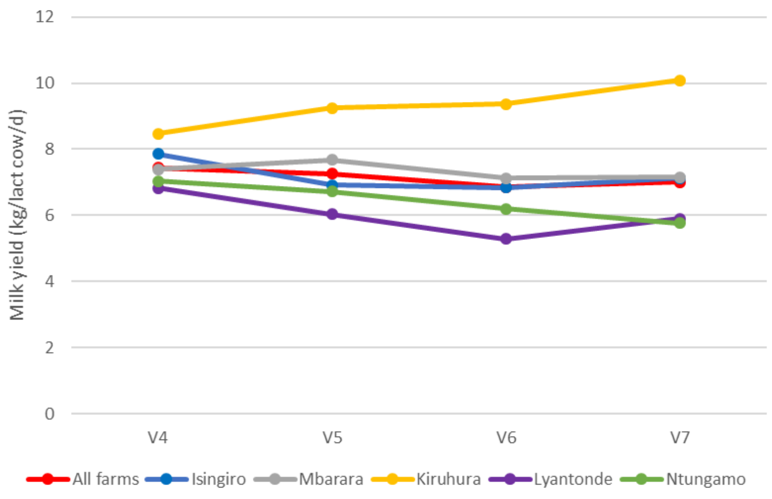

Figure 7 *Average test-day milk yield per lactating cow (kg/cow/d) in farm visits V4-V7.*

A strength of the present study was the use of on-farm measurements to quantify milk yield, which is also an important parameter for LCA as it explains a large part of the variation in GHG emission intensity among farms (De Vries *et al.*, 2019; Wilkes *et al.*, 2020). In other Ugandan or regional studies milk yields are often based on farmer recall methods, but these are known to yield less accurate milk yield estimates than test-day data (Migose *et al.*, 2020). Recall bias can occur due to several factors, such as memory failure or farmers’ high expectations. In the present study it was found that milk yield data showed only a moderate association with farmer recall data of the amount of milk ‘sold yesterday’ (Spearman rho correlation (R_s) ranging from 0.53 to 0.66 in V4-V6). The amount of milk ‘sold yesterday’ was collected via farmer recall, whereas milk yield was measured in sampled cows. On average across 3 farm visits, milk yield per lactating cow was 25% higher than milk sold per lactating cow, but this ranged from -53% (suggesting more is sold than produced, in 12 farms) to +66% among farms. As milk 'sold yesterday' is not likely to exceed the measured amount of milk (pers. comm. Paul Kimbugwe, SNV TIDE project), we expect the farmer recall data on milk sold was partly biased and excluded from the analysis.

Reproduction

Average calving interval (CI) was 483 days (SD 64 d), ranging from 341 to 703 days among farms. This was longer than the CI found by Garcia *et al.* (2008) (16 vs. 14 months). Average calving interval was significantly longer in farms in Lyantonde (514 days) than in Isingiro and Kiruhura (453 and 443 days; P<0.05), and showed a tendency to be shorter in farms feeding silage (P<0.10). Average ratio of lactating cows to dry cows in the herd was 0.7 dry cows per lactating cow (ranging from 0.03 to 2.7 among herds).

Average calving rate was 66%, ranging from 63 to 74% days among districts, but no significant differences were found (Table 6).

Demographics

On 47% of the farms one or more cows in the herd sample died during the total monitoring period (V1-V7). On average across all farms, mortality rate of adult cows in the herd sample was 3.2% (SD 4.8%; V2-V7), ranging from 0 to 23% per farm. Average cow mortality in our study was slightly lower than in Garcia et al. (2008) (4-5%). In Kiruhura, one or more cows died on 93% of farms (Table 6; P<0.05). On the contrary, in Lyantonde no cows died on 82% of the farms. Causes of mortality were not recorded.

On 81% of the farms one or more cows were culled between V1 and V7. On average across all farms, culling rate was 17% (SD 14.5%; V2-V7), ranging from 0 to 55% per farm. Culling rate was significantly higher in farms in Kiruhura (30%) than in other districts except for Mbarara (P<0.05). The relatively high culling rate in Kiruhura was not due to the lack of replacements in the herd sample in this district, because the same trend was observed for the fate of cows initially present in the herd sample (see Table 7 below). As herd size did not change significantly over time (Figure 4), culled cows were likely replaced by purchased cows or heifers.

Table 7 *Percentage of cows initially present in herd sample in V1 that were culled or died during the total monitoring period (V1-V7).*

District	N cows present V1	% cows culled (V7)	% cows died (V7)
Isingiro	648	15%	5%
Kiruhura	546	30%	7%
Lyantonde	477	16%	1%
Mbarara	684	16%	2%
Ntungamo	777	11%	7%

With regard to culling of young stock, most surplus animals were sold at older age: females were more often sold at the age of heifer (or cow) than calf (2.3 vs. 1.0 heads sold per farm during V1-V6), and males were more often sold at the age above 1y old (bull) than calf (3.7 vs 1.2 heads sold per farm during V1-V6).

3.3 Associations between farm characteristics and milk yield

District

Average 24-h milk yield was significantly higher in Kiruhura than in other districts (P<0.001), and was significantly higher in female-owned farms than in male-owned farms (P<0.05; Table 6). Milk yield was not correlated with herd size or land area (Spearman rho =0.1 and 0.0, resp.).

The relatively high milk yield of farms in Kiruhura compared to Lyantonde, Ntungamo, Isingiro and Mbarara was possibly due to the level of TIDE supported on-farm investments, which was highest in Kiruhura according to SNV-TIDE staff (pers. comm. Paul Kimbugwe of SNV-TIDE project, May 2021). Many farms in Kiruhura invested in water supply, fodder production, fencing and paddocking, which may have had a direct effect on the milk production. Higher milk prices and larger farm holdings in this district may have had an indirect effect. The reason of high average culling rate in Kiruhura (30%) was likely due to replacement of less productive cows by improved breeds (breeding through AI or purchased heifers).

Feeding

Average 24-h milk yield was significantly higher (19%) in farms feeding supplemental feed of fodder besides grazed grass than in farms with grazing-only (7.6 vs. 6.4 kg/cow/d; $P<0.005$). In particular, milk yield was higher in farms feeding (maize or Napier-) silage (8.1 vs. 6.6 kg/cow/d; $P<0.001$), or maize bran (8.0 vs. 6.8 kg/cow/d; $P<0.01$). No significant difference was observed for feeding of brewers spent grains, hay, or cut grass. Average 24-h milk yield was significantly higher (13%) in farms with paddocks (7.6 kg/cow/d) compared to other grazing systems (6.7 kg/cow/d; perimeter fence, various fencing, or other; $P<0.05$).

