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Abstract: In Tanzania, the ruminant livestock sector is relatively under-developed. Low productivity per animal and high methane emissions from low feed quality imply that there exists potential for achieving reductions in greenhouse gas (GHG) emissions concurrent with higher productivity, and therefore higher income and nutrition security for producers. Grazing lands represent the predominant feed sources for cattle (TLMI, 2015), however they are largely degraded. Continuing encroachment represents a major risk to Tanzania’s tropical forests and therefore national climate targets. This study uses an analytical approach and empirical data from dairy households in the southern highlands region to assess a range of policy interventions and their impacts on GHG emissions, income, and nutrition security. The impacts of the interventions on the household’s feeding and breed choice are explored in detail. The effect of higher quality feeding practices and improved animal genetics on reducing total land use is calculated based on the residual pasture intake required to meet animal energy requirements under higher quantity and quality of feed provision by the household. This change in land use is then used to estimate the potential by which the dairy sector can contribute to Tanzania’s climate commitments through reductions in deforestation and forest degradation. The policy interventions simulations are for improvements in credit availability, lower prices of dairy inputs, and development and regulation of dairy supply chains. The simulations suggest that \_\_, \_\_, and \_\_\_ are potential avenues by which policy can incentive households to adopt better feeding practices and improved animal genetics. Based on the model simulations, these interventions can lead to reductions in net GHG emissions intensities of \_\_\_, concurrent with up to \_\_ % growth in milk production per household. The estimated potential for land use under the simulations is up to \_\_%, from a baseline level of \_\_\_ to \_\_\_ ha kg-1 FPCM.

1. **Introduction**

About one third of Tanzanian households rely on cattle as a source of nutrition and income (NPS, 2017). Dairy in particular is central to the rural economy, and therefore poverty alleviation efforts, due to the high amount of cash income that can be received from the sale of milk relative to other livestock (Udo et al. 2015). Developing the dairy sector is an important part of both the agricultural and broader economic development objectives of the government (TLMI, 2015). The dairy sector is also responsible for about 25% of Tanzania’s total agricultural greenhouse gas (GHG) emissions (FAO, 2017). Further, degradation of grasslands and forest disturbance driven by overgrazing and crop/grassland expansion represents a significant indirect source of GHG emissions, and a lost potential sink for storing carbon. An estimated 51% of grasslands in Tanzania are degraded (Le et al. 2014), and as much as 70% of the total GHG emissions resulting from agricultural production over the period 2000-2010 are estimated to have resulted from deforestation and forest degradation (Carter et al. 2015). Reversing these processes may contribute to GHG emissions reductions in Tanzania’s national inventory reports under the United Nations Framework Convention on Climate Change (UNFCCC). Because grazing lands represent a major source of land occupation (TLMI, 2015), aligning livestock sector policies with country level GHG mitigation strategies may provide the basis for receiving climate financing under various forms of bi-lateral or multi-lateral climate agreements (e.g. Green Climate Fund, REDD+, or the Clean Development Mechanism).

The majority of milk produced by Tanzanian livestock producers is for home consumption (MALF, 2016), and therefore households generally use few external inputs, and allocate few household resources (e.g. labour, land) to improve dairy production practices. Commercialization, through increasing cash revenue from milk sales, offers potential for promoting input use and upgrading of dairy production practices, including adoption of improved breeds, home production of nutritious fodders, or purchases of supplemental feeds and livestock services (e.g. reproductive or health-related services). Various empirical studies have found that households that are integrated with (input or output) markets exhibit higher levels of technical efficiency (Henderson et al. 2017), especially when they produce for sale as opposed to home consumption (Hammond et al. 2017). Often production practices hat increase resource use efficiency are associated with lower GHG emissions intensities, and therefore promoting their adoption can be a strategy for reducing the carbon footprint (CF) of the dairy sector. Furthermore, these practices, by increasing milk yield per unit animal and land, may also reduce pressures on grazing lands and forest encroachment, thereby contributing to land degradation neutrality (Brandt et al. 2018). The Tanzanian dairy sector is however still largely characterized by producers who rely on little use of inputs, and with the vast majority owning indigenous cattle breeds (NBS, 2016). The main reasons for lack of adoption of improved production practices in the literature relate to the costs and risk associated with doing so (Refs needed).

Previous studies focussing on adoption of climate change mitigation for smallholders in East Africa focus primarily on input support. Paul et al. (2017) assessed subsidies for improved cattle breeds and supplemental feeds on the adoption of these practices/technologies, and in turn, food availability and GHG emissions for cattle owning households in Rwanda. Shikuku et al. (2017) assessed the same subsidies as well as improved credit access on household adoption, and in turn on, food security and methane emissions intensity for cattle owning households in Lushoto, Tanzania. While such forms of input support may provide the incentive for households to upgrade production practices, various authors (e.g. Hounkonoou et al. 2012) have argued that production oriented interventions alone have limited effectiveness if the terms upon which smallholders engage in the dairy value chain are not improved. Between 90-95% of milk marketed in Tanzania is done so informally, whereby producers sell small volumes of milk to various intermediaries (hawkers, traders, processors) on an irregular basis, and subject to significant price volatility (Omore et al. 2015). Producer prices in these informal markets are known to vary by as much as 100% between seasons (Bingi and Todel, 2010). The uncertainty in prices and volume demanded for smallholders participating in these informal milk markets have been argued to impede the adoption of improved practices/technologies (Kilelu et al. 2017). On the contrary, producers who are directly linked to processors, through contractual agreements that specify a fixed volume and price to be sold, have been found to exhibit higher levels of technical efficiency (Omore et al. 2015, Omondi et al. 2017). These types of processor linkages are independent of the household’s access to inputs, suggesting that it is not access to inputs *per se*, but the terms of participation in the dairy value chain, that drive practice upgrading. These findings suggest that the structure of the dairy value chain upstream from the producer is an important factor in the producer’s management practices, and therefore regulation of the dairy value chain, with the goal of stabilising milk revenue and providing improved forecasting capabilities by producers, may reduce the risk associated with practice adoption, and therefore enhance the uptake of improved practices by producers.

This study uses a mathematical programming (MP) model and empirical data to conduct *ex ante* analysis on the effects of the terms of market participation on the upgrading of smallholder dairy producers, and in turn, the CF of milk production. MP models are powerful tools for conducting *ex ante* analysis in the context of smallholder farm-households (e.g. Komarek et al. 2017, Louhichi et al. 2013). Such models link decision making theory, sometimes combined with risk[[1]](#footnote-1), with biophysical production models, in order to predict the effects of changes in policy or market conditions on decision making, technology adoption, and in turn household welfare or environmental outcomes (Van Wijk et al., 2014). The results can be interpreted as describing the effect of a given change in policy or market conditions on household decision making, under the overarching assumption of an economically rational, risk averse household head/farmer (Hazel, 1982). Adoption of improved feeding practices and improved animal genetics offer potential for reducing GHG emissions intensities through higher feed conversion efficiency (Herrero et al. 2013). However, the literature is in consensus that such practices do not lead to reductions in absolute emissions, as the improved productivity results in greater overall consumption, sale, and therefore higher total GHG emissions. This study aims to address this gap by including the impacts of such management changes on land use, and the extent to which offsets can be employed to negate changes in direct GHG emissions.

The objectives of this study were:

To assess *ex ante* the impact of changes in the mode of participation in the dairy value chain on household decision making with respect to breed adoption and feeding practices

To assess the impact of these changes on both total household milk production and GHG emissions associated with dairy production, including from land use change

To assess the impact of these changes on household welfare

The study focuses specifically on dairy producing households in the southern highlands dairy corridor (hereafter, SHDC).

1. **Methods**

**2.0 Overview**

* 1. ***Ex ante* analysis of policy interventions at household level**

The approach used for conceptualizing and modelling the farm-household is best described as a systems dynamics model. Systems dynamics is a methodology and mathematical modelling technique to frame and understand the dynamic behaviour of complex dynamic systems (Forrester, 1985). In the context of a smallholder farm household, these processes involve feedbacks between various stocks, flows, and sinks that influence the household’s management practices and determine the efficiency of the farm enterprise (Figure 1). Because practice upgrading involves outlays of either cash, labour, and/or land, these three factor endowments are explicitly accounted for based on farmer reports (Table 1). [few more sentences on very general aspects of model]. The model is written in the GAMS (General Algebraic Modelling System) Integrated Development Environment (Brooke et al. 2008) and is solved using CONOPT: a solver for large scale non-linear optimization models (DRUD, 1985).