These results are in line with a recent meta-analysis showing that only 2 out of the 9 evaluated management strategies consistently and significantly increased daily milk yield in East African smallholder dairy farms: adoption of improved cattle breeds and improved feeding (i.e. increasing diet quality and quantity; Bateki *et al.*, 2020). In our study particularly the feeding of maize silage, Napier silage, and maize bran showed significantly higher milk yields, and feeding silage was also associated with a shorter calving interval. Farmers increased the supply of maize silage in the dry season, which suggests feeding maize silage is an effective (adaptation) strategy to manage dry-season deficits. Our results are in line with Miyama et al. (2020), who found significantly higher milk yields of Ugandan cows fed supplementary concentrates and on farms applying rotational grazing. Also in southern Australia similar results have been shown for supplemental feeding and seasonal variation in pasture-based systems (Chapman *et al.*, 2008). Improved (dry season) feeding is particularly relevant for cows with a high genetic merit for milk production as pasture dry matter intake is the primary factor limiting milk yield of pasture-based dairy cows, (e.g. Leaver, 1985; Kolver and Muller, 1998). showed a tendency to be shorter in farms feeding silage ($P<0.10$).

Breed

Average milk yield was significantly higher (30%) in farms with Holstein Frisian (HF) as the predominant breed (i.e., >50% of cows in the study sample), compared to farms with mainly crossbreds (8.9 vs. 6.9 kg/cow/d; $P<0.005$). It should be noted, however, that the number of farms with HF was somewhat low (N=11) for drawing statistically valid conclusions. A significantly higher milk yield of exotic breeds compared to crossbreds was also found by Miyama *et al.* (2020; 11.2 vs. 7.3 L/cow/day, resp.) for farms in Mbarara district. Our results are also in line with Bateki *et al.* (2020) who concluded that adoption of improved cattle breeds is one of the two strategies significantly and consistently effective to increase milk yields in East African farms. As stressed earlier, it should be cautioned that a mismatch can arise between the genetic potential for milk production, the availability of quality forages in Uganda, and skill levels to manage improved breeds and high quality forages and pastures (Creemers and Alvarez Aranguiz, 2019).

Female farm management

Milk yield was 13% higher in female-owned farms than in male-owned farms (7.8 vs. 6.9 kg/cow/d). Part of this association can possibly be explained by the fact that female-owned farms were more often specialized dairy farms (vs. mixed crop-livestock farms) and that female-owned farms more often used paddocks.

Other

Milk yield was higher in farms without agroforestry ($P<0.01$), but this was possibly confounded. No significant differences in milk yield were observed for use of veterinary services or rainwater harvesting.

3.4 Carbon footprint

Average estimated GHG emissions of dairy farms in the study were 168 ton CO_2-eq per farm/year (including upstream emissions, i.e., cradle-to-farm gate). GHG emissions are often expressed per kg of edible product as functional unit, referred to as ‘emission intensity’. Estimated GHG emission intensity was 2.1 kg CO_2-eq per kg fat and protein corrected milk (FPCM) and 13.6 kg CO_2-eq per kg live weight. Estimated land use (i.e., on-farm and off-farm land used for feed and forage production) was 9 m2 per kg FPCM, and 61 m2 per kg live weight.

The average GHG emission intensity found in our study lies within the range of estimates of other LCA studies in Uganda and Kenya. According to FAO and New Zealand Agricultural Greenhouse Gas Research Centre (2019) the carbon footprint of dairy farms in Uganda ranges between 1.6 and 20.8 kg CO_2-eq/kg FPCM. This large range is mainly due to differences in production systems assessed (e.g., subsistence vs. market-oriented farms). For commercial farms, FAO and NZAGRC reported a range of 1.6 to 4.7 kg CO_2-eq/kg FPCM, which is comparable to estimates of GHG emission intensity in our study. Another LCA study in 6 districts of Uganda’s central cattle corridor by Kiggundu *et al.* (2019) estimated that the average carbon footprint of dairy farms was 74.9 kg CO2-e/kg protein for milk (using *i*-GLEAM), which is only slightly higher than average GHG emission intensity in our study (73.0 kg CO_2-eq/kg protein for milk).

In Kenya average emission intensities of 2.0 kg CO_2-eq/kg milk and 2.5 kg CO_2-eq/kg FPCM were reported by Weiler et al. (2014) and Wilkes et al. (2020; 382 dairy farms in central Kenya), respectively. Average GHG emission intensity in our study was lower than in Wilkes et al. despite a lower average milk yield in our study (1608 vs. 2450 kg FPCM/cow/y, resp.), which is notable given the importance of milk yield level for GHG emission intensity. The difference is likely due to a lower use of external inputs in farms in our study, particularly of supplemental feed, which contributed 5% to total GHG emissions in our study, vs. 19-25% in the study of Wilkes et al. Supplemental feeding can increase absolute emissions due to higher emissions from feed production, processing and transportation. It also increases emission intensity when the increase in emissions from feed production offset reductions in emissions due to a higher productivity of the cows. This shows the importance of using a life cycle approach when evaluating mitigation options.

In Tanzania GHG emissions intensities ranged between 5.8-5.9 kg CO_2-eq/kg fat and protein corrected milk for modern (improved cattle) sectors (Hawkins *et al.*, 2021). Average GHG emission intensity in our study was lower than in Hawkins et al., which is likely due to a lower average milk yield and inclusion of emissions due to land use change (LUC) in Hawkins et al. According to Hawkins et al., LUC contributed 46-66% of the total carbon footprint of dairy, whereas LUC was not included in our study. This finding highlights the importance of including LUC in future LCA studies in Uganda.

Data uncertainty is an important issue for GHG estimation using LCA, particularly in developing countries with data scarcity. This was also stressed by Wilkes *et al.* (2020), who found that uncertainty of the estimated carbon footprint of Kenyan dairy farms ranged from +28.2% to −22.8%, with milk yield, milk protein content, and feed digestibility ranking highest in sources of uncertainty. In the present study milk yield was measured, which reduced uncertainty, but milk protein content and feed digestibility were based on secondary data sources and expert opinion. Sufficient accuracy of these parameters should be warranted in future LCA studies. A longer monitoring period can improve the accuracy of estimates of technical herd parameters, particularly those on reproductive performance. In addition, as advised by IPCC, country specific emissions factors should be explored.

Sources of GHG emissions
In terms of types of GHG emissions, the largest part of total GHG emissions were caused by methane (CH_4), followed by nitrous oxide (N_2O) and carbon dioxide (CO_2; Figure 8).

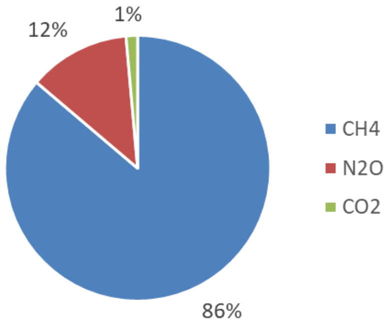

Figure 8 *Relative contribution of different types of greenhouse gases (CO_2-eq/farm/year).*

In terms of emission sources, the most important source of GHG was rumen enteric fermentation (CH_4), causing 83% of the total GHG emissions from farms (Figure 9). Remaining sources of GHG emissions were mainly manure (grazing, storage and treatment; CH_4 and N_2O; 11%) and feed production (N_2O and CO_2; 5%).