*Description of the Greening Livestock Dairy Household Survey*

The empirical basis of the model is derived from parameters obtained from a household survey conducted in the SHDC during 2017/2018 (GLDHS, 2018). The survey was conducted as part of the Greening Livestock project (ref). The goal of the project is the identification of appropriate incentives for the implementation, monitoring, reporting, and verification of low emissions development pathways in the livestock sector in East Africa. The survey was designed to provide a comprehensive baseline assessment of biophysical and socioeconomic factors relevant to the determination of the mitigation potential of GHG emissions from livestock production, including cattle ownership, feeding practices, reproductive and health practices, grazing and feed production practices. A series of modules were designed with the purpose of identifying potential constraints and trade-offs associated with adoption of intensification practices. This included household livelihood strategies, home food production, sources of income from farm production and offfarm income, a dietary diversity index, asset endowments, participation in extension services and farm co-operatives, and detailed labour input schedules for crop and livestock activities. A total of \_\_\_ households were surveyed across 5 administrative regions (Mbeya, Morogoro, Iringa, Njombe and Rukwa) in the southern highlands. The sampling procedure involved selecting villages and wards within each region, and then randomly selecting households within each village and ward. Only households owning either local (*Bos indicus*)or improved (*Bos indicus x Bos taurus*) cattle responded to the survey. A typology is developed whereby households are stratified by both livestock production system and cattle ownership. Households are identified as falling into one of two livestock production systems based on Robinson et al. (2011): mixed, crop-livestock or grassland based livestock systems. Households for which greater than 50% of cattle owned are improved (those having at least some genetics from *Bos taurus*) are categorized as intensive households, whereas those owning 50% or greater of cattle as local (*Bos indicus*) are categorized as traditional. The resulting four household types are shown in Table 1.

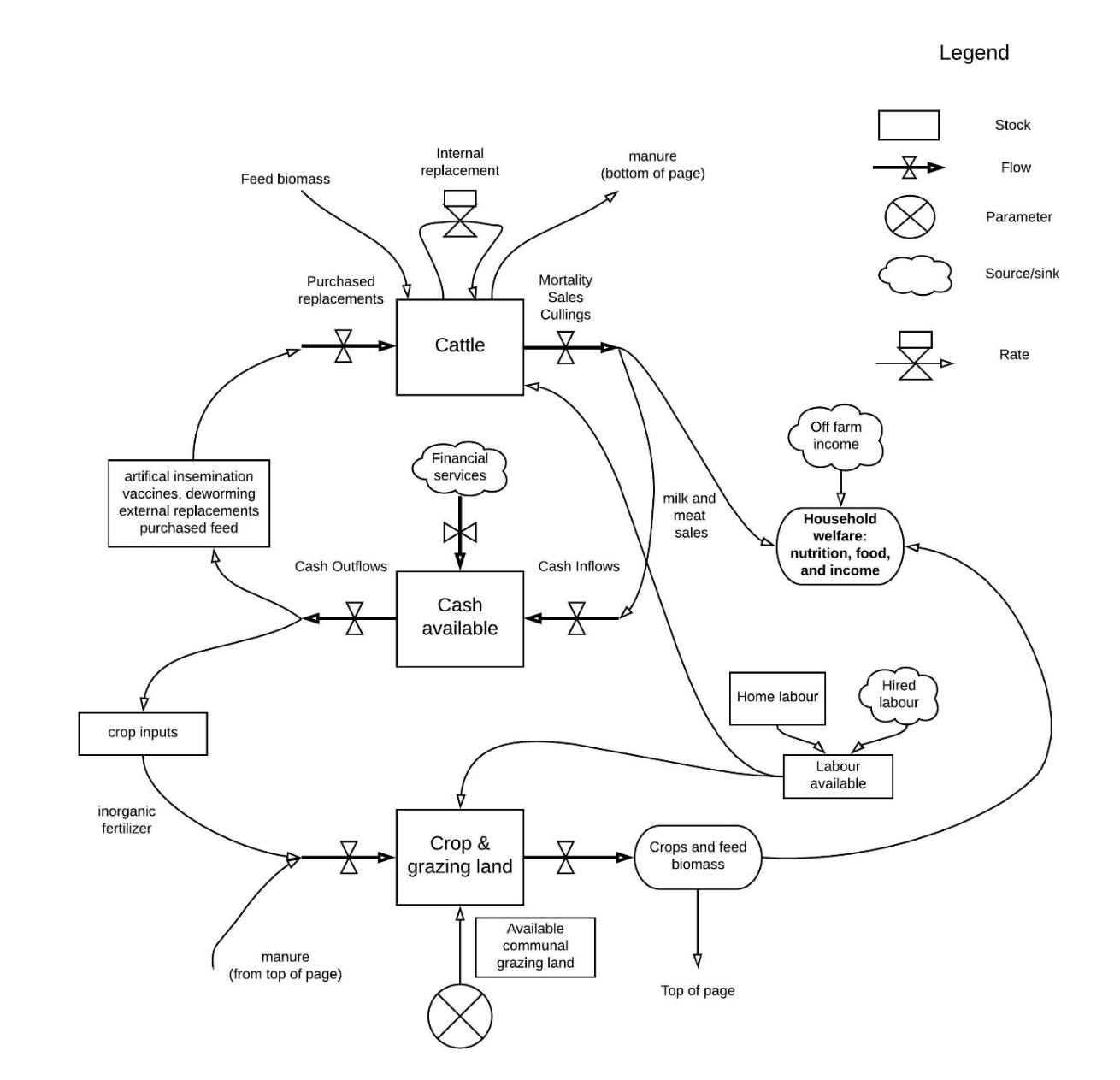


Figure 1: Systems diagram of farm household

Table 1: Resource endowments of farm-household typology

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Variable | Traditional-Grassland based | Intensive-Grassland based | Traditional-Mixed | Intensive-Mixed |
| Number of households |  |  |  |  |
| Arable land (ha) | 2 | 2 | 4 | 4 |
| Grazing land (ha) | -- | 1 | 2 | 2 |
| Cows owned  (head) | 3 local | 3 improved | 8 local | 5 improved |
| Dependentsa  (adult equivalents) | 4 | 4 | 5 | 5 |
| Home labour  (person-days month-1) |  |  |  |  |
| Marketed milk  (kg hh-1 yr-1) |  |  |  |  |
| Milk incomeb  (USD yr-1) |  |  |  |  |
| Non-milk farm income b  (USD yr-1) |  |  |  |  |
| Off farm incomeb  (USD yr-1) |  |  |  |  |

Source: GLDHS (2018)

Notes:

All values are means of sample stratification.

a Total household members are converted to adult male equivalents using the definition of adult male equivalent in Weisel and Dop (2012). These are \_\_\_.

b Values reported in the survey are converted from Tanzanian Shillings (TSh) to USD using an exchange rate of 2,254.60 TSh USD-1, which is the exchange rate effective of the mid-point of the implementation of the survey (February 2018).

* + 1. **Description of household model**

The basic elements of a MP model include an objective function, a series of decision/choice variables over which the model solves, and a series of constraints (Williams, 2013). The model adopted for this study is described as a recursive inter-temporal optimization model (Blanco, Flichman, and Belhouchette, 2011). Under this framework, the model objective function is executed sequentially over a multi-year time frame, with a time step of one year. The model time frame is set at 8 years, because it was theorized that this is approximately the amount of time over which the returns on investing in improved genetics and/or feeding should pay off [[2]](#footnote-2). In each iteration, the model results from the present iteration are used as initializing variables in the subsequent iteration. This approach therefore allows for the assessment of changes in stocks/flows as illustrated in Figure 1 throughout the model time period. For each iteration, the model solves for the household’s utility function. The model objective function is therefore defined as follows:

Maximize U = NPV -

Where U is the household’s utility function, NPV is the *net present value* of the farm enterprise, is a risk aversion coefficient, and is the standard deviation of net present value. The net present value is defined as follows:

NPV =

Where *Farm Income* is annual farm income (USD year-1), *Livestock Assets* is the total value of cattle owned by the household (USD), and *Value Food Consumption* is the total market value of household food production (USD). The *standard deviation of net present value* is calculated following Blanco-Gutierrez et al. (2011), based on the standard deviations of input prices and the farm gate milk price. The input prices for which risk is accounted for are feed prices, and replacement cattle. Under this approach, the standard deviation of NPV is calculated using the Monte Carlo method whereby prices are selected randomly from their probability distributions over a series of (i) iterations, and then the standard deviation of NPV is calculated as follows:

Where *i* represents the set over which the Monte Carlo simulations are run, and NPVi represents the NPV under the prices randomly selected in the *ith* iteration. The standard deviations of these prices are based on farmer reports in the survey. The decision variables of the model are the allocation of available arable cropland between food, fodder, and cash crops, purchase and selling decisions of cattle, as well as the animal diets. Production of crops is subject to an upper arable land constraint for the household. It is assumed households practice semi-grazing for local cattle, but improved cattle are exclusively stall fed, which is representative of practices with respect to households owning large ruminants in the SHDC. Cattle diets are comprised of a combination of different feeds, including grass from rangelands, as well as crop residues, pasture and improved fodders produced by the household using cut-and-carry production, and supplemental feeds purchased on open markets such as XXXX. Rangelands and pasture are distinguished in that the latter involves cultivation, whereas the former does not. Income from the dairy enterprise is based on the quantity of milk produced and marketed from lactating cows, as well as the sale of live animals and meat from culled animals, which are generally important sources of revenue for dairy producing households (Omondi and Baltenweck, 2016). In the SHDC, cash crops, including tea, banana, and coffee are commonly produced in addition to livestock and food crop production. Therefore, land dedicated to cash crops is considered as a model decision variable, assuming fixed gross margins, yields, and labour inputs. Off-farm sources of income, which includes employment income, remittances, and pensions, are exogenous (Table 1) and based on farmer reported values in the survey. For a more complete overview of the equations used, see Appendix B.

*Household resource endowments*

The land holdings per household are based on farmer reported values for owned and rented land in the survey (Table 1). Cattle in the SHDC are grazed on a combination of communal and private grazing land, where private grazing land is either owned by the household or owned by neighbouring farms (REF). Labour for cropping and livestock activities is obtained from labour provided by household dependents as well as hired in labour paid at market wage rates. The availability of home labour is specified based on the survey reported number of household dependents and their respective labour hours contributed to farm activities (Table 1). Hired labour is charged at a wage rate that is based on the farmer reported wages paid to workers employed for dairy and cropping related activities in the survey. These values are \_\_\_ USD person-day-1 for dairy labour, and \_\_\_ USD person-day-1 for crop labour. A cash constraint equation specifies the availability of cash from farm and off-farm sources on a monthly time step (Appendix B). This equation specifies that total cash income from off farm sources, from farm production, and loans are less than or equal to cash expenditure on farm and household related expenses in each month (Appendix B). Non-farm household expenditure is divided into two categories: food and non-food. The amount of money spent on each is calculated using a linear expenditure system (Louhichi and Gomez y Paloma, 2014) (Appendix B.4). This linear expenditure equation specifies food consumption based on the own price and income elasticities of demand, with prices of food based on \_\_\_, and own price and income elasticities of food demand based on Chongela et al. (2014).

**2.1.2 Cropping and Grazing**

Allocation of the household’s arable land to food, fodder (including pasture), and cash crops is an endogenous decision variable of the model. The availability of arable land (Table 1) determines the upper level of these types of crops that can be produced. The additional land owned by the household represents land available for grazing, which in addition to household available communal grazing land, represents the total amount of grazing land available for the cattle. The available crops to be grown are the most common types of crops for the three categories in the SHDC (Table 2). These include maize, beans, groundnut, sorghum, […] for food crops, coffee, tea, bananas, […] for cash crops, and. napier, desmodium, […] for fodder crops. The food crops are exclusively produced for household food consumption, whereas cash crops are exclusively assumed to be sold at market prices. The prices reported by farmers for the three cash crops are \_\_, \_\_\_, and \_\_\_ for coffee, tea, and bananas, respectively. Because these crops are perennials, the assumption is that the acreage decisions are made on a 3-year time step, beginning in the first year of the model. For food crops, crop residues are either harvested and provided as livestock feed, or allowed to stay on the field, where they are either consumed by grazing livestock or decompose and therefore form part of the fertility management of the soil.

The household survey was used to develop crop labour schedules for each crop and in each month of the season (Appendix A). From these crop labour schedules, the total labour requirements for the crop enterprise are calculated as follows:

Where Labour\_Cropm is the total labour requirements for the crop enterprise in a given month (person-days month-1), Area\_Cropc,m is the area dedicated to a given crop, c, in month, m, and Labour\_Cropc,m is the labour-input for crop, c, in a given month. The planting and harvesting dates for each crop are shown in Table 2. For a more complete description of the crop labour schedules, see Appendix A. The household survey was used to ascertain expenses on purchased inputs for crop production, including inorganic fertilizer, seeds, herbicides, and pesticides. These reported crop inputs along with the prices specified were then used to estimate gross margins for each crop, by subtracting the quantity of variable inputs per hectare multiplied by their respective market prices from the product of the crops’ yield and market price (Table 2).

Table 2: Crop and forage gross margins, yields and labour schedules

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Crop | Selling price  (USD  Mg-1) | Yield  (kg ha-1 yr-1) | Gross margin (USD ha-1 yr-1) | Harvest ratio | Crop labour schedules 2  ( O = planting dates, X = harvest dates) | | | | | | | | | | | |
| Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
| Maize | 226.2 | 3,574 |  |  | O |  |  |  |  | X | X |  |  |  |  |  |
| Beans | 575.3 | 5,104 |  |  | X |  |  |  |  |  |  |  | O | O |  | X |
| Sorghum | 307.4 | 967 |  |  |  | O | O |  |  |  |  |  |  |  | X |  |
| Millet | 329.1 | 917 |  |  |  |  | X | X |  |  |  |  |  |  |  | O |
| Groundnut | 399.2 | 705 |  |  |  |  | O | O |  |  |  |  |  |  |  | X |
| Cowpea | 440.9 | 600 |  |  |  |  | O | O | X | X | X |  |  |  |  |  |
| Banana | 383.7 | 7,598 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Pasture3 | -- | 1,500 | -- |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Napier4 | -- | 15,500 | -- |  |  |  |  |  |  |  |  |  |  |  |  |  |

Sources:

1 NBS (2016)

2 FAO CC (2017)

3  Rubanza et al. (2006)

4 Nyambati et al. (2010)

**2.1.3 Dairy cattle**

*Herd model*

Cattle have important multi-faceted roles in smallholder livelihoods (Weiler et al. 2004), and therefore a change in the size or structure of the herd has important implications for household welfare. The aim of the herd model is to assess the role of the stocking rate[[3]](#footnote-3) on the CF of milk produced by the household. Since low input livestock production systems generally have a low ratio of producing to non-producing animals (Bebe et al. 2002), reducing the associated ‘maintenance cost’ of the herd is proposed as a strategy for reducing the CF of dairy production systems (Mottet et al. 2015). Livestock numbers are accounted for using stage structured demographic equations (Hary, 2004). Cattle are disaggregated by breed (local and improved), sex (male and female), and cohorts representing different production stages of the animal’s life cycle. For females, these cohorts include female calves, heifers, and cows. The male cohorts includes male calves, steers, bulls, and castrated adult males. The quantity of animals in each cohort are considered in tropical livestock units (TLU) where one TLU is equal to 250 kg live weight. The amount of animals in each cohort are initially calibrated to farmer reports. In each period after period 1 of the simulation, these values are calculated based on net entries into the cohort (total entries minus exits) (Appendix C.1). The quantity of animals in a given cohort is therefore equal to those in the previous period, minus those that transitioned to the next cohort, plus those that entered the cohort from a younger production stage. Additional sources of exits/entries include mortality, calf births from adult females, sales/purchases, and culling due to old age. The assumption is made that all adult females are culled at the end of life and either consumed as meat or sold. Because local cows generally reproduce via natural mating, the assumption was made that one bull for every five cows was maintained by the household. Improved cattle are assumed to reproduce using AI, and therefore no specification is made related to the quantity of crossbred bulls. The parameters used in the equations for herd demographics are specified in Table 3.

The labour requirements for dairy cattle were estimated based on the dairy labour survey module (Appendix A). Total labour required for the herd is estimated based on required labour inputs per animal (person-days TLU-1 month-1). The total labour requirements for the dairy herd is therefore included in the model using the following equation:

Where Labour\_Dairym is the total labour requirements for the dairy enterprise in a given month, Quant\_Animala is the quantity of animals of a given cohort, a, and Labour\_Animala is the labour required per animal in cohort a.

The expenses related to the dairy enterprise are disaggregated into feed expenses, animal maintenance expenses (including for reproduction and health/veterinary services), and labour. Expenses on purchased feeds are based on the monthly amount purchased and the respective market price of the feed. The feed prices were obtained from farmer reports. These values are \_\_\_ , \_\_\_, \_\_\_, and \_\_\_ USD kg-1 for cottonseed meal, sunflower seed cake, maize grain, and maize bran, respectively. Farmers were asked to specify the amount of cash spent per year on reproductive services and health related services for their cattle. These reported expenses are used to estimate an annual expense per tropical livestock unit (USD TLU-1 yr-1), which is then aggregated to determine the total expenses for the herd. Livestock labour required over and above that provided by household members is charged based on farmer reported wage rates paid to agricultural workers for the dairy enterprise ( \_\_ USD person-day-1).