The largest contribution of methane from rumen enteric fermentation to total GHG emissions in our study (83%) was comparable to results found by Kiggundu *et al.* (2019) and FAO and NZAGRC (2019). In their studies enteric methane contributed 76% and 79% to total GHG emissions, respectively. The enteric methane contribution is much higher than the global average (about 50%). In the global average a higher productivity of cattle is assumed, causing a lower methane intensity, and larger contribution of emissions related to feed production for cattle.

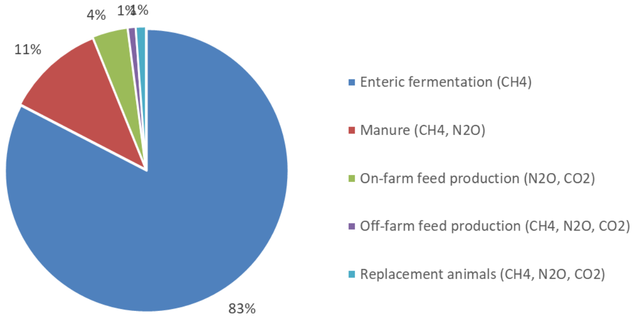

Figure 9 *Relative contribution of different sources of greenhouse gases (CO_2-eq/farm/year).*

For manure, main sources of GHG emissions were direct and indirect N_2O emissions (accounting for 80% of GHG emissions from manure) mainly emitted during grazing. Other emissions from manure were N_2O and CH_4 from manure storages. For feed production, most GHG emissions occurred during production of forages on the farm (pasture, maize silage, hay, cut grass, Napier silage, haylage, other fodders) and a smaller proportion occurred during production of purchased feeds (BSG, maize bran, banana peelings). GHG emissions from on-farm feed production were mainly direct and indirect N_2O emissions from organic fertilizer application and N sedimentation, and some CO_2 emissions due to energy use from field-work. Emissions related to production of on-farm feeds were highest per kg DM for maize silage, followed by pasture grass and Napier silage.

GHG emissions related to the import of replacement animals were low for the average farm (1%), but high in Kiruhura (10%) and Mbarara (4%), as farms in these districts had relatively high replacement rates and insufficient young stock as replacement.

3.5 Associations between farm characteristics and carbon footprint

Total GHG emissions per farm and per cow

Highest GHG emissions per farm were found in Kiruhura and Isingiro. In Isingiro this was mainly due to the large herd size (on average 51 cows per farm), whereas in Kiruhura this was partly due to large herd size and partly due to relatively high emissions per cow (Figure 10). The relatively high emissions per cow in Kiruhura was caused by a relatively high replacement rate (Table 6) and a relatively high milk yield of cows (2480 kg milk vs. on average 1440 kg milk in other districts). A high milk yield is associated with higher DM intake levels and increased manure excretion, leading to increased emissions from feed production and manure. GHG emissions per farm were lowest in Ntungamo, due to relatively small herds and low milk yields.

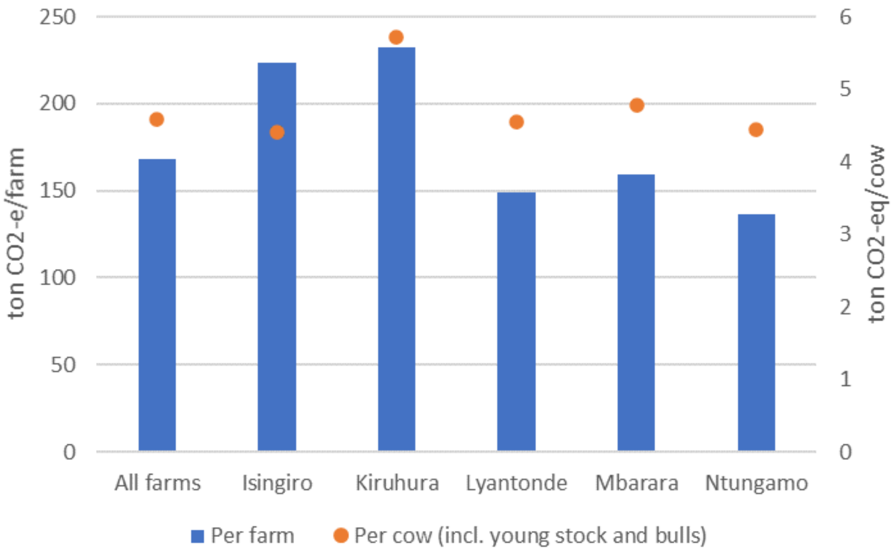

Figure 10 *Average GHG emissions per farm and per cow (incl. youngstock and bulls; ton CO_2-eq/year) across districts.*

Figure 11 shows differences in absolute emissions for different categories of farms, with regard to specialization (mixed vs. specialized), feeding (grazing only vs. supplemental feeding), and breed (crossbred vs. HF). Total farm emissions were slightly higher in specialized farms compared to mixed farms because of a slightly larger herd size and a higher productivity per cow (causing higher feed intake and manure excretion). In farms with grazing only, total emissions were higher than in farms with supplemental feeding because of a larger herd size (43 vs. 32 cows, resp.). When expressed per cow, emissions were similar across farm types, except for farms with HF as pre-dominant breed: in these farms mortality rates of youngstock, and to a lesser extent of mature cows, were high and caused increased emissions from required additional replacement animals to replace animals that died.

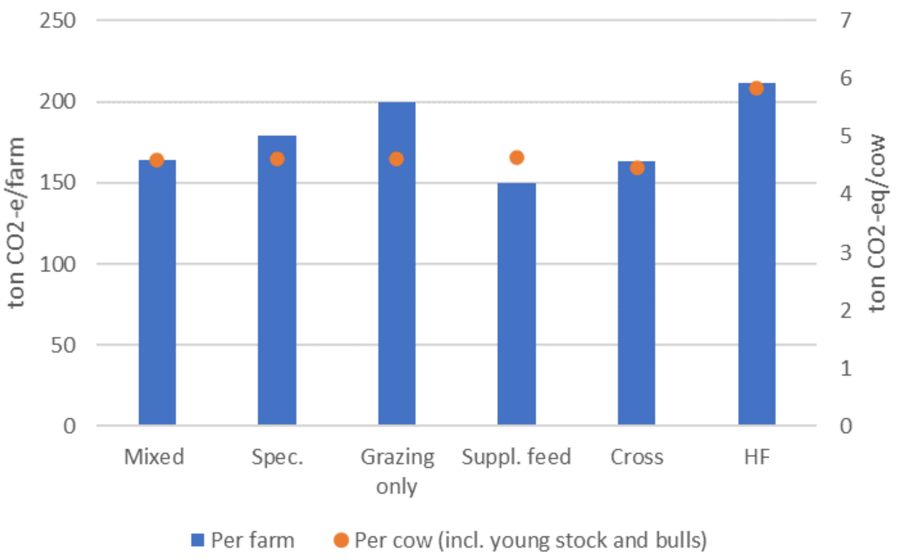

Figure 11 *Total GHG emissions per farm and per cow (ton CO_2-eq/year) across farm types (spec.=specialized).*