*Animal model*

Nutrition is the primary determinant of productivity per animal of a given breed. Because native pastures, crop residues and household scraps generally have insufficient energy and protein to meet maximum potential productivity, supplementing with improved fodders and/or concentrate feeds is necessary to meet potential animal productivity. Supplemental feeding increases milk yields during lactation (Shem et al. 2003, Muinga et al. 1992), and daily liveweight gain for growing cattle (Snijders et al. 2011). Improved feeding of young cattle is proposed for reducing time to maturity and increasing productive lifetime per animal (e.g. Bagley, 1993; Osuji et al., 2005). Lactation milk yield of up to 2,200 and 2,700 litres can be achieved for local and improved cattle respectively under optimal feeding conditions (Mruttu et al. 2016) and maximum growth rates of up to 890 and 1,060 g day-1  are attainable, for local and improved animals respectively (Tebug et al. 2017). Such productivity improvements may reduce GHG emissions intensities by reducing methane emissions intensity for lactating females, and by reducing the ratio of non-producing to producing animals, and therefore reducing the ‘maintenance cost’ of the herd (Mottet et al. 2015).

The impact of higher intake of energy and protein is considered by estimating the changes in milk yields and live weight gains for both breeds based on the total supply of metabolisable energy and protein. Available metabolisable energy and protein is calculated based on the dry matter intake of individual feeds and their respective energy and protein contents (Table 4). Energy requirements are calculated as the sum of maintenance, growth, lactation, pregnancy, and activity. Because improved animals are zero-grazed, energy requirements for activity are set at zero. Protein requirements are calculated as the requirements for growth, lactation, and pregnancy (Appendix C).

For local animals, the assumption is that the animal receives part of its diet in fixed proportions provided during stall feeding, and part consumed *ad libitum* during grazing. Since improved animals are exclusively stall-fed, the assumption is that the diet is exclusively obtained from a mixed ration. Because voluntary dry matter intake is dependent on the nutritive properties of the diet, dry matter intake per animal is estimated based on the diet’s dry matter digestibility, which is calculated based on the nutritive value all feeds consumed.

The required grazing land under changing dietary regimens is calculated from the total grazed *ad libitum* pasture intake and the yields of grazing lands in the SHDC (Rubanza et al. 2006) as follows:

Grazing\_Landy =

Where Grazing Landy is the total required land for grazing by the animals in a given year (ha hh-1 year-1), DM Intake is the *ad libitum* dry matter intake of grazed pasture for animals in cohort a (Mg TLU-1 yr-1)[[4]](#footnote-4), and pasture yield is the average dry matter yield of pasture land (Mg DM yr-1).

Table 3: Production parameters for local and improved cattle

|  |  |  |
| --- | --- | --- |
| Parameter | Local | Improved |
| Maximum lifetimea (years) | 13 | 13 |
| Calving intervalc (months) | 18-24 | 15-21 |
| Daily live weight gain1,(g hd-1 d-1) | 250-890 | 250-1,060 |
| Calf mortalitya (%) | 25 | 10 |
| Heifer mortalitya (%) | 13 | 10 |
| Cow mortalitya (%) | 7 | 10 |
| Age to maturity1,c(first calving)(months) | 36-48 | 30-36 |
| Milk yield per adult female1,b (kg hd-1 d-1) | 2-8 | 3-12 |
| Mature weight1,a (kg hd-1) | 260-380 | 360-400 |
| Dressing percentagea (%) | 51-53 | 51-53 |
| Reproductive expensesb (USD TLU yr-1) |  |  |
| Health expensesb (USD TLU yr-1) |  |  |
| Selling price – steers and bullsb (USD TLU-1) |  |  |
| Purchase price – heifersb(USD hd-1) |  |  |
| Purchase price – adult femaleb (USD hd-1) | 220-450 | 650-1,300 |

Notes:

1Values shown are ranges to account for the variation between management and household types.

Sources:

a Mruttu et al. (2016)

b GLDHS (2018)

c LSDS (2010)

d Bebe et al. (2003b)

e Creek (N.D.)

f Tebug et al. (2018)

Table 4: Nutrient properties of feeds used in the model simulations

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Feed | Dry matter  (g kg-1) | Digestible  energy  (MJ kg-1 DM) | Crude  protein  (g kg-1 DM) | Acid  detergent  fibre  (g kg-1 DM) |
| Grazed pasture2 | 300 | 10.4 | 50 | 394 |
| Conserved pasture1 | 916 | 8.7 | 24 | 538 |
| Maize residue2 | 290 |  |  | 359 |
| Bean residue2 | 250 |  |  | 76 |
| Sorghum residue2 | 281 |  |  | 350 |
| Groundnut residue2 | 269 |  |  | 439 |
| Napier2 | 179 | 10.2 | 100 | 425 |
| Maize silage2 | 325 | 13.0 | 69 | 270 |
| Maize grain2 | 863 | 16.1 | 94 | 538 |
| Cottonseed cake2 | 909 | 17.5 | 470 | 178 |
| Soybean meal | 879 | 18.2 | 518 | 83 |
| Sunflower meal2 | 890 | 11.8 | 320 | 320 |
| Fish meal2 | 921 | 21.3 | 754 | 0 |
| Maize bran2 | 887 | 13.4 | 120 | 145 |

Sources:

1Rubanza et al. (2006)

2 INRA (2017)

**2.2 Greenhouse gas emissions intensity of milk production**

The carbon footprint (CF) of milk production is estimated using a consequential life cycle assessment (Plevin et al. 2013, Thomassen et al., 2008). This approach is adopted because intensification and/or scaling up milk production involves greater reliance on purchased inputs produced off farm, as well as land use change resulting from increasing area dedicated to grass and/or cropland (both on farm and upstream). Therefore the full extent of these emissions sources, which includes LUC both on farm and upstream, and fossil fuel emissions associated with purchased inputs consumed by the farm, are included in the definition of CF. The land dedicated to crop and grassland in the base simulations is used as the baseline for the intervention scenarios, to estimate land use change related GHG emissions. The GHG emissions sources accounted for are therefore: CH4 from enteric fermentation, CH4 and N2O from managed manure and manure excreted on pasture, N2O from crop and grassland soils, CO2 emissions from processing and transportation of inputs manufactured upstream from the farm, CO2 emissions from land converted to cropland, and CO2 sequestration from offsets brought about by a reduction in land use. Additional GHG emissions sources, including those related to cattle respiration, farm field work, electricity consumption for milking, or the construction of farm buildings such as barns and sheds are omitted. Further, post-farm gate emissions associated with cooling, transportation, and processing of raw milk are excluded, and therefore the emissions intensity reported is for raw milk produced and consumed at home or sold at the farm gate. GHG emissions between meat and milk are allocated using an economic allocation function. GHG emissions intensity of milk is calculated based on the relative annual market value of milk produced by the herd relative to the annual market value of meat produced, at market prices reported by survey respondents. For preliminary analysis, these market values are 0.26 USD kg FPCM-1 and \_ USD kg (carcass weight)-1. A mass based allocation criterion was used to allocate total crop related emissions between feed for cattle and food and/or sale. The allocation is based on the grain to total biomass yield, based on the harvest ratios listed in Table 3.

*Net emissions intensity*

All the above described emissions sources are used to estimate the net GHG emissions intensity of milk production. Because C offsets may represent a negative emissions source, this value is included in the estimated GHG emissions intensity with a negative coefficient. Methane and nitrous oxide are converted to carbon dioxide equivalents using global warming potentials from the IPCC fifth assessment report, which take values of 28 and 265 kg CH4 and N2O kg-1 CO2eq (IPCC, 2013). The farm gate emissions intensity of milk production is calculated as kilograms of carbon dioxide equivalent emissions per kilogram of fat and protein corrected milk (kg CO2eq kg-1 FPCM). Milk production is converted to FPCM using the correction equation as specified by the International Dairy Federation (IDF, 2010), based on the milk fat and protein content of milk typically observed from dairy farmers in the SHDC. Milk fat percentages of 5.5 and 4.1 were used for local and improved cattle, respectively, and milk protein percentages of 4.1 and 3.5, for local and improved cattle respectively, were used (Rege et al. 2001)

The CF of milk production is therefore calculated as follows:

CF =

Where CF is the carbon footprint of milk production for the simulated farm (kg CO2eq kg-1 FPCM), Direct GHG Emissions are the sum of cattle, manure, soil, and farm input emissions as described above (kg CO2eq year-1), and and are calculated as described above (kg CO2 year-1) . Fat and protein corrected milk is in kg yr-1.

* 1. **Scenarios**

The research objectives as described above are to assess the role of market linkages on the upgrading behaviour of dairy producers, and in turn, the CF of milk production. Because previous studies exclusively focus on production oriented interventions (e.g. input subsidies), the aim of the present study was to isolate the effect of the household’s mode of participation in outputs markets on upgrading behaviour. A description of how these scenarios are implemented is described below.