GHG emissions per kg milk
Contrary to GHG emissions per farm, GHG emissions per kg milk (‘emission intensity’) were lowest in Kiruhura (1.8 kg CO_2-eq/kg FPCM). This was mainly caused by the high productivity level in Kiruhura, causing that emissions are diluted in more kg of milk. GHG emission intensity was highest in Ntungamo (2.6 kg CO_2-eq/kg FPCM), mainly due to relatively low milk yields and high mortality rates of cows and youngstock (Table 6). Other districts showed intermediate GHG emission intensities ranging from 2.0 to 2.2 kg CO_2-eq/kg FPCM, despite large differences in milk production levels (varying from 1200 kg milk/cow in Isingiro to 1700 kg milk/cow in Mbarara). In Mbarara, the effects of high milk yield levels on emission intensity were partly compensated by the relatively high mortality rate in young stock.

A similar trend was found for GHG emissions per kg live weight, with differences caused by the ratio used for allocation of emissions to milk and LW (based on LW and milk output; Thoma et al., 2013). For example, in Isingiro a relatively large part of emissions was allocated to live weight compared to milk, whereas in Ntungamo a relatively small part was allocated to live weight.

The milk yield level of cows has a large effect on methane emission intensity. In the Kenyan study of Wilkes et al. (2020), for example, milk yield at animal level explained 84% of the variation in methane intensity. Milk yield can be influenced in various ways, including improved feeding, breed, and animal health management. Although a high contribution of enteric methane justifies that mitigation strategies are focused on the reduction of enteric methane, it should be noted that efforts to reduce methane emissions could lead to increased emission elsewhere in the production chain. For example, a recent study in Indonesia showed that feeding an improved type of compound concentrate feed significantly increased milk yield and reduced enteric methane intensity, but led to a higher net GHG emission intensity due to high feed processing emissions (De Vries *et al.*, 2020). Also land use change emissions may cause net increased emission intensity, as shown by Brandt et al. (2019) for a combination of improvements in forage quality, feed conservation and concentrate supplementation in Kenyan dairy farms. Land-use change was not included in the present study, and should be considered when evaluating mitigation options related to feed and forage production. On the other hand, intensification does not per definition increase emission intensity, as shown by the low emission intensity of pasture-based systems in developed countries, i.e. 0.58 to 1.45 CO_2-eq/kg FPCM (Lorenz *et al.*, 2019).

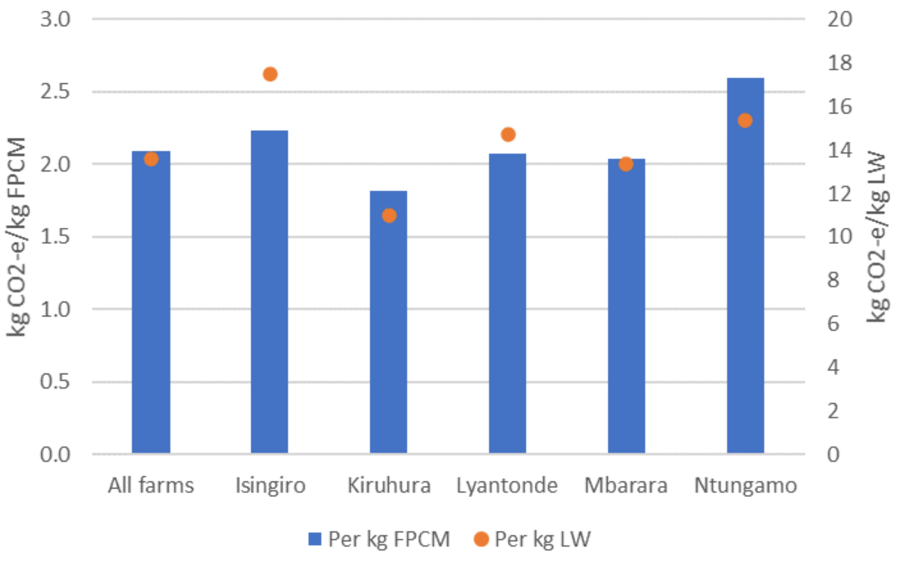

Figure 12 *GHG emission intensity in kg CO_2-eq per kg fat and protein corrected milk (FPCM) and per kg live weight per year, across districts.*

GHG emission intensity was lower in specialized farms than in mixed farms; and lower in farms with supplemental feeding than in farms with grazing only (Figure 13). In both cases this was mainly due to a higher productivity of cows (Table 6), and, to a lesser extent, a lower mortality.

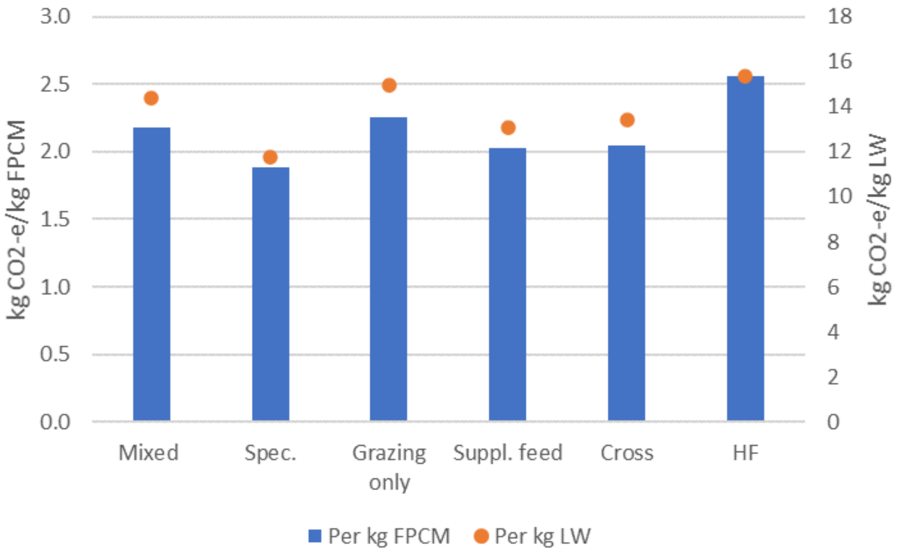

Figure 13 *GHG emission intensity in kg CO_2-eq per kg fat and protein corrected milk (FPCM) and per kg live weight (LW) per year, across farm types (spec.=specialized).*