*Production oriented interventions*

*Credit/loan availability*

The effect of loan availability for the household is assessed by providing an optional loan of up to 500 USD. The interest rate is fixed at 15%. The loan conditions are that a fixed annual payment towards the principle is paid every year after the loan is received, and the total length of time to pay off the loan is 10 years. Therefore in every year after the loan is received, the household pays expenses on both the loan repayment, as well as interest on the remaining principle.

*Feed input*

The most significant animal feeds for the dairy sector in Tanzania by quantity of production are maize grain, maize bran, fish meal, cottonseed meal, sunflower seed cake, and soybean meal (Geertz, 2014). The former three are used as an energy supplement, while the latter four are used as a protein supplement. The input intervention involves reducing the prices of these feeds by 30%.

*Availability of improved dairy genetics*

High mortality and low growth rates of cattle in smallholder farming systems generally imply that farmers are not able to maintain their herds through internal replacement, and are therefore required to purchase replacement heifers and cows off farm (Bebe et al. 2002, 2008). The quantity of improved replacement animals is generally low and therefore prices are high. To assess the impact of higher availability of improved replacement animals, a scenario is run with a 30% reduction of the mean price of replacement animals specified from farmer reports. These values are \_\_\_\_ USD for heifers and \_\_\_ USD for cows.

*Processor linkages*

A contractual engagement with a milk processor is simulated by specifying a guaranteed annual quantity and price received for milk. This involves a guarantee of 10,000 kg purchased per year, paid at a price of 0.26 USD kg-1. For any milk sales in addition to this value, the farm receives a market price of 0.20 USD kg-1.

The format for the scenarios conducted include (1) a base scenario, (2) a production oriented intervention scenario, based on credit, feed inputs, and replacement animals as described above, (3) a processor linkage scenario, as described above, without production oriented interventions, and (4) a scenario involving both production interventions and improved processor linkages (e.g. 2 and 3 combined).

1. **Results**
   1. Model Validation

Validation of the model involves comparing observed herd sizes and structure, milk offtake, and land allocation in the study region to the endogenously determined values from the base model simulation. This ensures that the model reproduces the production characteristics of dairy producers given the same exogenous factors.

3.2 Intervention scenarios

The total farm milk production, land use (total feed crop land and grazing area for dairy), farm gate greenhouse gas emissions intensity of milk, household income, and household nutrition security are presented for each scenario.

* 1. Sensitivity Analysis

Key sources of uncertainty in the modelling analysis are with respect to biomass yields and labour demands for biomass production. Due to high data requirements for acquiring labour data, and the high data and modelling requirements for estimating crop and pasture yields endogenously, we conduct sensitivity analysis by varying the values for these parameters.

Further, uncertainty exists in the initial land use undergoing conversion to cropland (in the case the household expands total crop production), as well as the types of land cattle graze on. Therefore these two sources of uncertainty are considered in the sensitivity analysis by considering the full range of initial C storage values for the land which undergoes conversion.

Table 5: Validation of base model

|  |  |  |  |
| --- | --- | --- | --- |
| Result | Base Scenarioa | Observedb | Percent deviation |
| Income from milk sales (USD hh-1 yr-1) |  |  |  |
| Milk Production (kg hh-1 yr-1)  Consumed  Sold |  |  |  |
| Herd Size (hd hh-1)  Cows (hd hh-1)  Non-cows (hd hh-1) |  |  |  |
| Land Use  Cropland (ha kg-1 FPCM)  Pasture (ha kg-1 FPCM)  Grazing Land (ha kg-1 FPCM)  Total Land footprint (ha kg-1 FPCM) |  |  |  |

Sources:

a Model calculated

b GLDHS (2018)

Figure 2: Greenhouse gas emissions intensities of milk production

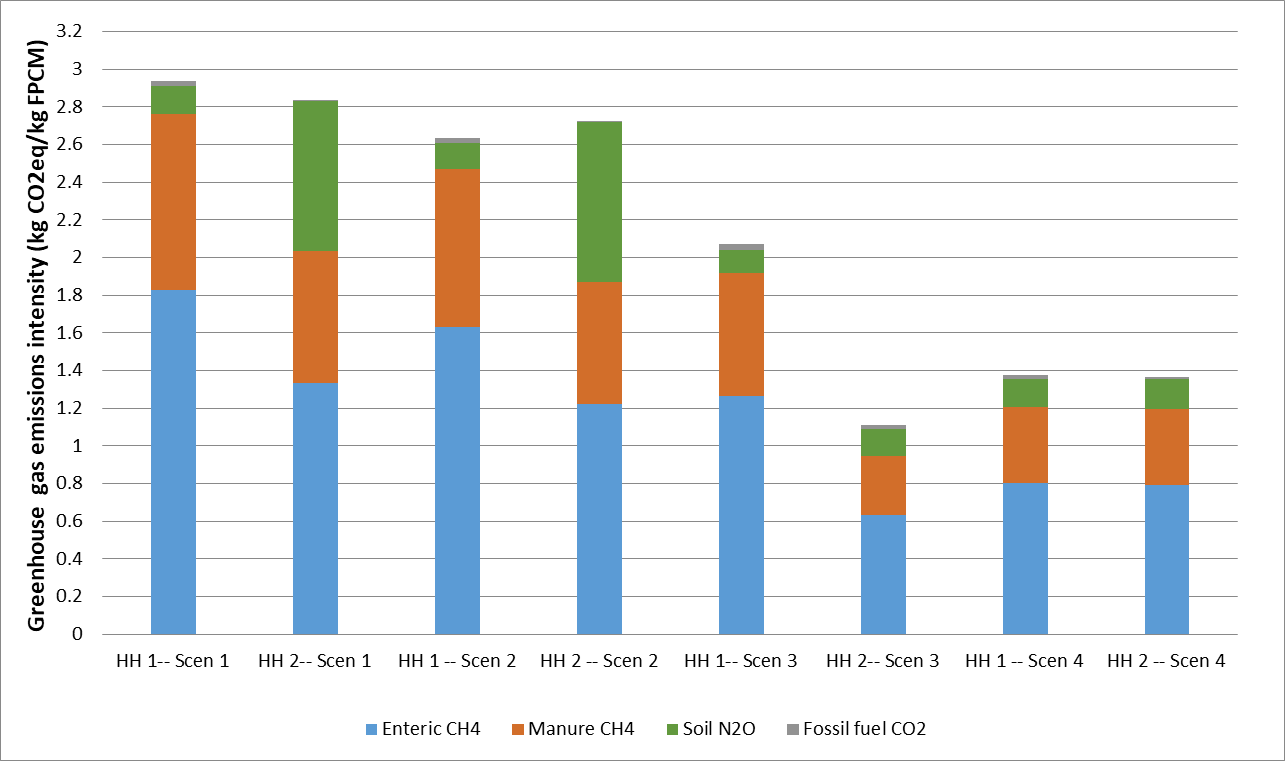


Table 6: Main model results

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Scenario** | Base | | Input subsidies | | Milk contract | | Milk contract & input subsidies | |
| **Household** | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| **Variable** |  |  |  |  |  |  |  |  |
| *Income (USD per household year)* |  |  |  |  |  |  |  |  |
| Dairy income | 499,938 | 817,284 | 381,635 | 2,641,772 | 580,439 | 2,248,287 | 2,567,332 | 3,473,629 |
| Total household income | 2,879,938 | 3,137,284 | 2,761,635 | 4,961,772 | 2,960,439 | 4,568,287 | 4,947,332 | 5,856,722 |
|  |  |  |  |  |  |  |  |  |
| *Production (kilograms per household per year)* |  |  |  |  |  |  |  |  |
| Milk production | 1581.5 | 1316.1 | 1550.3 | 8098.3 | 4122.3 | 9169.5 | 8692.2 | 9257.6 |
| Meat production | 434.7 | 877.8 | 426.4 | 80.4 | 380.9 | 79.5 | 89.0 | 217.4 |
|  |  |  |  |  |  |  |  |  |
| *Cattle*  *(Tropical livestock units)* |  |  |  |  |  |  |  |  |
| Local non-cows | 1.2 | 0 | 5.8 | 0 | 6.0 | 0 | 5.9 | 0 |
| Local Cows | 3.1 | 0 | 3.1 | 0 | 3.2 | 0 | 3.3 | 0 |
| Improved non-cows | 0 | 1.1 | 0 | 1.5 | 0 | 1.5 | 0.1 | 1.2 |
| Improved Cows | 0 | 2.2 | 0 | 4.3 | 0 | 4.3 | 1.1 | 2.2 |
|  |  |  |  |  |  |  |  |  |
| *Land (hectares)* |  |  |  |  |  |  |  |  |
| Cropland on farm | 1.13 | 1.40 | 01.0 | 2 | 1.03 | 2.01 | 2 | 0.7 |
| Cropland off farm | 1.13 | 0.60 | 0.96 | 2.33 | 2.63 | 3.43 | 3.34 | 1.2 |
| Rangeland | 0 | 0.81 | 1.55 | 2.53 | 0.69 | 1.24 | 2.85 | 0.1 |
| Pastureland | 1.82 | 3.28 | 0 | 3 | 3.11 | 3.13 | 3 | 3 |
| Total land use | 3.60 | 5.93 | 3.21 | 8.87 | 6.83 | 8.56 | 9.76 | 4.6 |

Source: Model output

1. **Discussion**

The dairy sector is not generally acknowledged as a direct driver of deforestation in sub-saharan Africa (Hosonuma et al. 2012). However, crop and grasslands are major occupier of land and therefore reducing land use offers one avenue for mitigating the net GHG footprint from dairy production (e.g. Foley et al. 2005). What does this study suggest in terms of the potential for using C offsets to reduce net GHG emissions from the dairy sector in Tanzania?