Supplemental feeding is known reduce enteric methane intensity due to increased milk yield, improved reproductive performance, lower replacement rates (reduced culling), and improved digestibility of the feed ration. Forage quality, especially digestibility, plays an important role in enteric methane production (Knapp *et al.*, 2014). Substituting high-fiber forage by an optimal amount of more digestible carbohydrate or low fiber sources will decrease the ruminal pH and can also increase milk production, which both lead to a reduction in methane intensity (Niu *et al.*, 2018). Our finding that GHG emission intensity is lower in farms with supplemental feeding supports the approach for GHG mitigation in the Ugandan NAMA, and is also 'climate-smart' as this strategy will not only reduce GHG emission intensity but may also improve farm productivity and income, and climate resilience. As discussed above, maize silage, Napier silage, and maize bran were associated with significantly higher milk yields. Our findings are in line with those of Brandt et al. (2019), who showed that improvements in forage quality (high-quality Napier grass), feed conservation (maize silage) and concentrate supplementation reduced GHG emission intensity in Kenyan dairy farms by up to 33%. Hawkins *et al.* (2021) estimated that better feeding of herds in Tanzania could increase milk yields by up to 60.1% and reduce emissions intensities by up to 38.0% for modern farms. Hawkins and colleagues also indicated that avoiding land use change (LUC) was a predominant cause of reductions in GHG emissions; feed intensification can increase LUC emissions, but this increase can be offset when (fertilizer-dependent) yield gains lead to avoided emissions from LUC.

Quality of pasture grass is expected to have a large influence on enteric methane emissions in studied farms as more than 90% of the dry matter intake (DMI) was grazed grass. The same quality of pasture grass was assumed for all farms, based on expert opinion about common pasture composition (Signal grass and Kikuyu grass, in equal proportions). For the total sample of farms this may have been an accurate estimate of the average pasture composition composition and quality, this may cause little bias in average carbon footprint for the total sample of farms. However, a large variation may be expected in composition and quality of pasture grass between farms. As farm-specific quality and botanical composition of pastures was not assessed in this study, grassland management strategies could not be compared in terms of carbon footprint. To evaluate the role of improved pasture management for GHG mitigation, farm- or farm-type specific monitoring of nutritional quality of pasture grass should be included in future LCA studies.

In line with results at the farm level, emission intensity was lower in farms with crossbreds than in farms with HF as pre-dominant breed, despite a significantly higher productivity of HF cows (1583 vs. 1814 kg milk/cow, resp.). This was mainly due to a higher mortality rates of young stock in HF herds (22% vs. 12% in farms with crossbreds), which offset reductions in emissions due to a higher productivity of the HF cows. Due to the high mortality rate less live weight output was generated and more replacement animals were assumed to be purchased to sustain the herd, of which emissions from raising these animals were allocated to the study farms (contributing 8% to total emissions in HF farms). Consequently, total net emission intensity was higher in HF farms, as the reduction in emissions due to a higher productivity of HF cows did not compensate the increase in emissions due to a high mortality rate. This emphasizes the need for a combined strategy of using improved breeds alongside adequate feeding and health management, including young stock management (Bateki *et al.*, 2020). To respond to the increasing demand for milk in Uganda, the use of exotic breeds rather than indigenous cattle will be an important strategy; in Uganda 90% of cattle are indigenous breeds contributing only 52% to total milk production, whereas exotic breeds contribute 48% (UBOS, 2018). This is in line with other studies promoting intensification as GHG mitigation strategy for dairy farming in East Africa and a means to reduce deforestation (e.g., Brandt et al., 2019; FAO and New Zealand Agricultural Greenhouse Gas Research Centre, 2019).

Other mitigation options

Besides mitigation options analyzed in the present study, other mitigation options are relevant for consideration in Uganda dairy farms:

- Improved animal health and fertility management: e.g. products and (veterinary) services, farmer education about management of transition cows;
- Sufficient and good quality drinking water provision, contributing to animal productivity, health and fertility;
- Improved forage management to increase forage yields and quality, such as improved fertilization or cutting the forage at an optimal growth stage. This can increase nutritive value, digestibility, feed intake and milk yield, and reduce GHG emission intensity (e.g. Knapp et al., 2014; Warner et al., 2017). Expanding land for forage production should be cautioned as this could cause deforestation and biodiversity loss (Sala et al., 2000), or, when arable land is used, food-feed competition.
- Fodder conservation (e.g., grass silage, maize silage) can be a strategy to compensate for dry season deficits, and thereby reduce GHG emissions (e.g. whole crop maize silage; Van Middelaar et al., 2013). Conversion of grazing land for maize production can cause high one-off CO_2 emissions, however, potentially taking several decades to compensate the annual emission reductions due to improved feeding (e.g. Van Middelaar et al., 2013). A better alternative is to close the yield gap of maize by increasing N fertilizer use, which can reduce

emission intensities due to avoiding emissions from conversion of grazing land (Brandt *et al.*, 2019; Hawkins *et al.*, 2021).

- Balancing rations, i.e. feeding cows according to their individual nutritional requirements, including important limiting nutrients in the feed ration of cows (mainly minerals, protein, and energy). This will not only improve productivity, but also animal health and feed use efficiency; and can be realized based on locally available feed resources. Substantial emission reduction has been shown in a 3-year ration balancing program in India (31% GHG reduction; Garg *et al.*, 2018).
- Feeding higher quality feed ingredients:
    - Concentrates; depending on initial production levels and amount of feed intake, it has been estimated that this strategy can potentially reduce up to 40% of total enteric methane (Gerber et al., 2013; Knapp et al., 2014). Note that the reduction in emissions due to increased milk yields can be offset by increased emissions elsewhere in the supply chain or due to land conversion.
    - High(er) quality by-products or crop residues (in terms of energy, protein, and minerals) can improve productivity and reduce GHG emission intensity, with less risk of land conversion and avoiding food-feed competition (Oosting et al., 2020).
    - (high quality) minerals and vitamins are important for milk production, but particularly for good reproductive performance and animal health.
- Production and use of renewable energy can contribute to reduced emissions.

Generally speaking, enhancing herd productivity will likely reduce GHG emission intensity. This requires improved herd management through combinations of improved feed supply and quality, animal fertility and reproduction, animal health and husbandry, and genetic potential. Improving fertility and reproduction will increase productivity of the herd in terms of milk and beef output, and is also beneficial to feed use efficiency and emission intensities as it reduces the number of non-productive animals because of shortening the dry period length. Additional young stock also provides socio-economic resilience as they can be sold for cash when needed. Cow fertility particularly has a strong interaction with feeding during the dry period and first part of the lactation. During this 'transition' period inadequate feed supply results in a negative energy balance, leading to low conception rates and increased calving intervals. Feeding, in combination with heat detection and timely insemination during the first 90 days are key to improved reproduction and productivity. This requires good quality feed rations and farmer education about management of transition cows.

With regard to feed additives, nitrate, 3-NOP and fats are effective measures to reduce enteric methane emissions from cattle, but these additives are costly, and there are still issues with practical application. When used correctly, there are no trade-offs to milk production, health, or milk quality. Expected reductions in enteric methane emission are: nitrate (at 1% in feed) 9-10%, 3-NOP 20-30%, and fats 7.5-10% (pers. comm. A. Bannink (WUR), July 2021). Also red seaweed is investigated, but currently not recommended due to potential trade-offs: human health risks; challenges in sustainable supply, production and storage; and ozone depletion (Abbott et al., 2020).

3.6 Availability and quality of feed and water

3.6.1 Annual average

Availability of feed and water

Across the whole study period, farmers were least satisfied about availability of industrial by-products (brewers spent grain, maize bran), crop residues, and drinking water supplied around milking (Table 8). They were most satisfied about the availability of pasture, drinking water supplied around grazing, concentrates, and silage.

Satisfaction about availability of pasture was higher in Mbarara than Ntungamo ($P<0.001$; Table 8). With regard to water availability, satisfaction about availability of drinking water during grazing was higher in Isingiro than in Mbarara and Ntungamo ($P<0.005$), and for drinking water during milking satisfaction was significantly higher in Kiruhura and Lyantonde than in Ntungamo (*P*<0.05). Other feeds were not statistically compared between districts because of low prevalence.

Table 8 *Average satisfaction of farmers about* ***availability*** *of feed and water scored on a 1 to 5 point scale, i.e. from "very dissatisfied" to "very satisfied" (number of farms "N", average "μ", and standard deviation "SD"), across 6 farm visits (V2-V7).*

	All farms			**Isingiro**			**Kiruhura**			**Lyantonde**			**Mbarara**			**Ntungamo**		
	N	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**
Pasture	101	3.8	0.65	17	3.7	0.74	15	3.8	0.24	17	3.9	0.47	25	4.2	0.46	27	3.4	0.79
Cut grass	32	3.5	0.78	1	4.0	-	6	4.2	0.29	-	-	-	8	3.5	0.51	17	3.1	0.85
Hay	12	3.4	0.96	1	4.0	-	1	4.0	-	-	-	-	8	3.2	1.10	2	3.5	0.71
Silage	33	3.7	0.57	7	3.9	0.34	5	4.1	0.51	2	3.5	0.29	11	3.8	0.53	8	3.3	0.65
Crop residues	7	3.0	0.83	-	-	-	-	-	-	-	-	-	5	3.1	0.69	2	2.7	1.41
Concentrates	5	3.8	0.24	-	-	-	1	4.0	-	-	-	-	-	-	-	4	3.8	0.25
By-products	28	2.9	1.02	4	3.3	0.39	1	3.0	-	1	4.0	-	14	3.0	0.95	8	2.5	1.33
Drinking water																		
-during grazing	101	3.8	0.58	17	4.2	0.28	15	4.0	0.28	17	3.9	0.53	25	3.6	0.62	27	3.5	0.65
-during milking	92	3.2	1.16	14	3.1	1.56	14	3.7	0.49	12	4.0	0.70	25	3.1	1.14	27	2.6	1.07

Quality of feed and water

Across the whole study period, farmers were least satisfied about quality of industrial by-products (brewers spent grain, maize bran), crop residues, and drinking water during milking (Table 9). They were most satisfied about the quality of concentrates, silage, and drinking water supplied around grazing.

Satisfaction about quality of pasture was significantly higher in Isingiro, Kiruhura, Lyantonde and Mbarara than in Ntungamo (score 3.3-3.9 vs. 2.6; *P*<0.05). With regard to water availability, satisfaction about availability of drinking water during grazing was significantly higher in Isingiro, Kiruhura and Lyantonde than in Ntungamo (score 3.8-4.1 vs. 3.0; *P*<0.005). Also satisfaction about availability of drinking water during milking was significantly higher in Kiruhura and Lyantonde than in Ntungamo (score 3.6 and 3.9 vs. 2.5; *P*<0.05). Other feeds were not statistically compared between districts because of low prevalence.

Table 9 *Average satisfaction of farmers about* ***quality*** *of feed and water scored on a 1 to 5 point scale, i.e. from "very dissatisfied" to "very satisfied" (number of farms "N", average "μ", and standard deviation "SD"), across 6 farm visits (V2-V7).*

	All farms			**Isingiro**			**Kiruhura**			**Lyantonde**			**Mbarara**			**Ntungamo**		
	N	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**	**N**	**μ**	**SD**
Pasture	101	3.4	0.88	17	3.3	0.76	15	3.8	0.26	17	3.9	0.42	25	3.7	0.83	27	2.6	0.91
Cut grass	32	3.2	0.94	1	4.0	-	6	4.1	0.16	-	-	-	8	3.3	0.87	17	2.8	0.94
Hay	11	3.3	0.81	1	3.7	-	1	4.0	-	-	-	-	7	3.1	0.81	2	3.1	1.30
Silage	33	3.6	0.54	7	3.9	0.36	5	3.8	0.24	2	3.6	0.53	11	3.5	0.68	8	3.4	0.55
Crop residues	7	2.5	1.00	-	-	-	-	-	-	-	-	-	5	2.9	0.80	2	1.4	0.59
Concentrates	5	3.9	0.18	-	-	-	1	4.0	-	-	-	-	-	-	-	4	3.9	0.20
By-products	29	2.8	1.08	4	3.4	0.46	1	4.0	-	1	4.0	-	15	2.7	0.81	8	2.5	1.59
Drinking water																		
-during grazing	101	3.6	0.79	17	4.1	0.42	15	4.0	0.32	17	3.8	0.47	25	3.5	0.49	27	3.0	1.10
-during milking	92	3.1	1.16	14	3.1	1.33	15	3.6	0.65	11	3.9	0.70	25	2.9	1.13	27	2.5	1.20

Associations between farm characteristics and farmers' satisfaction

Farms feeding silage were more satisfied about availability of pasture, and more satisfied about the availability and quality of drinking water during grazing and milking than farms not feeding silage (*P*<0.05). Farms with rainwater harvesting were more satisfied about availability of drinking water during grazing and milking, and quality of drinking water during grazing (*P*<0.05). Mixed farms were less satisfied about the quality of pasture than specialized farms (*P*<0.01). Farms with Holstein Frisian as predominant breed were more satisfied about availability of pasture than farms with predominantly crossbreds (*P*<0.05). No significant differences were found between grazing systems.

3.6.2 Seasonal variation

Availability of pasture and drinking water

With regard to (seasonal) changes in availability of feed and water over time, farmers were more satisfied about the availability of pasture grass in V5 than in V7 (*P*<0.05; 0.35 points difference on a 1-5 point scale; Figure 14). This was probably because the dry season of 2019 was less pronounced than in other years. Satisfaction about availability of drinking water during grazing tended to be different between farm visits, but this was not significant (*P*<0.10).