Other topics:

* How do baseline GHG emissions differ between farms?
* What are the tradeoffs between strategies to reduce greenhouse gas emissions and increase incomes and nutrition security for rural households?
* What types of policy interventions are most promising for reducing absolute GHG emissions?
* What is the role of land use in relation to the potential for GHG mitigation in the dairy sector?

**5.0 Conclusion**

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**Appendix A – Household labour availability and requirements**

A.1 Household labour availability

Labour availability from household members is specified based on the number of household members and an estimated amount of labour hours per person per week dedicated to farm labour. This value is summed up over all household members and converted to a monthly farm labour availability from household members (person-days hh-1 month-1), and enters the labour balance equation (Appendix B.3 below) as the available home labour.

A.2 Dairy cattle labour (as of 12.20.2017)

In order to develop a labour demand schedule for the household’s dairy enterprise, a subsample of the total survey sample responded to an additional module on labour activities related to the dairy enterprise. The households were asked about the amount of home and hired labour devoted to different categories of activities, as total hours per week per household. The activities of labour include on farm and off farm cattle herding, feed collection and storage, feeding, watering, maintaining cattle pens, milking, reproduction, and other. The sources of labour were disaggregated into household male, female, children, temporary hired, and permanent hired. The results are summarized in Table A.2. To obtain the labour requirement per livestock unit, total labour requirements per activity and by source (household and hired) were divided by the number of livestock owned per household. This labour requirement is converted to person-days (one person-day is equal to 7.5 hours of labour) and used to specify a monthly requirement, and enters the labour balance equation (Appendix B.3 Labour constraint), representing the labour requirements for maintaining the dairy herd (person-days month-1).

Table A.2: Labour requirements for dairy activities (as of 06/01)

|  |  |  |
| --- | --- | --- |
| Activity | Labour Hours Per Activity | |
| Hours per week per household  (hours week-1  household-1) | Hours per TLU  per week  (hours head-1 week-1) |
| Herding own-farm | 3.22 | 0.95 |
| Herding off-farm | 8.88 | 2.27 |
| Feed Collection and Storage | 11.74 | 5.63 |
| Feeding | 21.21 | 9.86 |
| Watering | 32.04 | 12.9 |
| Maintaining cattle housinga | 9.42 | 4.03 |
| Milking | 30.44 | 11.60 |
| Animal Reproduction | 0.20 | 0.05 |
| Other | 0.07 | 0.02 |
| Total | 117.02 | 47.31 |

Source: GLDHS (2018)

Notes: a cleaning pens,

A.3 Cropping Labour Data

In order to develop labour schedules for cropping activities, a subsample of households (n= ) were asked detailed questions relating to the labour dedicated to different cropping activities, including food, cash, and fodder crops. The questionnaire asked respondents the number of person-days devoted to individual activities for a given crop and in a given production cycle (one season for annual crops, one growing cycle for perennials) (Table A.3.1 and A.3.2). The activities included all major activities associated with crop production, from pre-harvest to post-harvest activities, including storage and transportation. Next, the labour inputs are converted to intensity levels (person-days of labour per hectare). Finally, a monthly labour requirement schedule per crop is developed by linking this activity data to the growing season in the local region per crop. The resulting value expresses person-days of labour per month per hectare (person-days month -1  ha-1) and is used as a labour requirement for that given cropping activity in the labour balance equation (Appendix B.3 – Labour balance).

Table A.3.1 – Annual Crop Labour Data

|  |  |  |  |
| --- | --- | --- | --- |
| Crop | Purpose | Harvests per growing cycle | Yield  (kg ha-1) |
| Maize | Food | 1-2 |  |
| Beans | Food | 1 |  |
| Sweet Potatoes | Food | 1 |  |
| Millet | Food | 1 |  |
| Sorghum | Food | 1 |  |
| Groundnut | Food | 2 |  |
| Tomatoes | Cash | 2 |  |
| Tea | Cash | 2 |  |
| Coffee | Cash | 2 |  |
|  | Cash |  |  |
|  |  |  |  |

Table A.3.2 – Perennial Crop Labour Data

|  |  |  |  |
| --- | --- | --- | --- |
| Crop | Purpose | Number of years per production cycle | Yield  (kg ha-1) |
| Beans | Food | 1 |  |
| Sweet Potatoes | Food | 1 |  |
| Groundnut | Food | 2 |  |
| Tea | Cash | 2 |  |
| Coffee | Cash | 2 |  |
|  | Cash |  |  |

Table A.3.3 Annual food crop labour data

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Activity | Maize  (n = ) | | Beans  (n = ) | | Sweet Potatoes  (n = ) | | Millet  (n = ) | | Sorghum  (n = ) | | Groundnut  (n=) | |
| Total  (mandays plot-1) | Intensity  (mandays ha-1) | Total (mandays plot-1) | Intensity  (mandays ha-1) | Total  (mandays plot-1) | Intensity  (mandays ha-1) | Total  (mandays plot-1) | Intensity  (mandays ha-1) | Total  (mandays plot-1) | Intensity  (mandays ha-1) | Total  (mandays plot-1) | Intensity  (mandays ha-1) |
| Land Clearing |  |  |  |  |  |  |  |  |  |  |  |  |
| Land Preparation |  |  |  |  |  |  |  |  |  |  |  |  |
| Planting |  |  |  |  |  |  |  |  |  |  |  |  |
| Weeding/Cleaning |  |  |  |  |  |  |  |  |  |  |  |  |
| Pruning |  |  |  |  |  |  |  |  |  |  |  |  |
| Fertilizing |  |  |  |  |  |  |  |  |  |  |  |  |
| Harvesting |  |  |  |  |  |  |  |  |  |  |  |  |
| Processing |  |  |  |  |  |  |  |  |  |  |  |  |
| Storage |  |  |  |  |  |  |  |  |  |  |  |  |
| Transporting |  |  |  |  |  |  |  |  |  |  |  |  |
| Total |  |  |  |  |  |  |  |  |  |  |  |  |

Table A.3.4 Annual cash crop labour data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Activity | Tomatoes  (n = 6) | | Tea  (n=) | | Banana  (n=) | |
| Total  (mandays plot-1) | Intensity  (mandays ha-1) | Total  (mandays plot-1) | Intensity  (mandays ha-1) |  |  |
| Land Clearing | 0 |  |  |  |  |  |
| Land Preparation | 6 |  |  |  |  |  |
| Planting | 4.5 |  |  |  |  |  |
| Weeding/Cleaning | 9.5 |  |  |  |  |  |
| Pruning | 0.5 |  |  |  |  |  |
| Fertilizing | 3 |  |  |  |  |  |
| Harvesting | 6.5 |  |  |  |  |  |
| Processing | 4.5 |  |  |  |  |  |
| Storage | 0 |  |  |  |  |  |
| Transporting | 0 |  |  |  |  |  |
| Total |  |  |  |  |  |  |

Notes: All labour data is per growing cycle (one season).

Table A.3.5 Annual fodder crop labour data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Activity | Napier | |  |  |
| Total  (mandays plot-1) | Intensity  (mandays ha-1) |  |  |
| Land Clearing | 0 |  |  |  |
| Land Preparation | 6 |  |  |  |
| Planting | 4.5 |  |  |  |
| Weeding/Cleaning | 9.5 |  |  |  |
| Pruning | 0.5 |  |  |  |
| Fertilizing | 3 |  |  |  |
| Harvesting | 6.5 |  |  |  |
| Processing | 4.5 |  |  |  |
| Storage | 0 |  |  |  |
| Transporting | 0 |  |  |  |
| Total |  |  |  |  |

Notes: All labour data is per growing cycle (one season).