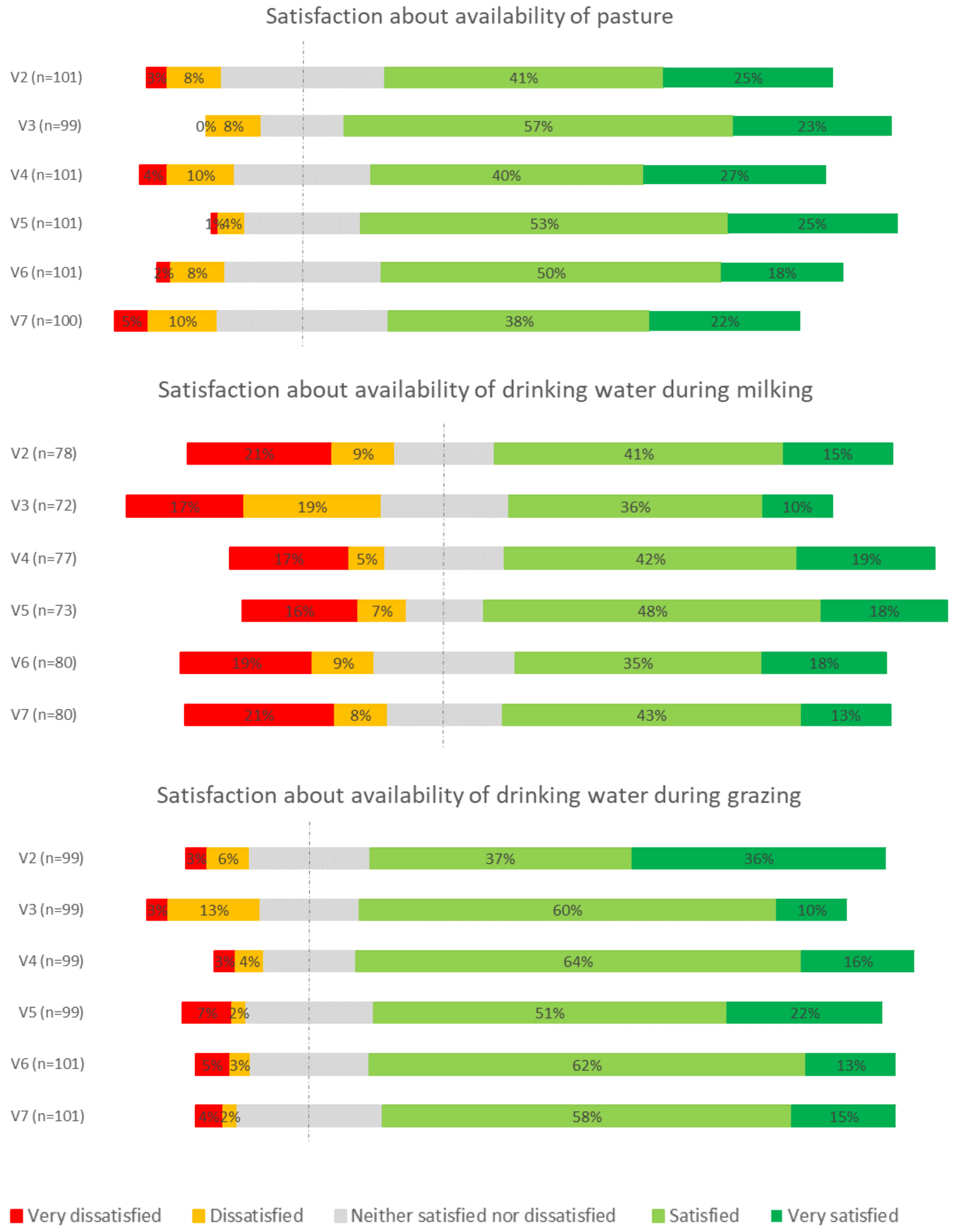

Figure 14 *Satisfaction of farmers about the* ***availability*** *of pasture and drinking water over time (farm visits V2-V7), scored on a 1 to 5 point scale, i.e. from "very dissatisfied" to "very satisfied".*

Seasonal changes in satisfaction (as represented by the difference between the highest- and the lowest satisfaction score across farm visits) about the availability of pasture were larger in Isingiro and Ntungamo than in Kiruhura and Mbarara (Table 10; P<0.05). Seasonal changes in satisfaction about the availability of pasture grass were not influenced by grazing system (also not when districts were included as confounding factor). For availability of drinking water, seasonal changes in satisfaction were larger in Ntungamo than in other districts (Table 10; P<0.05). There was no significant difference between grazing systems or use of rainwater harvesting.

Quality of feed and water

With regard to (seasonal) changes in quality of feed and water over time, farmers were more satisfied about the quality of 'pasture grass' in V3 and V5 compared to V6 and V7 (P<0.05). This was likely because the dry season of 2019 was less pronounced than in other years. Satisfaction about quality of 'drinking water during grazing' did not differ significantly between farm visits.