**Appendix B – Summary of household mathematical programming model**

**B.1 Objective function**

The household mathematical programming model is summarized as follows. The model maximizes an objective function subject to a series of constraints and identities which define household resource endowments, and the relationships between the endogenous decision variables and production. The mathematical specification of the model is as follows:

Maximize U = NPV -

By choosing area allocated to food, cash, and fodder crops, and replacement and feed purchases for the dairy enterprise, and,

Subject to:

Household cash constraint

Household labour constraint,

Household arable land for crop production,

Household total crop and pasture land,

and model identities defining relationships between the decision variables and farm production.

The above objective function is further defined as follows: U is the household’s utility function, NPV is the net present value of the household, including farm income, farm assets, and food consumption, is the standard deviation of net present value, and is the risk aversion coefficient. Off farm income is assumed exogenous.

Net present value is further defined as follows:

Where FI is farm income (USD yr-1), the sum of CI, crop income (USD yr-1) , LI, livestock income (USD yr-1) , and Livestock Assets (USD). VFC is the value of food consumption (USD yr-1). A 10 year horizon is set (Y = 10). The discount rate used is 4 %.

Crop income is revenues from crop sales minus cash expenses on crop inputs. The selling prices of crops and prices of inputs are specified in Table 4 and section 2.1.1 of the text, respectively. Cash expenses on crop inputs include fertilizer, seeds, and labour. Cash expenses on the dairy enterprise include replacements, feeds, breeding services, health services, and hired labour.

The types of risk considered are biomass yields (crops and pasture), and output prices (crops and milk). Variation in the biomass yields are specified based on the historical standard deviation of the individual types of biomass, in relation to a trend line (representing annualized average change in yields) (see text Table 4). The standard deviation of net present value, is then calculated based on the standard deviation of the underlying yields and prices.

**B.2 Cash constraint**

The cash constraint equation considers the inflows and outflows of cash for the household in each time period. It is defined as follows:

Farm Incomem + Off Farm Incomem = Farm Expensesm + Household Expenditurem + Net Savingsm

Where Off Farm Income (USD yr-1) is equal to off farm employment income, pensions, and remittances. Farm expenses are the sum of expenses for crop and livestock production (as described above). Household expenditure is the sum of cash expenses for household food and non food expenses. Food expenses by the household are defined below. Non food expenses are set at \_\_ % of annual household income. Net savings is equal to savings in month m (USD) minus loans in the same period (USD). Loan expenses are the sum of the payment on principle (USD) and the expenses on loan repayment (USD).

**B.3 Labour Constraint**

A household level labour balance equation ensures that total labour requirements for farm activities is supplied by either home or hired labour. The farm activities include labour allocation per crop and livestock.

Labour\_Requirement,m = + LabourCrop

Where

Labour\_Requirement m is the total household labour requirement for farm activities in month m

is the area dedicated to crop c (ha)

is the required labour input for crop c in month m (person days per month)

is the quantity of cattle (hd) in cohort a

a is the quantity of labour input per head of cattle in cohort a (person-days per month)

The index a includes all cohorts of cattle in the herd, including male and female calves, heifers, steers, cows, castrated adult males, and bulls

The following equation specifies the source of labour for farm activities:

Labour\_Requirementm = Home\_Labourm + Hired\_Labourm

Where

Home\_Labourm is the total availability of labour from household members (person-days per month)

Hired\_Labourm is the quantity of hired labour (person-days per month)

**B.4 Arable land constraint**

Arable land area

Where

Arable land area is the total land holdings of the household (owned plus rented) which are arable) and suitable for growing crops (ha).

**B.5 Total land constraint**

+ Pasture\_Land Total land availability

Where

Pasture\_Land is total land available for grazing, which is the sum of owned and communal grazing land (ha)

Total land holdings is total land holdings of the household (owned and rented) (ha)

**B.6 Household expenditure**

A Linear Expenditure System, as used in Louhichi and Gomez y Paloma (2014), calculates the quantity of food consumed by the household each year:

piqi = γi +βi (I − ∑ γj pj )

Where

0 < βi < 1

= 1

qi – γi >0

where pi is the price of good i, qi is the quantity of good i consumed by the household; I is household income from farm and non-farm activities. βi and Υi are the parameters in the Linear Expenditure System. This system considers ∑γjpj as subsistence expenditure and I− ∑γjpj as supernumerary income (Sadoulet and de Janvry, 1995). To compute βi and Υi we adapted the income elasticities of food demand for Tanzania from Chongela et al. (2014) and the Frisch parameter for Africa south of the Sahara from Aguiar et al. (2016).

**Appendix C – Livestock**

**C.1 Stage structured mathematical accounting of herd cohorts**

The quantity of cattle of a given breed and cohort in each time period are defined in the following equation:

Qm,a,b = Qm-1,a,b - Net transitsm-1,a,b - Deathsm-1,a,b - Offtakem-1,a,b + Birthsm-1,a,b + Net Purchasesm-1,a,b

Where Qm,a,b is the quantity of cattle of a given breed, b, a given cohort, a, in month m, Transits represents the fraction of animals that transition from one cohort to the next, Deaths represents the fraction of animals that exit due to mortality, Offtake represents the animals that are culled for meat consumption (at home or sold), Net Purchases is equal to purchase of replacement animals minus those sold, and Births represent new born calves that are born from adult females maintained by the household. The cohorts include male and female calves, heifers, steers, adult females, and bulls. The breeds include local (Bos Indicus) and improved (Bos Taurus, potentially mixed with Bos Indicus).

The specification of the above parameters for stage structured demographics are based jointly on model parameters, and endogenous variables dependent on household decision making. The transits are calculated based on the growth rate and the amount of time from which calves transfer to heifers/steers, and heifers/steers transfer to adults. The offtake regime is also dependent on household management. For households relying on sexed semen, males are kept within the herd in a ratio sufficient to reproduce. The ratio of adult males to females for self reproducing households is based on sex ratios obtained from GLBS (2018). For households relying on AI, males are sold after reaching maturity. Adult females are maintained until the end of life and sold for meat. Deaths are equal to the cohort specific mortality rate multiplied by animals per cohort. Births per adult female are dependent on the calving interval.

Replacement heifers and cows are purchased in order to sustain the herd (internal replacement rate is not sufficient to meet household requirements for cows). Purchases on replacement females are needed as smallholder dairy herds are generally not self sustaining (Bebe et al, 2003a). Therefore, the purchases of replacement heifers and cows is sufficient to maintain the desired cow population on farm.

**C.2 Nutrient requirements of dairy cattle**

Where is total metabolisable energy intake, is metabolisable energy intake for maintenance, MEgrowth is metabolisable energy intake for growth, MElactation is metabolisable energy intake for lactation, MEpregnancy is metabolisable energy intake for pregnancy, MEactivity is metabolisable energy intake for activity. All values are in MJ hd-1day-1.

Where MPtotal is total intake of metabolisable protein, MPgrowth is metabolisable energy intake for growth, and MPpregnancy is metabolisable energy intake for pregnancy. All values are in kg head-1 day-1.

**Appendix D – Carbon footprint of milk production**

**D.1 Emissions from livestock and agricultural soils**

*Methane and nitrous oxide from enteric fermentation and manure*

Methane from enteric fermentation is calculated as a function of the methane conversion factor (Ym) using the following equation from FAO (2017):

Ym = 9.75 - .05 x DMD

Where Ym represents the fraction of dietary gross energy intake converted to methane (%), and DMD is the dry matter digestibility of the diet (g/100 g DM) as described above. Next, methane produced from enteric fermentation per animal per day is estimated based on the following equation from IPCC (2006):

Where is methane production from enteric fermentation (kg CH4 head-1 day-1), GEI is gross energy intake (MJ head-1 day-1), and 55.65 converts energy in MJ to methane in kg (55.65 MJ kg-1 CH4). Because feeding is endogenous, total methane production from enteric fermentation is calculated for each animal maintained by the herd, based on the animal’s individual intake of GEI and the individually calculated Ym, and converted to an annual value. Methane produced from manure per animal per day is estimated based on the amount of volatile solids produced from manure using the following equation from IPCC (2006):

Where VS is volatile solids excretion (kg VS head-1 day-1), DE is the digestible energy of the feed (percentage), (UEGE) is urinary excretion as a fraction of gross energy, ash is the ash content of manure, and 18.45 is a conversion factor for dietary gross energy per kg of dry matter (MJ kg-1). [assumptions about UExGE and ash content]. Next, methane emissions from manure are estimated as follows:

= VS

Where is the daily methane emitted for a given animal (kg CH4 head-1 day-1), Bo is the methane producing capacity, 0.67 is a conversion factor for m3 CH4 to kg CH4, MCF is the methane conversion factor. Since improved animals in the model are not allowed to graze, a MCF of 5% is used, which is the IPCC default factor for solid storage in warm climates. For local animals, the MCF is calculated as a weighted average of that for confined animals (5%) and that for manure excreted on pasture, which takes a value of 2.0%, which is the default value for unmanaged manure in warm climates (IPCC, 2006).

In order to estimate nitrous oxide emission from manure management and manure excreted on pasture, first nitrogen intake per animal is estimated based on the animal’s diet, next nitrogen retained is estimated based on requirements for lactation and gain. Direct and indirect N2O emissions are then estimated from the resulting N excretion per animal using the relevant emission factors. N intake per animal is estimated based on IPCC (2006) as follows:

Where is daily N consumed per animal (kg N head-1 day-1), and CP is the crude protein concentration of the diet (kg kg-1 DM), 6.25 converts dietary protein to N. N retained for lactation is estimated as follows:

Where is nitrogen retained for lactation per animal, milk is milk yield per animal, and milk protein is the milk protein percentage of milk (%). Nitrogen retained for weight gain is estimated using the following equation from NRC (2001):

Where is the nitrogen required for weight gain (kg head-1 day-1), weight gain is the animal’s daily weight gain (kg head-1 day-1), NEGain is the animal’s net energy requirements for gain, 1000 is a conversion factor from g to kg. Finally, the amount of excreted nitrogen is estimated as follows:

NitrogenExcreted = Nitrogenintake - Nitrogenretained

Where NitrogenExcretd is nitrogen excreted per animal per day (kg N head-1 day-1). Direct nitrous oxide emissions per animal per day are then estimated using:

N2ODirect = NitrogenExcretedEF3

Where 44/28 converts nitrogen to nitrous oxide, and EF3 is the emission factor for direct N2O emissions from manure management. Indirect N2O emissions from manure include that from volatilization and leaching. In order to estimate these two sources of N2O, first the amount of manure lost through volatilization and leaching is estimated, and next, the amount of N2O emissions from both sources is estimated. The equation used to estimate N losses from volatilized N is as follows (IPCC, 2006):

NVolatilized =

Where Fracgas is the fraction of excreted N volatilized as NH3 and NOx gas in the manure management system. A value of \_\_ is assumed (IPCC, 2006). Next, nitrous oxide from volatilized N is calculated as follows:

N2OVolatilization = NVolatilization  EF4

Where N2OVolatilization is the amount of volatilized N2O from manure, and EF4 is the emission factor for atmospheric deposition of nitrogen on soils and water surfaces, kg N2O (kg NH3 + NOx)-1. A default value of 0.01 is assumed (IPCC, 2006). The equation used to estimate N losses through leaching is as follows from IPCC (2006):

NLeaching =

Where NLeaching is the amount of manure nitrogen that is leached per animal per day (kg N head-1 day-1). Next, nitrous oxide from leached N is calculated as follows:

N2OLeaching = NLeaching  EF5

Where N2OLeaching is nitrous oxide emissions from leached manure N (kg head-1 day-1). A default value of 0.0075 kg N2O-N kg-1 N is used (IPCC, 2006). To calculate total leaching N2O emissions for the herd, the daily value per animal is summed up over all animals in the herd, and converted to an annual

**D.2 Agricultural soils emissions**

*Nitrous oxide emissions from crop and grassland soils*

The land footprint of dairy production in the model is the sum of all rangeland, managed pasture, and cropland used for feed production. Nitrous oxide emissions from crop and grassland soils represents a significant GHG emissions source (Pelster et al. 2017) and therefore fluxes of these soils are calculated and included in the definition of GHG emissions intensity. The total flux of GHG emissions from these soils are estimated as follows:

N2OSoils

Where N2OSoils is the total annual flux of nitrous oxide from crop and grassland soils (kg CO2eqyear-1), land\_use represents the different categories of land use (Table 5), arealand\_use represents the area (ha) dedicated to a given land\_use, and fluxland\_use represents the annual N2O flux from a given land use (kg CO2eq ha-1) (Table 6; Total GHG flux).

Table 6: Greenhouse gas fluxes and carbon storage parameters of land use

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Land Use | N Emission Factor  (kg N2O kg N-1) | Greenhouse gas fluxes | | Allocation Factor  (fraction) |
| CO2 Flux  (Mg ha-1 yr-1) | N2O Flux  (kg ha-1 yr-1) |
| Native  Pasture | -- | 13.4a  (2.6)a | 2.3a  (1.3)a |  |
| Napier | 0.5c  (0.2)c | 6.7a  (1.2)a | 0.5a  (0.2)a |  |
| Maize | 0.5c  (0.2)c | 4.2a  (0.8)a | 0.9a  (0.7)a |  |
| Sunflower | 0.5c  (0.2)c | 5.8b  (1.5)b | 0.18b  (0.15)b |  |
| Cottonseed | 0.5c  (0.2)c | 5.8b  (1.5)b | 0.18b  (0.15)b |  |

Sources:

a Rosenstock *et al* (2016)

b Pelster *et al* (2017)

c Kim *et al* (2016)

d Wilcock *et al* (2012)

e Nel *et al* (2013)

Notes:

**D.3 Land use change emissions**

*Carbon dioxide emissions from land use change*

Converting native ecosystems and/or grasslands to cropland results in CO2 losses from land use change (Guo and Gifford, 2002). This land use change can occur through an increase in the area allocated to feed crop production on farm, as well as an increase in the purchase of feed crops produced upstream from the farm. CO2 emissions from cropland conversion are calculated in relation to the total amount of cropland dedicated to feed production in the base scenario. The quantity of CO2 emitted from land conversion is calculated considering the variation in C storage contents in the land undergoing conversion to cropland. Soil C emissions/sequestration from land use change is believed to follow an exponential curve (Arrouays et al., 2002; Milne et al., 2005; Soussana et al., 2004), with the greatest CO2 emissions/sequestration occurring immediately after LUC. CO2 emissions after LUC occurs are therefore estimated based on an exponential function:

= ( (1-

Where is the quantity of CO2 emitted from cropland conversion in a given year (kg CO2 yr-1), is the total change in area (ha) dedicated to cropland for cattle feed relative to the baseline scenario, e is the exponential constant, k is a rate constant, y is the number of years since management change, and is the maximum change in C storage between the land undergoing conversion and cropland. Because the type of land undergoing conversion is unknown, the value used for the C storage content for the initial land use is based on a weighted average of C storage contents of all possible non-urban land uses in the SHDC. The actual data sources and procedure used for calculating this value is described in Appendix D. The value used for preliminary analysis is 100 Mg C ha-1. The value calculated above is converted from Mg C yr-1 to kg CO2  yr-1 and included in the reported CF of milk production for the farm.

**D.4 Carbon density of land**

Mean carbon density of land (Mg C ha-1) for each district is calculated as a weighted average of percentage of non-urban land area allocated to a given land category, and the respective carbon density of that land use. The C densities are based on Willcock et al. (2012) and take values of 416.9 Mg C ha-1 for forestry, 162.1 Mg C ha-1 for grassland, and 127.9 Mg C ha-1 for cropland. The land use is based on MODIS raster data for the year 2012 (Channan, Collins, and Emmanuel, 2014). The mean C densities (MCD) of land for each district are calculated as:

Where Area is the total land area of land use I in region r (ha), and Carbon\_Content is the C content of all 5 IPCC pools in land use I (Mg C ha-1).The categories of land use are shown in

Table D.3: Land use areas per region (Mha)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Land use | Region | | | | |
| Mbeya | Morogoro | Iringa | Njombe | Rukwa |
| Cropland | ha | ha | ha | ha | ha |
| Grassland | ha | ha | ha | ha | ha |
| Shrubland | ha | ha | ha | ha | ha |
| Forest | ha | ha | ha | ha | ha |
| Total |  |  |  |  |  |

Source: Channan, Collins, and Emmanuel (2014).

1. Incorporation of risk in such models, through either changes in gross margins (Dake et al. 2005) or climate variability (Kingwell et al. 1993). [↑](#footnote-ref-1)
2. This value is based on the assumption that the return on investing in crossbred genetics and/or higher quality feeding is not realized until the cow has produced the majority of its lifetime milk yield, equal to around the 4th or 5th parity (Dizyee, Baker, and Omore, 2017). [↑](#footnote-ref-2)
3. Stocking rate will be defined in this study as the total number of animals maintained by the household, as opposed to the alternative definition which relates cattle to the amount of land used for feed production (e.g. head ha-1 or TLU ha-1). [↑](#footnote-ref-3)
4. Note this value is calculated as the required feed intake in addition to the feed provided during stall feeding. [↑](#footnote-ref-4)