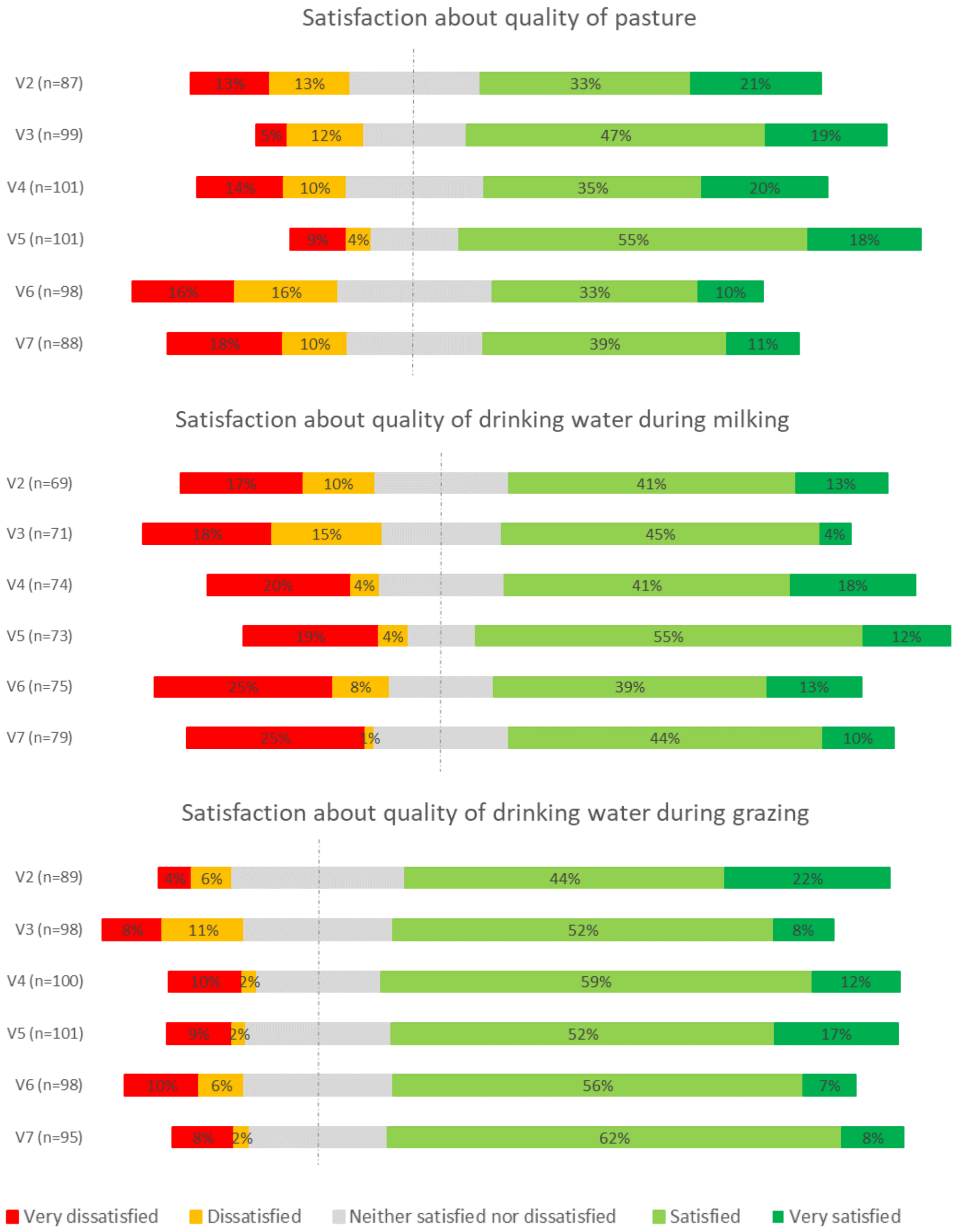

Figure 15 *Satisfaction of farmers about the **quality** of pasture and drinking water over time (farm visits V2-V7), scored on a 1 to 5 point scale, i.e. from "very dissatisfied" to "very satisfied".*

Seasonal changes in satisfaction (as represented by the difference between the highest- and the lowest satisfaction score across 6 farm visits) about the quality of pasture grass over time were larger in Isingiro and Ntungamo than in Kiruhura (Table 10; *P*<0.05), and larger in mixed farms compared to specialized farms (P<0.05). There was no significant difference between grazing systems (also not when districts were included as confounding factor).

With regard to quality of drinking water during grazing, seasonal changes in satisfaction were larger in Ntungamo than in other districts except for Lyantonde (Table 10; P<0.05), and smaller in farms with paddocks than in farms with other grazing systems (1.2 vs. 1.7, P<0.05; results not shown in Table 10). There was no significant difference between farms with or without rainwater harvesting.

Table 10 *Seasonal changes in satisfaction as represented by the average difference between the highest- and the lowest satisfaction score across 6 farm visits (V2-V7; standard deviation between parentheses).*

		District					**System**		**Grazing system**				**Rain water harvesting**	
	All farms	Isingiro	Kiruhura	Lyantonde	Mbarara	Ntungamo	Mixed	Spec.	Paddock	Perimeter	Mixed fence	Other[1]	No	Yes
Difference in satisfaction about:														
- availability of pasture	1.7	2.2	1.2	1.8	1.2	2.1	1.7	1.7	1.6	1.8	1.8	1.7	1.7	1.7
	(0.9)	(1.0)^{ac}	(0.8)^{b}	(0.6)^{abc}	(0.7)^{b}	(1.0)^{c}	(1.0)	(0.7)	(1.0)	(0.6)	(1.0)	(0.7)	(0.7)	(1.0)
- quality of pasture	2.1	2.4	1.2	1.8	2.0	2.4	2.2	1.7	2.1	1.9	2.2	2.1	1.9	2.1
	(1.0)	(1.1)^{a}	(0.7)^{b}	(0.8)^{ab}	(1.0)^{ab}	(1.0)^{a}	(1.0)^{a}	(0.9)^{b}	(1.2)	(0.6)	(1.0)	(1.1)	(0.9)	(1.1)
- availability of drinking water during grazing	1.5	1.1	1.0	1.6	1.2	2.6	1.7	1.3	1.4	1.6	2.1	1.3	1.5	1.6
	(1.1)	(0.4)^{a}	(0.8)^{a}	(0.9)^{a}	(0.6)^{a}	(1.4)^{b}	(1.2)	(0.7)	(1.1)	(0.9)	(1.3)	(0.8)	(1.0)	(1.1)
- quality of drinking water during grazing	1.5	1.3	1.1	1.4	1.1	2.2	1.5	1.4	1.2	1.6	1.9	1.4	1.5	1.4
	(1.0)	(0.6)^{a}	(0.8)^{a}	(0.7)^{ab}	(0.7)^{a}	(1.3)^{b}	(1.1)	(0.8)	(0.9)	(0.9)	(1.3)	(0.7)	(1.0)	(1.0)

[1] including stall feeding with limited grazing (n=3) and (partly) open grazing/free range system (n=7)

4. Conclusions and recommendations

The objective of this study was to evaluate effects of dairy farming characteristics and practices on technical performance and GHG emissions of dairy farms participating in the SNV TIDE project.

Results showed that:

- Milk yield was significantly higher in female-owned farms than in male-owned farms; farms feeding supplemental feed or fodder than in farms with grazing-only; farms with paddocks than in farms with other grazing systems; and farms with Holstein Frisian (HF) as predominant breed than in farms with predominantly crossbreds.
- Mortality rate of young stock was significantly higher in farms with HF as predominant breed than in farms with predominantly crossbreds;
- Calving interval tended to be shorter in farms feeding silage than in farms not feeding silage;
- GHG emission intensity was lower in specialized farms than in mixed crop-livestock farms; farms with supplemental feeding than in farms with grazing only; and farms with crossbreds than in farms with HF as predominant breed.

Based on these results, the following recommendations are made for practitioners:

- Feeding silage or maize bran, paddocking, and using HF breeds show potential to increase milk yield;
- Feeding silage shows potential to contribute to improved reproductive performance;
- Specialization and supplemental feeding show potential to reduce GHG emission intensity. but It should be noted, however, that feeding of supplemental feed with a high carbon footprint can cause the opposite effect (i.e., increase emission intensity). The use of HF breeds also has potential to reduce GHG emissions, but this requires a lower young stock mortality in HF herds and thus more attention for young stock management.

The following recommendations are made for future research:

- The use of life cycle assessment (LCA) is important in the evaluation of mitigation options because reductions in emissions can be offset by increased emissions elsewhere in the production chain or through land use change.
- Land use change should be included in future LCA studies.
- The role of improved pasture management for GHG mitigation should be further explored, by including farm- or farm-type specific quality of pasture grass in LCA studies.
- Country specific emission factors for Uganda should be explored in environmental research.
- Sufficient accuracy of data in the life cycle inventory should be warranted in future LCA studies, especially for milk yield, milk protein content, and feed digestibility. A longer monitoring period can improve the accuracy of estimates of technical herd parameters, particularly those on reproductive performance.

Our findings support the focus on improved feeding in the Ugandan Nationally Appropriate Mitigation Actions (NAMA), as improved feeding was shown to have simultaneous beneficial effects on GHG emission reduction, farm productivity and climate resilience.

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To explore
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